ABSTRACT

BURCHELL II, MICHAEL REED. Practices to Reduce Nitrate-Nitrogen Losses from Drained Agricultural Lands. (Under the direction of Dr. R. Wayne Skaggs).

Two practices were studied to reduce nitrate-nitrogen (NO_3^--N) losses from drained agricultural lands - shallow subsurface drainage systems and in-stream constructed wetlands.

Twenty-one months (January 2001-September 2002) of data was collected from two drainage systems located in a swine waste application field with a bermuda/rye grass rotation at the NCDA – Tidewater Research Station near Plymouth, NC. Drains in Plot 1 were 1.5 m deep and 25 m apart, while the drains in Plot 2 were 0.75 m deep and 12.5 m apart. Decreased drain depth reduced drainage outflows by 42% during the study. Nitrate-nitrogen concentrations in groundwater at the 90-120 cm and the 150-180 cm depth were significantly lower in Plot 2 (22.9 and 0.1 mg/L respectively) than in Plot 1 (39.1 and 15.5 mg/L respectively) in 2002. This difference was most likely a result of higher water tables and a larger reduced zone formed with the shallow drainage system, which increased denitrification potential. However, the average NO_3^--N concentration in the drainage water from the shallower drains (7.6 mg/L) was significantly higher than in the deeper drains (2.4 mg/L) in 2001. In 2002, there was no significant difference in the average NO_3^--N concentration in the drainage water from the shallow drains (15.7 mg/L) and the deeper drains (12.8 mg/L). On average, NO_3^--N export from the shallow subsurface drains was 8 kg/ha in 2001 and 27 kg/ha in 2002. Nitrate export from the deeper drains was 6 kg/ha in 2001 and 37 kg/ha in 2002. During the entire study, an average of 8 kg/ha less NO_3^--N was exported from the shallow subsurface drainage

system. Decreased export observed in 2002 from the shallow subsurface drainage system was significant at the 10% level, but not for the entire 21-month period. Lack of significant difference in export between the drainage systems was most likely due to a lack of long-term data collection, a reduced number of drain flow/water quality observations (only 3 drains per plot), and possible low application of swine waste on one area of the deeper drainage plot. To evaluate the long-term effect of installing shallow subsurface drainage systems, the model DRAINMOD was calibrated with these field observations. The results of these simulations indicated that shallow drains would reduce drainage outflows by 23% at this site. Using the observed average NO_3^--N concentrations in the drainage water at this site in 2002, the total mass of NO_3^--N exported could be reduced by as much as 16%, or nearly 11 kg/ha-yr, by installing shallow subsurface drains at this site.

The second study consisted of a wetland mesocosm experiment to determine if organic matter (OM) addition to soils used for in-stream constructed wetlands would increase NO_3^--N treatment. Not all soils are suitable for wetland substrate, so OM addition can provide a carbon and nutrient source to the wetland early in its development to enhance denitrification and biomass growth. Eight batch studies, with initial NO_3^--N concentrations ranging from 10-120 mg/L, were conducted in 2001 and 2002 in 21 surface-flow wetland mesocosms. The results indicated that increasing the organic matter content of a Cape Fear Loam soil from 5% to 11% enhanced NO_3^--N wetland treatment efficiency in 7 of the 8 batch studies, but increases to 16% OM did not. Wetlands constructed with dredged material from the USACE Eagle Island Confined Disposal Facility in Wilmington, N.C., with initial OM of 12%, showed no improvement

in NO_3^--N treatment efficiency when increased to 18%, but did show increased NO_3^--N treatment efficiency in 7 of the 8 batch studies when increased to 22%. Increased OM additions to the Cape Fear soil increased biomass growth in the wetlands in 2001, but not in 2002. Increased OM additions to the dredged material had no affect on biomass growth in the wetlands in either year. Results of this research indicate that increased OM in the substrate will reduce the area required for in-stream constructed wetlands to treat drainage water in humid regions. It also serves as a demonstration of how dredged material can be used successfully in constructed wetlands, as an alternative to costly storage by the USACE.

Practices to Reduce Nitrate-Nitrogen Losses from Drained Agricultural Lands

By

Michael R. Burchell II

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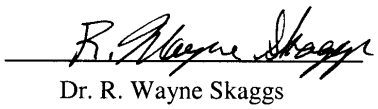

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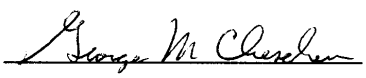

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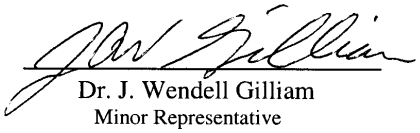

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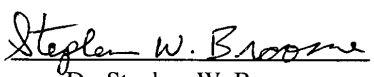

Dr. Stephen W. Broome
Member of Advisory Committee

DEDICATION

To Mom and Dad, who never wavered in their support through this long and arduous journey. I could not have done it without you!

BIOGRAPHY

Michael R. Burchell II was born on July 13, 1970 to Michael and Helen Burchell. He grew up in Providence, N.C., in Caswell County. Both of his parents were educators, so the importance of education was stressed throughout his life. He was also strongly supported by his parents in his numerous sporting endeavors, including football, baseball, and golf. He graduated as the Salutatorian of his class at Bartlett Yancey Senior High School in 1987.

After high school, Michael enrolled in North Carolina State University in Raleigh, N.C. He received his B.S. in Biological Sciences in 1992. After his sophomore year at NCSU, he became a member of the Rugby Club, where he played every season until graduation, and was President of the club in 1992.

After graduation, he took an internship with the U.S. Army Corps of Engineers in Vicksburg, MS., where he worked on innovative treatment technologies for bioremediation of contaminated sediments. While there, he obtained a M.S. from the University of Mississippi in Civil Engineering, with a concentration in Environmental Engineering. During his last six-months there, he worked with Dr. Charles Lee who sparked his interest in alternative uses for dredged material and constructed wetlands.

In August 1997, Mike returned to NCSU to pursue a Ph.D. degree in the Biological and Agricultural Engineering Department under the direction of Dr. R. Wayne Skaggs. He received the USDA – National Needs Fellowship in 1997 and became a Ph.D. candidate in December 2000. While there he worked on reducing nitrogen losses from subsurface drainage systems, and continued his connection with Dr. Lee at the Corps in constructed wetlands research. While a student, Mike managed to compete in over 10 sprint triathlons.

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"No man is an island", and by the same regard, no Ph.D. degree can be obtained without some support along the way. I received more than my fair share during my tenure at NCSU from numerous sources. This research is a product of the North Carolina Agricultural Research Service. The study was supported by funding from the U.S. Army Corps of Engineers Engineering Research and Development Center in Vicksburg, MS. It was also partially supported by USDA-NRI project 99-351028571 and by funds provided by the Plastic Pipe Institute.

First of all, I would like to thank my committee chair Dr. R. Wayne Skaggs for all of his support during my time in the department. I am indebted to him for allowing me to work with him, and to his being flexible in helping me customize a research project that I was passionate about. I truly appreciated the confidence he showed in me to be intimately involved in the planning, design, troubleshooting, maintenance, and budgeting of the projects, rather than just data analysis. I am sure that this better prepared me for a career in environmental engineering. The completion of my dissertation took longer than anticipated, yet he stood by me to the end, offering encouragement along the way. His patience with me on those days when I just didn't "catch on" will always be appreciated, and served as a lesson in how I should treat others when I am in a position of authority. I could always count on a subtle signal from him that maybe I should have thought more about a question he posed before I spoke, which resulted in my learning to think through these problems and questions more efficiently and professionally. It was truly an honor to work with Dr. Skaggs, and his influence will be with me for the rest of my career.

The rest of my committee also deserves special thanks. Dr. George (Chip) Chescheir was instrumental in helping work out experimental protocols and interpreting data. Dr. Wendell Gilliam was of great assistance in allowing the use of the Soil and Water Laboratory for water quality analysis of drainage, groundwater, and wetland samples. He was also pivotal in my understanding of the mechanisms that may be behind water quality trends observed in this study. Dr. Stephen Broome was most helpful in the constructed wetlands project. His experience was very helpful in planning, executing, and analyzing data from the wetland project. I truly enjoyed working with all of you, and I really appreciate all of the time you spent helping me achieve this goal.

Dr. Charles Lee from the USACE – Engineering Research and Development Center (ERDC) was integral in supporting this project. Not only did he help in the wetland project development, he was also integral in providing funding for the project through his programs at ERDC. He provided excellent assistance on many occasions in the field, and advice on occasions that are too numerous count. He was also a good friend, and his support during this project on all levels will never be forgotten. Thanks Dr. Lee.

A special thanks to Dr. Jason Osborne from the Department of Statistics at NCSU for his contributions to data analysis, and to Dr. Sarah Liehr from the Biological and Agricultural Engineering Department at NCSU for her comments and contributions to the manuscript.

I worked very closely with Wilson Huntley and Jay Frick in installation of the drainage and wetland systems. Wilson was my main contact to help with troubleshooting and maintenance of the site. Jay designed the electronics for monitoring of the system, and also helped in troubleshooting electronic problems in the field. Eugene Boyce provided support from Plymouth, N.C., and would periodically check the site for problems, and would assist in

many tasks around the site. Jeremy Goodwin came on for the summer of 2002, and handled many of the day to day operations for a couple of months, which allowed me to focus on data analysis and writing. Thanks to all of you for helping me out so many times!

Others in the BAE department helped out enormously. Dr. Rod Huffman was very helpful at the beginning of the study in the use of his drill rig in surveying the site. Other BAE faculty including Dr. Mike Boyette, Dr. John Parsons, Dr. John Classen, Dr. Jay Cheng, Dr. Phil Westerman, Dr. Devendra Amatya, Dr. Robert Evans, Dr. James Barker, Ron Sheffield and Andy Slate all were very helpful by allowing me to drop by with questions pertaining to their particular expertise, or to use their equipment.

The BAE Shop was instrumental in building wetland tanks and manhole tops, and providing expert opinions to solve problems encountered during the installation phase of this project. Thanks to Charles Sherwood, David Buffaloe, Ken Coats, Willie Jones, and Alan Tharrington.

Other staff in the BAE department were important in this endeavor. Jonathan Smith provided equipment and advice on numerous occasions. Mark Rice allowed me to use some of his equipment, and provided expert advice on constructed wetlands. L.T. Woodlief provided excellent support in the field and transport of large equipment and materials to the field. Carolyn Mitowski was very helpful in downloading digital images from the field study, and helping create several presentations during my program. Phil Harris and Keith Sorenson helped make modifications to several of my sensors used in the field.

I am particularly grateful to the Biological and Agricultural Environmental Analysis Laboratory and the Soil Science Analysis Laboratory at North Carolina State University for

soil, water, and plant analysis. Phyllis Carter and Rachel Huie, as well as their staffs, were both very helpful and patient with my many requests.

There were several generous donations to the study. The plastic pipe for the drainage study was donated by the Crumpler Plastic Pipe in Roseboro, N.C. Roger Collins at Coastal Refrigeration donated materials and labor for insulating the wetland mesocosm tanks. Cindy Frick with BION Technologies in Clayton, N.C. donated biosolids used in the wetlands study. You contributions were very important in making this project happen.

Without a good site, there cannot be a good research project. Thanks to Mr. John Smith and the staff at the USDA – Tidewater Research Station in Plymouth, NC where the research was conducted. Mr. Smith could not have been more hospitable, and provided excellent advice and support along the way. A special thanks to Jewell Tetterton , Teron Sloan, and their respective crews, for all of their help and patience with my many questions. You dropped what you were doing many, many times to help me out, and I want you to know there was absolutely no way this project could have worked without your support. Thanks also to Dr. Dave Lindbo and Dr. Carl Crozier at the station for helping with soils identification at the site.

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TABLE OF CONTENTS

LIST OF TABLES

Page

CHAPTER 3

APPENDIX 1

LIST OF FIGURES

Page

CHAPTER 1

CHAPTER 3

APPENDIX 1

APPENDIX 2

APPENDIX 3

INTRODUCTION

North Carolina is faced with many challenges in remediating and preserving the environmental quality of its land and water. Two of these challenges include non-point source pollution of the state's streams and estuaries and decreasing land area for the disposal of dredged materials from the state's waterways. Two agricultural practices that have been implicated in contributing to excessive nutrient export are land application of swine waste and agricultural drainage. Water management practices to reduce these nutrient losses from agricultural facilities are extremely important. Discovering alternative uses for dredged material would decrease the amounts of land required for disposal, protecting land and reducing governmental costs.

Runoff of nutrients originating from agricultural land receiving conventional inorganic and/or organic (primarily animal waste) fertilizers is of major concern in contributing to the non - point source pollutant loading to the state's waters. For example, it is estimated that 70% of the nitrogen entering the Neuse River is derived from non - point sources, with the large majority originating from agricultural runoff (NCDENR, 1996). A recent estimate in the Neuse River Basin in N.C. showed that 58% of the non-point source pollution in the basin was attributable to agricultural practices (NCDWQ, 2000). One of the major nutrients of concern is nitrogen. Excessive nitrogen loadings may cause eutrophication of surface waters, leading to algal blooms, turbidity, shifts in fish populations, or even fish kills (Gilliam et al, 1997). Nitrogen in various forms applied as conventional fertilizers or animal waste to agricultural lands is likely to be, or ultimately transformed to, nitrate-nitrogen (NO_3^--N). Nitrate is very mobile, and that which is not utilized by plants or

microorganisms moves into groundwater. Therefore, NO_3^--N is found at various concentrations in the groundwater below essentially all fertilized agricultural fields. This NO_3^--N can potentially move laterally with groundwater into field ditches or streams, where it contributes to surface water degradation. Nitrate in groundwater has also been found to contaminate drinking water wells in rural areas of the state (Spruill et al., 1997). Human consumption of water with elevated levels of NO_3^--N has been linked to the infant disorder methemoglobinemia (Metzler and Stoltenberg, 1950) and to non-Hodgkin's disease lymphoma in adults (Weisenburger, 1990). Due to these health concerns, current drinking water standards are 10 mg/L for NO_3^--N (USEPA, 1994), but concentrations as low as 1-2 mg/L can lead to eutrophication in nitrogen limiting waters. The N.C. state government is taking steps to reduce the environmental impacts of nitrogen loads from agricultural facilities. The N.C. Department of Environment, Health and Natural Resources (DEHNR) proposed rules 15A NCAC 2B.0231-.0236 to reduce the average nitrogen load delivered to the Neuse River Estuary by 30 percent of the average annual load delivered during 1991-1995. Rule 15A NCAC 2B.0231-.0238, effective in August 1998, established the nitrogen reduction options (local strategies or implementation of Best Management Practices (BMPs)) for agricultural facilities to make this reduction within five years.

Animal operations in N.C. have been recognized as a major contributor to non-point source nutrient pollution of streams and rivers. N.C. catapulted from 7th to 2nd in the nation in swine production within 5 years from the late 1980's to the early 1990's (Barker and Zublena, 1995). This increased the number of swine in the state from 2.5 million to 10 million, but at this time, there is a moratorium in N.C. restricting further growth. The rapid expansion of the swine industry proceeded without first understanding the

environmental ramifications. Some of the areas put into production in eastern N.C. were poorly drained areas adjacent to rivers and estuaries (Burkholder et al., 1997). These operations generally dispose of animal wastes by collecting it in an anaerobic lagoon system, and then applying the liquid to crops as a nutrient source. Typically, farmers in N.C. are allowed to apply swine lagoon effluent at rates based on realistic yield estimates and nitrogen requirements of a crop. Even with proper application techniques, not all of the nutrients are assimilated by the crop, allowing the remaining nutrients to be lost in surface runoff or through leaching to groundwater.

Improved subsurface drainage in poorly drained areas in eastern NC has transformed many areas into croplands that often exceed the production of naturally well-drained soils (Evans et al., 1995). As much as 75% of soils in the lower coastal plain in N.C. are considered poorly drained under natural conditions (Evans et al., 2000). An estimated 1 million ha. of the 2.7 million ha of cropland in N.C. is drained (Pavelis, 1987; Evans et al., 1995). Drainage has received criticism for increasing nitrogen loadings in areas adjacent to nutrient sensitive waters, because creating a well-drained soil increases the probability that NO_3^--N can move off-site in shallow groundwater or through drainage conduits. Research into drainage techniques such as controlled drainage have shown much promise in reducing nitrate losses to surface waters, but this practice is most effective in relatively flat landscapes (Evans and Skaggs, 1989, Evans et al., 1992; Skaggs, 1999).

Dredging operations by the U.S. Army Corps of Engineers to maintain navigable waters along the N.C. coast is an extensive and expensive operation that continues daily. Wilmington Harbor and the Atlantic Intracoastal Waterway (AIWW) alone produces an estimated 2 million cubic yards of material each year (USACE – CESAW 1997;1998). Some

of this material can be beneficially placed on nearby beaches, but most must be stored in confined disposal facilities (CDFs). Construction and maintenance of these CDFs pose a major expense to the federal and local governments. Alternative uses for this dredged material could help reduce expense by reducing the volumes to be disposed, and in some instances, generate revenue.

This dissertation investigates several environmental related topics under scrutiny in N.C. Chapter 1 deals with the drainage strategy of using shallow subsurface drains (0.75 m depth) rather than deep subsurface drains (1.5 m depth) to reduce NO_3^--N losses from beneath agricultural fields. The drains were placed beneath a swine waste land-application field at the North Carolina Department of Agriculture – Tidewater Research Station (NCDA-TRS) near Plymouth, N.C., so topics relating to swine waste are also explored in this chapter. Since data on soil properties, precipitation, irrigation depths, weather, etc. were available from the drain depth study, they could also be used as inputs into the drainage simulation model DRAINMOD (Skaggs, 1978). In Chapter 2, DRAINMOD was calibrated with the observed drainage data in Chapter 1, and then used to simulate the long-term effects of shallow subsurface drainage systems on drainage outflows and NO_3^--N export. Despite all of the current BMPs available or being evaluated to eliminate NO_3^--N losses from agricultural fields, some NO_3^--N is still likely to be lost in drainage water exiting the facilities. Chapter 3 evaluates the feasibility of using constructed wetlands as another potential NO_3^--N removal strategy. Constructed wetlands optimized for NO_3^--N removal and positioned in strategic areas in the landscape, such as a drainage outlet canal, may serve as a final polishing step for drainage water leaving agricultural facilities. Soils located at sites where constructed wetlands are to be utilized for NO_3^--N treatment are not always suitable as

wetland substrate, because they would fail in providing ideal conditions for denitrification and plant establishment in the first few years after construction. This study evaluates the ability of mesocosm-scale surface-flow constructed wetlands (SFCWs), with six different substrates with varying organic matter amendments, to remove NO_3^--N from drainage water. Three of the substrates contain soil and soil blends available on site at the NCDA - TRS. Dredged material (from the Eagle Island Confined Disposal Facility in Wilmington, N.C.) and dredged material blends comprise the other three. While the relationship between organic matter addition to wetland substrate and NO_3^--N removal efficiency is the primary research goal, the dredged material is specifically being evaluated as an alternative to disposal in CDFs managed by the U.S. Army Corps of Engineers.

The goal of this study is to add to the BMP toolbox for reducing NO_3^--N losses to N.C. waters, and to improve the overall understanding of mechanisms involved so that similar methods could be applied in other scenarios or regions. For example, in this study, evaluation of drain depth on nitrate losses is conducted using a swine-waste land-application field, but results could also be applied to other poorly-drained fields receiving inorganic fertilizers. The use of shallow subsurface drainage may be applicable in regions with rolling or sloped topography, where the use of controlled drainage to minimize water and nitrate loss is not economically feasible because of the numerous water control structures that would be required. Constructed wetlands to remove NO_3^--N may also be used in industrial and municipal applications. The use of dredged material as wetland substrate could be applicable wherever dredged material is readily available.

Objectives

1. Evaluate the effect of subsurface drainage depth and intensity on nitrate losses in drainage water and on shallow (< 2.5 m) groundwater quality.
2. Use the model DRAINMOD to simulate the long-term effects of shallow subsurface drainage systems on drainage outflows and NO_3^--N export using inputs observed data obtained from the drain depth experiment site.
3. Evaluate, at the mesocosm scale, whether the addition of organic matter to the substrate in surface-flow constructed wetlands increases nitrate treatment efficiency by enhancing conditions favorable for denitrification and plant growth in the early stages of the wetland's establishment.
4. Evaluate the feasibility of using dredged material based substrate in surface flow constructed wetlands as an alternative to disposal.

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CHAPTER 1

EFFECT OF SHALLOW SUBSURFACE DRAINAGE SYSTEMS ON NITRATE LOSSES

INTRODUCTION

Background

Drainage has been used to convert millions of hectares of poorly drained soils into highly productive agricultural lands. Of the over 170 million ha of cropland in the U.S., nearly 31 million ha require artificial or improved drainage for agricultural production (Pavelis, 1987; Skaggs et al., 1994). Subsurface drains, consisting of tile drains or corrugated plastic tubing, have been installed in just over 15 million ha of rural lands in the U.S. (Pavelis, 1987). Approximately 30% of the cropland in the Midwest incorporate tile drainage systems (Zucker and Brown, 1998; Davis et al., 2000). Subsurface drainage is also important in North Carolina and other southeastern states. As much as 75% of soils in the lower coastal plain in North Carolina are considered poorly drained in their natural state. Subsurface drainage has transformed much of this land into cropland with production that often exceeds that of naturally well-drained soils. In North Carolina, where drainage projects were initiated as early as the late 1600s (Evans and Skaggs, 1989), an estimated 1 million ha of the 2.7 million ha of cropland in N.C. is drained. Subsurface drainage systems are employed on approximately 15% of these lands (Pavelis, 1987; Evans et al., 1995; Evans et al., 2000; Skaggs, 1999b; Skaggs and Chescheir, 2003).

By removing excess water, drainage creates a more aerobic soil environment, which increases root activity and nutrient availability, while creating a more balanced

microbial population with decreased crop pathogens. Artificial or improved drainage also improves the timeliness of planting, and effectively lengthens the growing season. In addition, trafficability (relating to tillage, planting and harvesting) is increased and soil compaction is reduced as a result of properly designed drainage systems. All of these benefits are later translated into increased production and profitability (Skaggs and van Schilfgaarde, 1999).

Nitrate Losses Associated with Drainage

Despite the success in increasing agricultural production, drainage has come under increased scrutiny for its impact on surface and groundwater quality. While improved subsurface drainage generally decreases sediment and phosphorous losses because of decreased surface runoff (Skaggs and van Schilfgaarde, 1999), increased losses of nitrate-nitrogen (NO_3^--N) from these systems are common and well documented. Reviews of literature on the subject (Baker 1980; Skaggs et al., 1994; Gilliam et al., 1999), indicate, with few exceptions, that improved subsurface drainage results in increased NO_3^--N losses. Nitrate entering surface water contributes to eutrophication and algal blooms, whose decomposition leads to hypoxia (dissolved oxygen less than 2 mg/L), which in turn leads to fish kills and degradation of the aesthetic quality of streams and lakes (Gilliam and Terry, 1973; Gilliam et al., 1999). Recent studies indicate that nitrate entering the Mississippi River, which contributes 90% of the flow into the Gulf of Mexico, has resulted in a seasonally fluctuating 13,000 – 20,000 km^2 hypoxic zone that has persisted for the last decade in the Northern Gulf of Mexico (Mitsch et al. 2001; Rabalais and Turner, 2001). Elevated NO_3^--N levels in

drinking water supplies, including drinking water wells in rural areas, also pose a potential problem to human health. Due to NO_3^--N related health concerns such as methemoglobinemia (Metzler and Stoltenberg, 1950) and more recently non-Hodgkins lymphoma (Weisenburger, 1990), the EPA established the drinking water standard as 10 mg/L (USEPA, 1994).

The extent of NO_3^--N loss from subsurface drainage systems is site specific, and is influenced by many different factors (drainage design, fertilization rates, precipitation, etc.) and chemical/biological mechanisms (denitrification, plant uptake, microbial assimilation, and other dissimilatory reductions besides denitrification (Hill, 1996)). Subsurface drainage water from agricultural fields frequently averages between 8 and 20 mg/L NO_3^--N (Gilliam et al., 1999), and can be significantly higher than the current drinking water standards. In an extensive survey by Baker (1980), NO_3^--N concentrations in drainage water ranged from 0.6 mg/L in a hay pasture in Vermont to 61.2 mg/L in a heavily fertilized corn field in Ohio. Evans et al. (1991) surveyed 14 sites in N.C., and found an average loss of 31 kg/ha/yr NO_3^--N from the sites that were dominated by subsurface flow (i.e. tile drains or ditch drainage systems in soils with high hydraulic conductivities). One site in that survey with exclusively subsurface tile drains lost nearly 40 kg/ha/yr NO_3^--N. Table 1 shows ranges of NO_3^--N losses from subsurface drainage reported in selected studies across North America.

Reasons for Nitrate Losses from Subsurface Drainage Systems

Naturally well-drained soils in agricultural production will typically yield higher concentrations of NO_3^--N in shallow groundwater than what is observed in poorly-

Table 1. Yearly average NO_3^--N concentrations and losses in subsurface tile drainage water from selected field studies. **Note** - unless otherwise indicated, inorganic fertilizers were used in these studies.

Location (Study Duration)	Crop and Management Scenario	Avg. yearly NO_3^--N concentration (range) mg/L	Avg. NO_3^--N loss (range) kg/ha	Reference
Iowa (1970-1973)	Corn	21 (2 – 44)	31 (0 - 93)	Baker et al.(1975)
Iowa (1974-1978)	Corn	20 (15 – 23)[Lo] 41 (17 – 61)[Hi]	27 (18 – 32) [Lo] 48 (31– 72) [Hi]	[1]Baker and Johnson (1981)
Iowa (1990-1992)	Corn, Corn/Soybean Various tillage	22 (6 – 86)	38 (15 – 107)	Bjorneberg et al. (1996).
Ontario, Canada (1991-1994)	Corn Various Tillage	11 (10 - 11)	26 (23 – 30)	Drury et al. (1996)
Southern Minnesota (1973-1975)	Corn	21 (15 - 25)[1x] 31 (13 – 43)[2x]	18 (6 – 25) [1x] 31 (4 - 59) [2x]	[2]Gast et al. (1978)
Minnesota (1982-1992)	Corn Various tillage	13 (5 - 24) [CT] 12 (6 – 21) [NT]	48 (3 – 139) [CT] 45 (3 -113) [NT]	[3]Randall et al. (1995)
Minnesota (1988-1993)	Corn, Corn /Soybean	28 (13 - 40)	211	[4]Randall et al. (1997)
Minnesota (1988-1993)	Alfalfa/CRP	3 (0 - 4.1)	6	[4]Randall et al. (1997)
Indiana (1988-1991)	Corn Various Drain Spacing	25 (14-38)	47 (14-105)	Kladivko et al. (1999)
North Carolina (1980-1983)	Grain and vegetables	14.8	55	[5]Jacobs and Gilliam (1985)
North Carolina (1971-1974)	Corn		27 (25-28)	Gambrell et al. (1975)
North Carolina (1991 – 1993)	Corn/Soybean /Wheat		17 (8 – 31)	Chescheir et al. (1996)
North Carolina (1977-1979)	Coastal Bermuda (Swine Waste)	6 [1x] 18 [2x] 27 [4x]	31 [1x] - 193 [4x]	[6]Evans et al. (1984)
Iowa (1993-1998)	Various crops and N management systems (Swine waste)	11 (2-32)		Kanwar et al. (1999)

[1] **Lo** - low nitrogen application, **Hi** - higher nitrogen application
[2] **1x** - Recommended N application, **2x** – twice the recommended N application. Losses reported by Gast et al. (1978) are based on only approximately 6 weeks of flow per year [3] **CT –** Conventional tillage, **NT** – No tillage [4] **NO_3^--N loss** data is a 4 year total
[5] **NO_3^--N loss** estimated through DRAINMOD simulation [6] **1x** - Recommended swine waste application, **2x** – twice the recommended swine waste application, **4x –** four times recommended swine waste application. **NO_3^--N loss** data is a 20 month total

drained soils (Gambrell et al., 1975). Gilliam et al. (1979) state that soil characteristics are the factors that most consistently influence the amount of NO_3^--N in a soil profile, due to their influence on denitrification. A fine soil texture, for example, can reduce water movement and more easily maintain reduced conditions below the soil surface, increasing denitrification rates and reducing NO_3^- - N concentrations in drainage water (Gilliam et al., 1979). Poorly drained soils limit groundwater flow from a site, therefore possessing higher water tables for extended periods. This allows the soil to become saturated nearly to the soil surface (e.g. allowing anaerobic zones to form). Soil saturated for an extended time becomes anaerobic, allowing organic carbon to accumulate in the soil profile at levels that exceed well-drained soils. These conditions are very favorable to denitrification ($NO_3^- \rightarrow N_2$), which reduces nitrate in groundwater. Therefore, the combination of reduced groundwater outflow and increased denitrification reduce NO_3^- - N losses from poorly drained soils.

The same principles hold true when drainage is artificially improved, essentially creating a well-drained soil from a poorly drained soil. Gilliam and Skaggs (1986) described the impact of improving drainage on three similarly cropped soils in eastern North Carolina. One site, which only had surface drainage improvements and exhibited poor subsurface drainage characteristics, exported 3.7 kg/ha/yr NO_3^--N. This number increased with the second site, which employed drainage ditches spaced at 100 meters, to 15.7 kg/ha/yr. The drainage system on the third site provided the best drainage. It was comprised of drainage ditches with 100 meter spacing with two-equally spaced subsurface tile drains between them, and yielded NO_3^--N losses of 32.4 kg/ha/yr. This example clearly shows the direct correlation of improved drainage and NO_3^--N losses.

There are other reasons why improving the drainage status of the soil results in increased NO_3^--N losses. Improved aeration through reduction in water table depth results in increases in mineralization of soil organic matter and nitrification ($NH_4^+ \rightarrow NO_3^-$) as well as decreases in denitrification. The result is an increase of the highly soluble NO_3^--N in the soil water that is intercepted by the subsurface tile lines and then exported from the field (Skaggs et al., 1994; Davis et al., 2000). Therefore, the concentration of NO_3^--N in tile drainage water is heavily dependent on the aeration status of the soil (Bengtson et al., 1988). Hydrologically, subsurface drainage increases infiltration and reduces the retention time of the shallow groundwater in the soil profile. Because subsurface drains deliver shallow groundwater more quickly to surface water, the possibility of NO_3^--N adsorption by plants is also decreased, further contributing to increased export (Gilliam et al., 1999).

The magnitude of NO_3^--N losses from a site appears to be consistently correlated to the volume of subsurface drainage. However, because of variations in drainage intensity and to fluctuations in annual precipitation, drainage flow volumes can be highly variable from site to site and from year to year. Baker et al. (1975) reported a range of 0 – 93 kg/ha NO_3^--N losses from corn fields in Iowa, and explained the variation was highly dependent on flow volume. Bjorneberg et al. (1996) found in their study of subsurface drainage with various tillage practices in Iowa, that NO_3^--N loss primarily correlates with drainage flow volumes, not drainage water concentration. Kladviko et al. (1999) evaluated the effect of 5, 10, and 20 m drain spacing (at constant depth) on drainage intensity and NO_3^--N losses. They found substantial increases in drainage

volumes and NO_3^--N losses with decreased drain spacing, despite small differences in drainage water NO_3^--N concentrations.

It should be noted that there are many other factors that may affect NO_3^--N losses in tile drainage. Over application of N fertilizer may leave larger pools of residual NO_3^--N that can exit the soil profile in drainage water. Studies by Gast et al. (1978), Baker and Johnson (1981), and Randall et al. (1990) show increased NO_3^--N losses with increasing nitrogen fertilization rates, which is not surprising given the nitrogen removal rates of many crops average around 50% (Gilliam and Terry, 1973; Gilliam et al., 1999). If crop nitrogen uptake is further suppressed by drought or other environmental factors, NO_3^--N losses from tile drainage may become elevated even under recommended nitrogen fertilization rates (Randall et al., 1997; Skaggs, 1999b). Cropping system can also affect the losses of nitrate from subsurface drains. Perennial grasses such as alfalfa generally exhibit lower losses than corn or soybeans (Baker, 2002 in press). Randall et al. (1997) found that nitrate losses from a continuous corn and corn – soybean rotation in Minnesota were 35 and 37 times what was lost from perennials. The researchers reasoned that the extended growing season and deeper root system of the perennials increased the uptake and immobilization of the fertilizer N, and reduced drainage volumes due to a longer period of evapotranspiration.

A particularly interesting scenario that affects nitrate loss from subsurface drains may result when a period (1 to 2 years) of low precipitation is followed by above average precipitation. Drought reduces the amount of crop uptake and increases N mineralization rates. Therefore, nitrate levels can accumulate in the soil because lower water tables increase aerated conditions, reducing the potential for soil denitrification. When

excessive rainfall occurs, the nitrate is flushed from the soil and can result in large discharges of NO_3^--N (Skaggs et al., 1995; Randall et al., 1997; Kladivko, 1999; Davis et al., 2000; Mitsch et al., 2001).

Minimizing Nitrate Losses

Water management strategies must be developed to satisfactorily balance the need for food production and environmental protection. Reduction of nitrate loads directly from subsurface drains may be accomplished in several ways:

1. Reduction of nitrogen inputs to the crop (application based solely on the Realistic Yield Estimate for the particular crop)
2. Reducing the volume of drainage water leaving the fields
3. Creating a soil environment that maximizes denitrification potential in the soil matrix surrounding the drains.

The first management strategy can significantly reduce nitrate losses alone and is increasingly employed. Strategy two may be accomplished by designing and managing drainage systems so that only the minimum volume of drainage water needed to satisfy the drainage requirement of a crop is released. This strategy conserves water and reduces nutrient loads (Skaggs and van Schilfgaarde, 1999). Strategy three can be accomplished in conjunction with strategy two; drainage volume is reduced by maintaining higher water tables during periods, such as the winter months, when trafficability and protection of the crop from water logging not a concern. This creates a thicker anaerobic zone within the soil environment, which increases the potential for denitrification before soil water reaches the drains (Gilliam et al., 1974).

One strategy that has been successful in certain landscapes is controlled drainage. Controlled drainage (CD) is a water management strategy in which a structure, such as a flashboard riser, is positioned in the drainage outlet canal to regulate drainage outflow (Evans et al., 1995). As more water is held in the outlet canal, water table depths within the adjacent fields will be raised over the subsurface drain tiles. This effectively maintains water within the soil profile for longer periods of time, reducing drainage outflow, increasing the amount of water available for evapotranspiration and the probability for denitrification.

The success of CD in reducing nitrate losses from drainage systems has been well documented. Willardson et al. (1972) in California observed that submergence of tile drains could reduce nitrates through increases in dilution and denitrification of the soil water before entering the drains. Research on CD in N.C., beginning in the mid - 1970s, sought to increase crop production through water conservation while protecting water quality. Gilliam et al. (1979) found that using drainage control on a poorly drained soil in eastern N.C. resulted in a 50% reduction in flow volume when compared to an uncontrolled system. They observed that the higher water tables did not affect the NO_3^--N concentrations in drainage water. Drainage control reduced uncontrolled drainage system losses of 25-30 kg/ha/yr NO_3^--N by roughly 50%. They found that the reduction in nitrate was directly proportional to the volume of drainage water reduced. The researchers reasoned that this reduction represented a real decrease in the amount of NO_3^--N leaving the fields, because drainage control forced water to leave via deep seepage where it was denitrified.

Evans et al. (1991) reported controlled drainage results from 14 sites in N.C. representing 125 site years of data. Controlled drainage reduced drainage outflows by as much as 30% when compared to no control. Total nitrogen (TKN + NO_3^--N) was reduced by as much as 45%. Although CD reduced NO_3^--N concentrations by as much as 10-20%, the reduction of NO_3^--N losses was primarily due to the reductions in drainage outflow.

Drury et al. (1996) did observe a significant decrease in drainage water NO_3^--N concentration using CD in Ontario, Canada. Drainage outflow was reduced by 24 % and NO_3^--N concentration in drainage outflow was reduced by 25% using CD, resulting in a 43% reduction in NO_3^--N export.

Wesström et al. (2001) conducted field studies on CD in Sweden, where the mean average temperature is 7.5 °C. they found that CD reduced drainage outflows by 79 and 94% in two successive years. This corresponded to a 78% and 94% reduction in nitrate loss, when compared to conventional drainage. There was not much difference in the NO_3^--N concentrations between CD and conventional drainage during the winter months. However, one of the CD replicates showed a marked decrease during the spring and summer months, and the authors hypothesized that warmer temperatures may have helped stimulate denitrification in the saturated layers, lowering the NO_3^--N concentration in the drainage outflow.

The state of N.C. has adopted controlled drainage as a Best Management Practice (BMP) for reducing nitrate losses and has provided cost-share assistance under the North Carolina Agricultural Cost Share Program for farmers who want to implement the system (Evans et al., 1991). Currently, CD is practiced on over 125,000 ha of cropland in N.C.

To be effective in reducing N losses, CD requires proper management of the water control structures. Proper timing in adjusting water levels at the control structures is critical in maintaining the effectiveness of a CD system from both a production and water quality standpoint. Management during the winter months and early spring, when most of the drainage occurs in N.C., is critical.

Controlled drainage is best suited for relatively flat landscapes (slopes <0.5%), where drainage from relatively large land areas can be controlled with a single structure. As the slope increases, more structures are required, and the practice becomes too expensive for practical application (Evans and Skaggs, 1989; Skaggs, 1999b). Because of these factors, further research needs to be conducted to develop methods of reducing nitrate losses from drainage systems that has reduced management requirements and can be implemented on sloping sites.

Shallow Subsurface Drainage

Skaggs and Chescheir (2003) proposed that installation of shallow subsurface drainage systems may reduce NO_3^--N loss in a manner similar to CD. Typically, drains are placed at a depth of 1-1.5 meters. By installing drains at a shallower depth, the elevation of the drainage outlet is increased in a manner similar to what is obtained using CD. Higher water tables that can be managed in CD systems could also be achieved with the use of shallow subsurface drains. Reduced drainage outflows, increases in ET, increases in deep and lateral seepage, and a resulting thicker reduced zone below the drains that may promote denitrification, could all work to reduce nitrate losses. Figure 1 shows schematically the changes in reduced zone with conventional subsurface drains,

CD, and shallow subsurface drains. Since no control structures would be needed as in the case of CD, management of the system would be reduced and shallow drains could be installed on lands with greater slopes. Skaggs and Chescheir (2003) used DRAINMOD simulations to evaluate the losses of NO_3^--N in drainage systems with drain depths ranging from 0.75 to 1.5 m. In order to provide sufficient drainage, shallower drains must be placed closer together. Therefore, the drain spacing for the 0.75 m depth was 28 m, and 55 m for the 1.5 m drain depth. These spacings were chosen to achieve adequate drainage conditions and maximum profits from continuous corn grown on a Portsmouth sandy loam. Results from a 40 year simulation showed a 60 % reduction (31 kg/ha to 12 kg/ha) in predicted NO_3^--N losses by using the shallower drainage system. Although results of their simulation study appear promising, there is little field data to support or refute these findings, which Skaggs and Chescheir (2003) presented as a hypothesis.

Schwab et al. (1980) measured NO_3^--N losses from drains at 50 cm deep and 6 m spacing with drains 100 cm deep and 12 m spacing in a Toledo silty clay in Ohio. During the period where both drainage systems were operating simultaneously (1974- 1978), there was a 25% reduction (14.9 kg/ha to 11.2 kg/ha) in NO_3^--N losses in the shallow drainage system. However, there was one year that the shallower system NO_3^--N losses (10.4 kg/ha) exceeded the deeper drain system losses (6.6 kg/ha). Gordon et al. (1998) in Nova Scotia, measured NO_3^--N losses from two relatively shallow drainage systems, with drain depths of 50 cm and 80 cm both spaced at 12 m. Total drainage was reduced by 45% and NO_3^--N loss was reduced by 34% (13.1 kg/ha to 8.7 kg/ha) in the shallower drainage system. Nitrate concentrations in the drainage water were not significantly different in the two systems, but on average, the NO_3^--N concentration in the shallower

drainage system was almost 2 mg/L higher. While results of both of these studies support the hypothesis of Skaggs and Chescheir (2003) that NO_3^--N losses from drained lands can be reduced by using shallow drains, it must be recognized that neither study was designed to evaluate the effect of subsurface drainage depth on NO_3^--N losses.

In a study in Illinois, research by Cooke et al. (2002) does specifically address the hypothesis proposed by Skaggs and Chescheir (2003). Preliminary results are based on one year of field data on drains at approximately 0.61, 0.91, and 1.22 m in depth. Drain spacing were 15 m for the 0.61 m depth, and 30 m for the 0.91 and 1.22 m tile depth. Two replicates were monitored at the 0.61 and 0.91 cm depth, but due to field constraints, only one replicate of the 1.22 m depth was installed and monitored. On average, total drainage outflows from the 0.61 m drains were 30% and 48 % less when compared to the 0.91 m and 1.22 m depth, respectively. Total NO_3^--N losses were on average 39% (31 kg/ha to 19 kg/ha) and 51% (39 kg/ha to 19 kg/ha) less in the shallow 0.61 m drains when compared to the 0.91 and 1.22 m deep drainage systems. Nitrate concentrations in the drainage water were not significantly different between the depths. Variability in the drainage outflows and NO_3^--N concentration between the replicates, especially in the 0.91 m treatment, was observed, making it difficult in this study, as well as in other studies of this nature, to reach conclusions with confidence. The authors stressed the importance of collecting several years of data to smooth out the climatic variations, before conclusions and recommendations can be made.

Objectives

The objective of this field study was to evaluate the effect of subsurface drainage depth on NO_3^--N losses in drainage water and on shallow (< 2.5 m) groundwater quality. Essentially this was a field test of the hypothesis proposed by Skaggs and Chescheir (2003) that NO_3^--N losses from shallow subsurface drains installed at 0.75 m depth will be less than from drains installed at 1.5 m depth. Because there have been few field studies to evaluate the effect of drainage depth on NO_3^--N export from drained agricultural lands, this research may contribute to the limited data that has been collected on this subject. Differences in drainage volumes and drainage water NO_3^--N concentrations will be examined closely to provide further insight of the mechanisms that may influence differences between shallow and deep subsurface drainage systems.

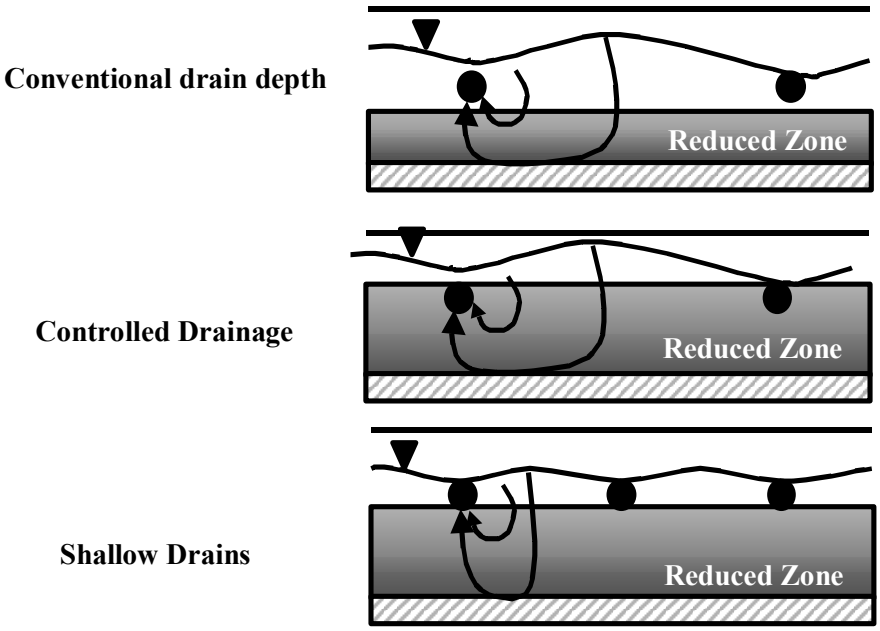

Figure 1. Schematic representing water table depth and reduced zones for conventional drainage, controlled drainage**,** and shallow drain depth. Arrows represent a few flow lines for drainage passing through reduced zones (from Skaggs and Chescheir, 2003).

MATERIALS AND METHODS

Site Description

The study site is located in the lower coastal plain of North Carolina at the North Carolina Department of Agriculture – Tidewater Research Station's Swine Research Unit in Plymouth, N.C. (see Figure 2). The drainage system was installed on a 2.5 ha beef cattle pasture, which is immediately adjacent to a 0.4 ha swine lagoon. Site surveys in the summer of 1998 revealed that significant lagoon seepage was limited to areas north of the proposed research plot. The soil of the research plot was classified as Cape Fear Loam (fine, mixed, semiactive, Typic Umbraquualt), a very poorly drained soil with slow permeability and a seasonal high water table of 0- 30 cm typically occurring during the winter or early spring.

Site preparation began in August of 1999. The site was leveled and disked, and old stumps were removed. Electrical service for the required pumps was connected to the swine houses, adjacent to the site, in late October through early November.

Drainage Design

Two drainage plots were designed based on DRAINMOD simulations, and installed during the period of November 1999 and March 2000. Figure 3 shows the site schematic. Depths and spacing for the drainage systems were selected not only to satisfy the objectives for this research, but to also provide adequate drainage for the field. All drainage pipe for this study was donated by Crumpler Plastic Pipe, Inc. (Roseboro, N.C.). The drain tile consisted of 10 cm corrugated, slotted polyethylene tubing with a knitted fabric "sock" envelope to prevent sand from entering the drain. Five - 125 m drain lines were installed in each plot on 0.07% slope using a wheel trencher (Joe Taylor, Washington, N.C.). The average depth of

the drain tile installed in the deep drainage plot (Plot 1) was approximately 1.44 m, with a drain spacing of 25 m. The average depth of the drain tile installed in the shallow drainage plot (Plot 2) was approximately 0.70 m, with a drain spacing of 12.5 m. There was some difference in drain depth along each lateral of both treatments due to the drain slope of 0.07%. All drains flowed from west to east. In November 2000, to further isolate the research plots hydraulically, a 5 mil thick plastic curtain was installed vertically to a depth of 1.5 m between Plot 1 and 2 and between Plot 2 and the drainage canal that bordered the plots to the south.

The middle three drains in each plot were intercepted by observation manholes, at the eastern end of the plots. The outside drains served as guard drains to hydrologically isolate the middle three drains. The observation manholes were constructed of 1.22 m diameter corrugated aluminum culvert pipe (Cahoon Farms Inc, Arapahoe, N.C.), with lightweight aluminum tops. The manholes in Plot 1 were 2.3 m long, and were installed to a depth in which the prefabricated 10 cm inlet stub (positioned 1.5 m below the ground surface) intercepted the lateral drains. Manholes in Plot 2 were 1.8 m long and installed to a depth in which the inlet stub (positioned 0.75 m below the ground surface) intercepted the shallower lateral drains. Solid plastic pipe was used to connect the lateral lines with the manhole. Concrete floors, approximately 15-20 cm thick were added to both sets of manholes, and were slightly sloped toward the center, with a gutter to direct flow to the outlet of the manhole. Each of the manhole outlets was connected to the main collection lines with solid plastic pipe. Drainage water leaving Plot 1 flowed into a 115 m long, 15 cm diameter corrugated, perforated polyethylene pipe approximately 2 m deep that drained to the Plot 1

sump. Drainage water leaving Plot 2 flowed into a second main, 177 m long and 1.4 m deep, which flowed to the Plot 2 sump. Both mains were on a 0.10% slope and flowed north.

Outlet sumps for each of the plots were installed in November of 1999. The sumps were constructed of 0.91 m diameter corrugated aluminum culvert (Cahoon Farms Inc, Arapahoe, N.C.). A well point system, (Thompson Pump and Wellpoint Systems Goldsboro, N.C.), was installed to draw the water table down in the area where the sumps were to be installed. With the water table drawn down, a large pit was dug with a backhoe in order to install both of the sumps at once. Sump 1, designed to collect water from the deeper (1.5 m) drains, was 2.4 m long, and was installed at a depth to intercept the 2 m deep main. Sump 2, designed to collect water from the shallower (0.75 m) drains, was 2.2 m long and was installed at a depth to intercept the 1.4 m deep main. The mains were connected to each of the sumps near the bottom through a 15 cm aluminum inlet stub. Floors for both of the sumps were constructed of concrete approximately 30 cm deep, gently sloping toward the center. A small collection sump 45 cm wide by 45 cm deep was carved into the flooring of each sump to hold the primary pumps at a lower depth.

The permanent drainage water pumping systems were installed May – June 2000. A primary pump (1 HP-230V Zoeller E140, Ihrie Supply Raleigh, N.C.) and a secondary overflow pump (1/2 HP-230V Zoeller E137, Ihrie Supply Raleigh, N.C.) was installed in each sump. Each pump was equipped with a float switch, which activated the pumps when the water level within the sumps reached a certain depth. The primary pumps from each sump were connected to a common 7.6 cm schedule 40 PVC underground pipe that discharged into two - 11.4 m^3 Norwesco polyethylene storage tanks (AgriSupply, Garner, N.C.). This water was stored for use in a wetland mesocosm study. Overflow from these

storage tanks was discharged into an outlet canal that flowed north from the site. The secondary overflow pumps, installed at an elevation within the sumps approximately 20 cm higher than the primary pumps, were connected to a second 7.6 cm diameter schedule 40 PVC underground pipe that discharged directly into the outlet canal. The overflow pumps were connected to a separate 7.6 cm diameter schedule 40 PVC lines in March 2002 to increase pumping capacity.

Field Monitoring Systems

Field monitoring systems (refer to Figure 3) consist of water table recorders, groundwater monitoring wells, soil redox probes, soil temperature probes, and a manual rain gauge. Water table recorders, one for each plot, were installed in March 2000 at the midpoint between drains P1A and P1B in Plot 1 and at the midpoint between drains P2A and P2B in Plot 2. Each of the water table recorders consisted of a 10 cm diameter screened Schedule 40 PVC well installed to a depth of 3 m. Each station was equipped with a float, counterweight, pulley, potentiometer, and Blue Earth™ Micro-485 microprocessor (Blue Earth Research, Mankato, MN), all housed in a fiberglass weatherproof box. The Blue Earth™ microprocessor was programmed to record water table elevations hourly.

Three-groundwater monitoring well nests were installed in each plot. Nests in Plot 1 were installed at the midpoint between drains P1A and P1B, P1B and P1C, and between P1C and the guard drain on the south end of the plot. Similarly, well nests in Plot 2 were installed at the midpoint between drains P2A and P2B, P2B and P2C, and between P2C and the guard drain on the south end of the plot. Wells were constructed of 5 cm diameter schedule 40 PVC. Each nest contained four wells screened to collect groundwater samples at the

following depths; 30-60 cm, 90-120 cm, 150-180 cm, and 210-240 cm. The well screen was covered with a protective sock to reduce sediment entering the well. Wells were installed using a 10 cm diameter auger with a drill rig. After the holes were augered, the wells were inserted and back-filled with washed sand to just above the depth of the well screen. Soil was then backfilled around the wells to 30 cm below the ground surface. Bentonite was then used to cap the soil around the well.

Platinum-tipped soil redox probes, constructed as described in Kunickus (2000) were installed in triplicate at depths of 60, 90, 120, 150, and 180 cm at the midpoint between the P1A and P1B drains in Plot 1 and the P2A and P2B drains in Plot 2. A salt bridge for the reference electrode used in monitoring soil redox was installed at a depth of 60 cm adjacent to the redox probes. The recipe for the salt bridge can be found in Kunickus (2000).

Soil temperature probes (HOBO® TMC6-HA, Onset Computer Corp, Bourne, MA) were weatherproofed (with adhesive rubber) and installed at 15, 45, 75, and 105 cm, at the midpoint between the P1A and P1B drains in Plot 1 and between P2A and P2B in Plot 2. They were connected to a HOBO® 4 channel external datalogger (H08-006-004 Onset Computer Corp, Bourne, MA), housed in the water table recorder weatherproof box. Soil temperatures at the various depths were recorded hourly.

A manual rain gauge was mounted on the fence at the site and was used to verify rainfall data collected by a Campbell Scientific CR-10® weather station approximately 1.5 km southwest of the research plot.

Drainage Observation Manholes/Instrumentation

Planning of the instrumentation for the drainage flow and water quality sampling began in September 2000; installation and testing was finally completed in December 2000. Figure 4 shows a schematic of the instrumentation in each of the observation manholes.

Because of the limited clearance between the drainage inlet into the manhole and the outlet, streamlined tipping buckets were used to measure drainage flow. The tipping buckets were custom made (Golden Rule Plastics, Haw River, N.C.) from 6.4 mm thick PVC sheets. The tipping buckets were limited to a height of 13 cm and were 62 cm long, resulting in an approximate volume of 2.5 L per tip. The tipping buckets were mounted on a frame made of 1.9 cm diameter schedule 40 PVC and fittings. The frame was secured to the observation manhole floor with masonry screws. Each tipping bucket was routinely calibrated after installation to maintain drainage flow measurement accuracy. Calibration factors used during the study can be found in Appendix 1-A.

Flow measurements were conducted using a redundant datalogging system. Magnetic reed switches were used to signal each tip. A magnet (Hamlin 57135, Newark Electronics, Greensboro, N.C.) was mounted to each side of the tipping bucket. A reed switch (Hamlin 59135-010, Newark Electronics, Greensboro, N.C.) was mounted to each side of the tipping bucket frame, with aluminum angle, at the height of the magnet. The reed switch was positioned so as to allow 1 cm clearance with the tipping bucket magnet. After each tip of the bucket, one reed switch signaled the main datalogger, a Blue Earth™ Micro-485 microprocessor. This microprocessor continuously counted tips but only recorded the hourly sum. The second reed switch signaled the backup datalogger, a HOBO® event recorder (H07-002-04, Onset Computer Corp, Bourne, MA). This redundant datalogger recorded

each tip and the time, but was limited to 8000 readings. Both data loggers were housed in weatherproof fiberglass boxes.

Drainage water samples were taken on a continuous, flow proportional basis with Sigma 900 automatic samplers (Hach USA, Loveland, CO.). The Blue Earth™ Micro-485 microprocessor was programmed to signal the sampler to take one-100 mL sample, from the drainage line at the observation manhole, for every 1900 L of drainage flow. The sampling frequency was later increased to one sample for every 950 L of flow because of below average precipitation during the study. Drainage water sampled by the automatic sampler was collected in a 10 L plastic carboy housed within the sampler.

Equipment and instruments at each water table recorder and observation manhole were powered by 12 V DC batteries. The gel batteries (Model DG 12-7F, Batteries Plus Raleigh, N.C.) at the water table stations were charged by a 1.4 W, 30 V SA1 solar panel (Solarex TF170491, Atlantic Solar, Baltimore, MD), mounted at a 45° angle facing south. Each 12 V DC battery was charged by a 5.1 W, 30 V SA5 solar panel (Solarex TF570491, Atlantic Solar Baltimore, MD), mounted at a 45° angle facing south.

Each observation manhole and field monitoring equipment location was enclosed by an electric fence to prevent damage by cattle. The observation manholes were connected to the main electric fence line surrounding several pastures at the station. The fences enclosing the field monitoring equipment in each plot were electrified with solar powered boxes.

Swine Waste Irrigation System Installation

Water from the nearby swine waste lagoon was applied as the nitrogen source to the subsurface drained plots. An irrigation system was installed at the research site in June 2000

to apply wastewater to the drained field. The system was designed to be compatible with an Amadas A1375 Rain Bird hard hose travelling gun irrigation system. A 9 m, 15 cm diameter Z-pipe made of steel was welded to connect to the irrigation pump and lead from the lagoon berm. The Z-pipe was connected to a 15 cm diameter PVC pipe which lead to the first irrigation hydrant. The two hydrants were connected by 15 cm diameter PVC pipe and spaced 49 meters apart. Both hydrants were supported underground with concrete pressure blocks. All pipe was buried approximately 75 cm deep.

Irrigation of swine lagoon wastewater began in September 2000. Irrigation water was applied with a Nelson series 150 Big Gun at a 24 degree trajectory and 2.2 cm diameter nozzle ring (Nelson Irrigation Co. Walla Walla,WA). Pressure at the gun was maintained at 75-80 psi, determined through calibration, to provide coverage of the field while minimizing application of the wastewater outside of the confines of the research plots. Coverage was accomplished with two passes of the irrigation gun from south to north across the plots. The pasture was under a bermudagrass (May through October) /ryegrass (November through April) rotation. Nitrogen application to the field was based on the realistic yield estimate for these grasses under grazing. The North Carolina Cooperative Extension Service (NCCES) recommends 232 kg/ha/yr (207 lb/ac/yr) plant available nitrogen (PAN) could be applied on the bermudagrass from late Spring through late Summer. Recommendations for the ryegrass winter annual was 56 kg/ha/yr (50 lb/ac/yr) PAN, irrigated in the Fall and then again in the following Spring. Rain gauges were placed along a line across the field, at a height of 1 m, to measure depths of wastewater applied. Samples of wastewater from the lagoon and from the rain gauges were collected during each irrigation event to calculate the amount of total nitrogen applied to the plots.

Data Collection Procedures

Initial drainage water sampling

Drainage water sampling and water table monitoring at the research site began in March 2000. Grab samples of drainage water were collected monthly or after rainfall events to assess background water quality before application of swine waste. Frequency of grab sample collection increased to weekly or biweekly sampling in July, continuing through October. In November 2000, automatic samplers were installed programmed to obtain daily samples. The composite samples were collected and analyzed biweekly through December 2000. Water table monitoring began in March 2000; data were downloaded from the site every 4-6 weeks.

In January 2001, when all systems had been installed and tested, a more regimented sampling and data collection scheme was initiated. Water table data stored by the Blue Earth™ Micro-485 microprocessors were downloaded monthly through March and then biweekly thereafter. Drainage flow data recorded by the HOBO◆ event recorder and the Blue Earth™ Micro-485 microprocessor were downloaded weekly and biweekly, respectively. Soil redox monitoring, which began after installation in March 2001, took place weekly, with readings measured with an Accumet pH/mV meter (AP63, Fisher Scientific Pittsburgh, PA) connected to a Ag/AgCl reference electrode (Jensen Instruments, Tacoma, WA). Soil temperature data were downloaded every 4-6 months.

Groundwater wells and the composite drainage water samples were collected biweekly for water quality analysis. The sampling scheme was supplemented by collecting samples weekly or with grab samples following several major precipitation events or following waste irrigation events. Groundwater wells were purged prior to sampling. Each

of the 10 L plastic carboys within the automatic drainage water samplers contained 10 mL sulfuric acid (H_2SO_4), so the composite drainage water was acidified to pH 2-3 prior to collection for analysis. Samples were collected from the wells and the automatic samplers in 500 mL plastic bottles, acidified with H_2SO_4 to pH 2-3, and then frozen before analysis. All drainage water, groundwater, and precipitation samples were analyzed by the Soil Science Analysis Laboratory at North Carolina State University using a LACHAT Quickchem 8000 instrument for NO_3^-- N (Cadmium Reduction Method, Standard Method 4500 -NO_3^- F (APHA, 1995)), ammonium (NH_4^+-N) (Automated Phenol Method, Standard Method 4500 -NH_3^+ G with salicylate substituted for phenol (APHA, 1995)), and ortho-phosphate (o-PO_4^-) (Ascorbic Acid Method, Standard Method 4500 –PF (APHA, 1995)). Dissolved organic carbon (DOC) was measured using a combustion-infrared method on a Shimadzu® analyzer (Standard Method 5310 B (APHA, 1995)). Drainage water and groundwater samples were also analyzed for total kjeldahl nitrogen (TKN) and total phosphorous (TP). After the first six months of sampling, analysis of the groundwater samples for TKN and TP was reduced to a frequency of two months. Analysis for TKN and TP included digestion followed by automated analysis using a Lachat Quickchem 8000 (*modified* Macro Kjeldahl Method 4500-N_{org}-B for TKN and Method 4500-P B for TP (APHA, 1995)). More detailed descriptions of these methods employed by the Soil Science Analysis Laboratory can be found in Birgand (2000).

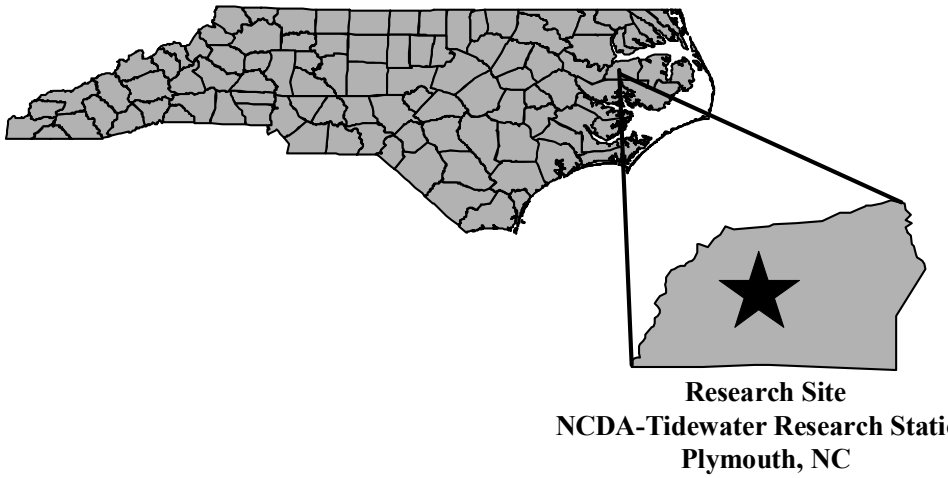

Figure 2. Research Site Location

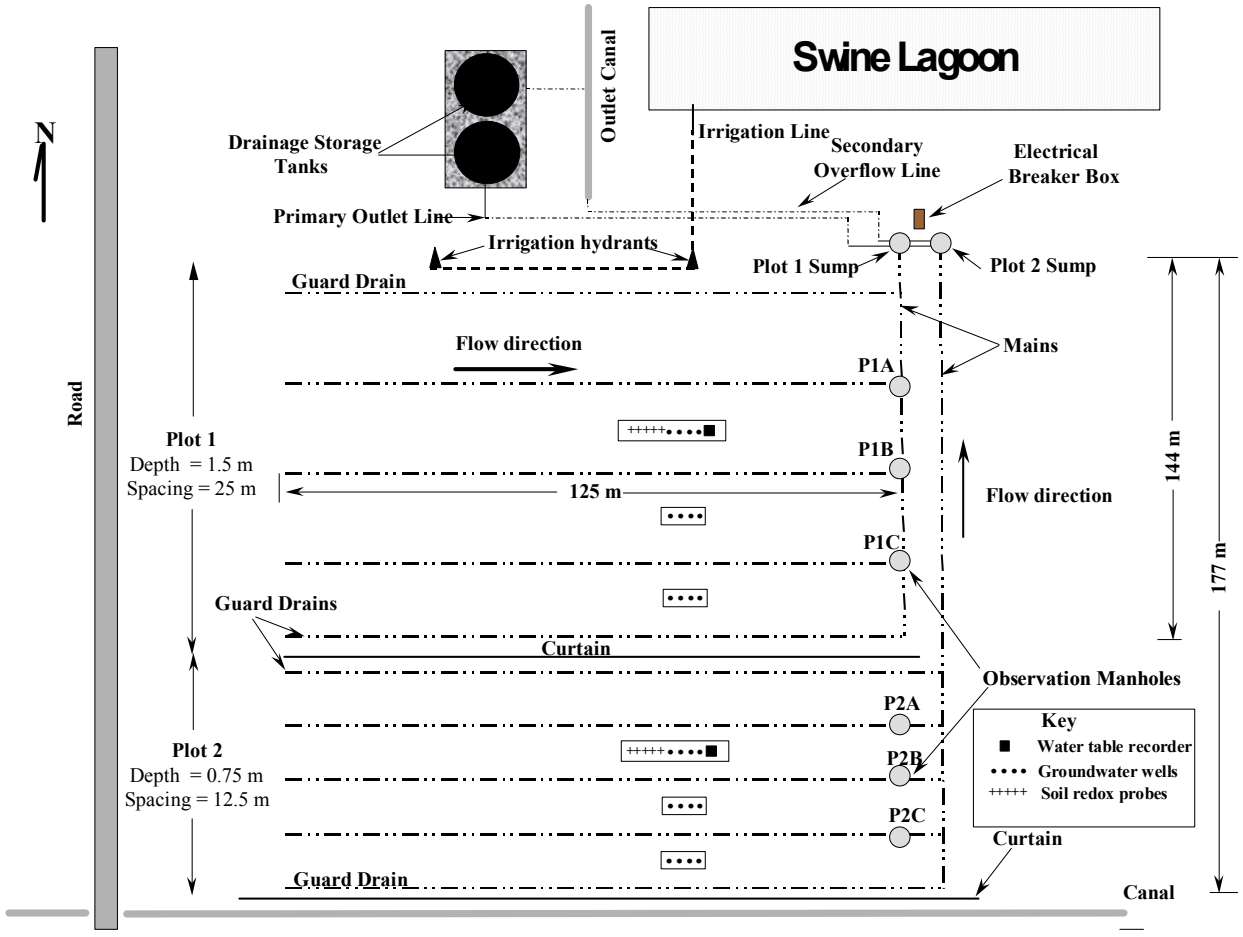

Figure 3. Drainage site schematic

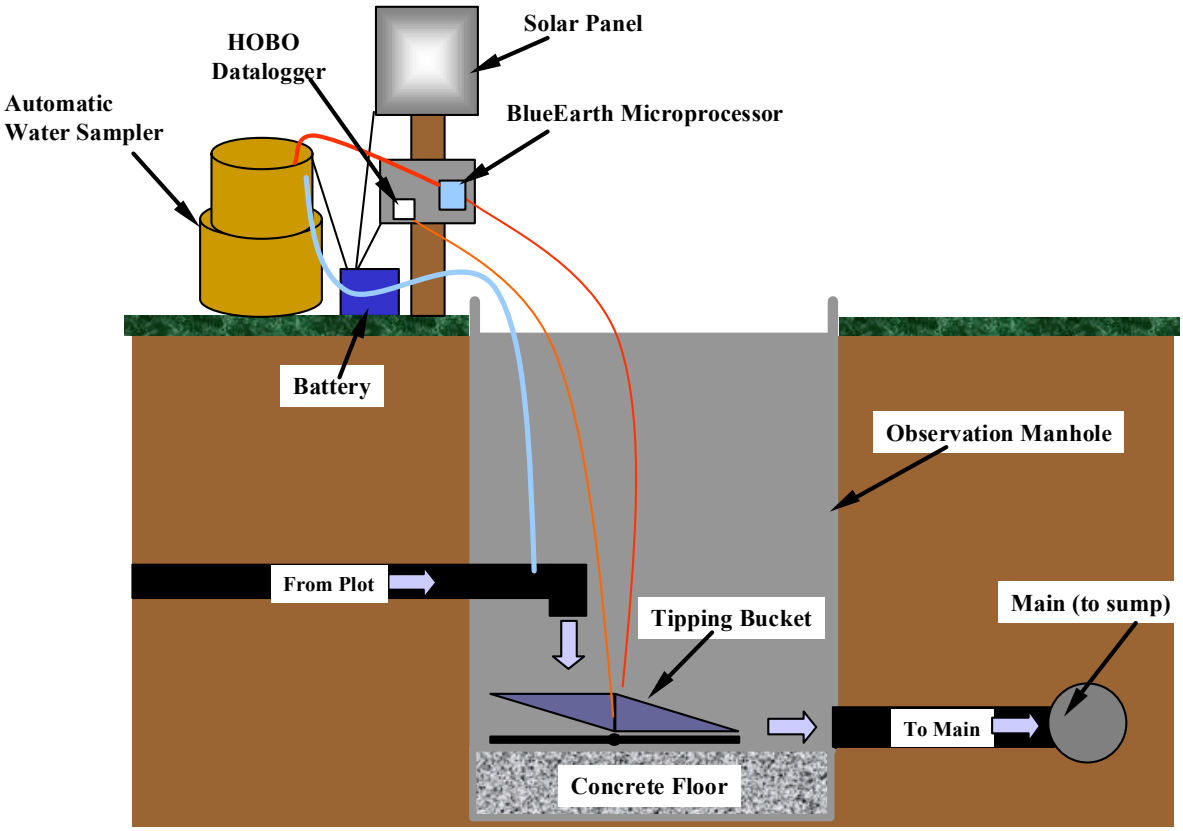

Figure 4. Observation manhole and instrumentation schematic.

RESULTS AND DISCUSSION

Data from the drainage study were analyzed for the 21-month period, January 1, 2001 through September 30, 2002. Precipitation during the majority of the study period was below normal (Table 2). Average yearly precipitation for the study site is 1310 mm, based on data collected from 1948-2000 at the Tidewater Research Station. Total precipitation at the site in 2001 was about 771 mm; 41% below the annual average. Rainfall totals recorded from January through September 2002 (1004 mm) were only slightly below the precipitation expected through September of an average year (1059 mm), but exceeded the total rainfall recorded at the site in the entire year of 2001. Total precipitation recorded during the 21-month period was 1775 mm., 25% less than the long- term average of 2369 mm.

Hydrology

As has been shown in previous field studies and simulations, subsurface drainage flow volumes for the shallow drains were less than for the deep drains in 2001 and in 2002. Table 3 shows the flow measured from each drain in 2001 and through September in 2002. The three replicate subsurface drains at 1.5 m depth in Plot 1 are identified in this table and all following tables as P1A, P1B, and P1C, and the drains at 0.75 m depth in Plot 2 are identified as P2A, P2B, and P2C. On several occasions, it was necessary to estimate flow from the drains due to malfunctions in the drainage system. Estimates of drainage during flooding of the observation manholes were based on a water balance, incorporating water table data and the volume drained/ water table depth relationship

obtained from the soil water characteristic of each plot. Estimates of flow from drains when at least one of the other drains from that plot was flowing, were made from a linear relationship between the drains within each plot. Daily flow data for each plot, and a more detailed description of flow estimates is found in Appendix 1-B through 1-D.

On average, the subsurface drainage from the deeper drains in Plot 1 exceeded the drainage from the shallow drains in Plot 2 by about 10 cm each year. During 2001, when there was below average precipitation, the subsurface drainage volumes from the more shallow drains were 59% less than that from the deeper drains. During 2002, the subsurface drainage volumes in both plots were much higher due to increased precipitation, and drainage volumes from the shallow drains were 33% less than that from the deeper drains. Overall, during the study period, shallow subsurface drains reduced drainage by 42%. Analysis of variance (ANOVA) of the means of the cumulative drainage volumes in 2001, 2002, and during the entire study indicated that shallow subsurface drainage significantly reduced drainage outflows at the study site. Figure 5a and b compare the average cumulative flow signatures of Plot 1 and Plot 2 during 2001 and 2002.

Water table profiles, measured at the midpoint between the drains in Plot 1 and Plot 2, are compared in Figure 6a and b. Several gaps in the water table data occurred because of malfunctions in the recorders. The most notable malfunction occurred in January 2002, when the counterweight attached to the water table float stuck, resulting in missed data on the rising leg of the water table during several rainfall events. The hourly values for the water table depths for each plot were averaged in 2001 and 2002, and the difference between these means were assumed to reflect the average difference in water

table depth between each plot. The water table depth in Plot 2 (drain depth 0.75 m), was on average 26.7 cm less than in Plot 1, (drain depth 1.5 m). In 2002, the water table depth for the shallow drains was 22 cm lower than for the deep drains.

Nitrate Concentration of Shallow Groundwater and Subsurface Drainage

Nitrogen inputs

Nitrogen was applied to the Bermuda and rye grass pasture by irrigating water from a swine waste lagoon. Application rates and times were based on calibration of the travelling gun irrigation system, and the plant available nitrogen (PAN) of the swine wastewater, which varied throughout the year. The N.C. Agricultural Extension Service (NCAES) (Barker, 1990) defines PAN for swine waste application without cultivation to grazed land as:

$$\mathbf{PAN_{applied}} = 0.5 \times NH_4^+ - N + 0.5 \times (TN - NH_4^+ - N)$$

where $TN = TKN + NO_3^-$- N, and $TKN = NH_4^+$ - N + organic-N. The NCAES recommends 231.5 kg PAN /ha/yr (206.5 lb/ac/yr) to bermudagrass and 56 kg PAN/ha/yr (50 lb/ac/yr) for the ryegrass winter annual. As seen from the above equation, approximately half of the nitrogen added is considered PAN to account for volatilization, uptake by cattle, and transformations that would make the nitrogen unavailable to the crop. Based on the time of irrigation and the PAN of the lagoon water, application was calculated to be below the NCCES recommended rate, which is 287.5 kg PAN /ha/yr. However, according to calculations based on measured irrigation depth and the PAN of

irrigation samples collected in rain gages during irrigation, 311 kg PAN /ha/yr was applied in 2001, while 205 kg PAN /ha/yr had been applied in 2002 (through September). Appendix 1-E includes data on individual irrigation events.

Nitrogen was also added to the research plot by rainfall. Total nitrogen added to the plot in 2001 and 2002 was 18.7 and 21.7 kg/ha, respectively, based on the yearly average of NO_3^--N, NH_4^+-N, and TKN concentrations in the rainfall.

The final nitrogen input came from cattle redeposition while grazing. Although grazing schedules were maintained, no data was collected on nitrogen deposited on the field as manure.

Shallow groundwater quality

Tables 4 and 5 show the average NO_3^--N concentrations in wells at various depths in 2001 and 2002. The Mann-Whitney or Wilcoxon two-sample test (SAS, 1989) was used to compare the NO_3^--N concentrations of the entire sample population at each well depth of Plot 1 with Plot 2. In 2001, there were no differences between the NO_3^--N concentration in the groundwater at the 90-120 cm depth in Plot 1 ($n = 15$) and Plot 2 ($n = 51$) (5% level, $p = 0.11$). The large difference in sample size at this depth is due to water table depth at the predetermined times for sampling (i.e. there was water in the wells for the shallow drains more often than for the deeper drains). The average concentrations in Plots 1 and 2 were both around 2 mg/L NO_3^--N, well below the EPA drinking water standard of 10 mg/L. Nitrate-nitrogen concentrations at the 150-180 cm depth were lower in Plot 2 ($n = 65$) than in Plot 1 ($n = 64$) at the 5% level ($p < 0.0001$). However, average concentrations in all wells at this depth were less than 0.1 mg/L, so

even if the statistically significant differences were due to drain depth, the effect on concentration was negligible for 2001.

The effect of swine waste application on groundwater quality was evident in 2002. Concentrations of NO_3^--N in both plots rose due to application of swine lagoon effluent especially at the 90-120 cm depth and in the 150-180 cm depth. Figure 7a and b compare the average NO_3^--N concentrations observed in Plot 1 and Plot 2 at these depths in 2002. Concentrations of shallow groundwater at the 90-120 cm depth averaged 39 mg/L NO_3^--N in Plot 1($n = 33$), and 23 mg/L NO_3^--N in Plot 2 ($n = 54$) (shallow drains). Statistical analysis indicated this difference to be significant ($p<0.001$), so it appears that the shallower drains had some effect on NO_3^--N concentration of the groundwater at the 90-120 cm depth. At the 150-180 cm depth, NO_3^--N concentrations in Plot 1($n = 60$) averaged over 15 mg/L, but less than 0.1 mg/L in Plot 2 ($n = 60$). This difference was significant ($p <0.0001$), so it also appears that shallow subsurface drains reduced NO_3^--N in groundwater at the 150-180 cm depth, compared to the plot with the deeper drains.

Concentration of NO_3^--N in the deepest wells, those screened from 210 – 240 cm depth remained low (<0.05 mg/L) throughout the study and did not appear to be affected by the difference in drainage depth in either year. However, the observed low NO_3^--N concentrations in these deep wells supports the idea that a thick reduced zone results in denitrification of groundwater that leaves the field through deep seepage.

The groundwater wells at 30-60 cm were not useful in determining effects of subsurface drainage depth on groundwater quality. Water table depths were infrequently at 30-60 cm depth in either plot. Only two samples from Plot 1 and one sample from Plot 2 were collected from this depth in 2001. Similarly, in 2002, only six samples and

four samples from Plot 1 and Plot 2, respectively, were collected from this depth. These sample numbers were too small to make inferences about the effect of subsurface drainage depth on groundwater quality at the 30-60 cm depth, and therefore were not analyzed statistically. Concentrations for all of the shallow groundwater depths are reported in Appendix 1-F.

Discussion of groundwater results

The differences in groundwater quality observed in 2002 may be explained by the difference in average water table depth and soil redox potential (Eh) in each plot. The water table depth in Plot 2 (0.75 m drain depth) was 22 cm higher than in Plot 1 (1.5 m drain depth). The closer the water table is to the surface, the greater the potential for the shallow soil layers to be anaerobic, and therefore there is a greater potential for denitrification to occur at shallow soil depths. This appears to be the case in this study, based on the observations in 2002. The average depth of the water table in Plot 1 was approximately 101 cm, while the average depth of the water table in Plot 2 was approximately 79 cm. This would place the water table on average within the range of the 90 – 120 cm wells in Plot 1 and about 10 cm above the 90-120 cm wells in Plot 2. The increased number of aerobic microsites that would be present at that depth in Plot 1 could account for the higher NO_3^--N concentrations observed, because denitrification potential would be lower.

Soil redox potential (Eh) was measured at the midpoint between the A and B drains of Plot 1 and 2. These weekly readings were used to attempt to assess any difference in denitrification potential that may arise due to differences in water table

depth. Eh readings measured in plot 1 and Plot 2 for the entire study are shown in Figure 8a and b. Each point represents the average of three readings taken at each depth (60, 90, 120, 150 and 180 cm). Figures 9 to 13 show the soil Eh of Plot 1 versus Plot 2 at 60, 90, 120, 150, and 180 cm for the entire study. Denitrification is generally believed to begin to occur when the Eh falls below 350 mV (Patrick, 1960; Ponnamperuma, 1972; Engler and Patrick, 1974). Because platinum-tipped Eh probes only measure redox potential at a point (perhaps representative of a few mm^3 of soil), results can be highly variable. Several probes inserted in a 15 cm radius, such as was done in this study, may give variable readings depending on whether the probe was inserted into a root channel, a clay aggregate, or in a sand pocket, because each may have very different water/air retention properties and carbon availability.

At the 60 cm depth, the effect of the shallow drainage in Plot 2 seemed to have the greatest effect on Eh. The average Eh for the study at this depth was 444 mV in Plot 1 and 207 mV in Plot 2, and this difference was significant at the 5 % level with a t-test assuming unequal variances. Surprisingly, Eh at the 90 and 120 cm depth did not appear to be significantly different between Plots 1 and 2. Average Eh values during the study at the 90 cm depth were 282 mV in Plot 1 and 274 mV in Plot 2. Average Eh values at the 120 cm depth were 187 and 214 mV for Plots 1 and 2, respectively. Both of these Eh levels should be sufficient for denitrification. Despite these similarities, NO_3^--N concentrations observed at the 90-120 cm depths were lower in Plot 2 than in Plot 1. This may be a result of the increased potential for denitrification at the 60 cm depth in Plot 2.

At the 150 and 180 cm depth, Eh values in Plot 2 were significantly lower than in Plot 1 at the 5% level. It should be noted that the data for the 150 cm depth were only analyzed through March 2002 since the Eh electrodes in Plot 2 appeared to malfunction, starting in April 2002. Average Eh values measured at the 150 cm depth were –30 and – 131 mV in Plots 1 and 2 respectively. There was little variation in Eh at the 180 cm depth, since this depth was saturated throughout the study. Average readings in Plots 1 and 2 were –92 and –143 mV, respectively. Despite the statistical differences in the actual Eh readings, the redox potentials for both plots at the 150 and 180 cm depths were far lower than what is required for denitrification. In this case, the redox measurements do not serve to explain the difference in NO_3^--N concentration found in Plot 1 (15.5 mg/L) and in Plot 2 (0.1 mg/L) groundwater at the 150-180 cm depth. The redox measurements indicate there should be no difference in Plot 1 and Plot 2 at this depth, but as mentioned earlier, the average of three measurements may not be sufficient to provide a true picture of the redox status of the soil. Despite these redox measurements, the NO_3^--N concentration at the 150-180 cm depth was much less in Plot 2; probably due to the thicker reduced zone resulting from the shallow drain depths.

A study by Kliewer and Gilliam (1995) support these observations. They examined water table effects on denitrification using 56 cm undisturbed cores of Cape Fear loam obtained from NCDA – Tidewater Research Station in Plymouth, NC. The cores were subjected to static water table levels of 15, 30 and 45 cm, and yielded denitrification of 341, 260, and 86 kg N/ha respectively over the November-April study period. The researchers concluded that for this soil, the most denitrification occurs through the soil profile when water levels are maintained near the surface. However,

denitrification rates were highest at deeper soil depths for the various water table depths. Rates will increase near the soil surface as long as oxygen diffusion is limited at this depth and NO_3^--N does not become rate limiting.

Subsurface drainage water quality

Table 6 shows the range and average NO_3^--N concentration in subsurface drainage water in Plots 1 and 2. One of the goals of this research was to determine if higher water tables resulting from shallow subsurface drains would also reduce the NO_3^--N concentrations in the drainage water. In both 2001 and 2002, the average concentration of NO_3^--N and the flow-weighted average NO_3^--N concentration of the drainage water in the shallow drains in Plot 2 exceeded that of the deeper drains in Plot 1. Nonparametric methods were necessary to test for equality of NO_3^--N concentrations in the drainage water of each plot within each year due to the non-normally distributed data and inhomogeneity of variance across plots within each year. As in the comparison of groundwater NO_3^--N concentrations, the Mann-Whitney or Wilcoxon two-sample test (SAS, 1989) was used to compare the entire sample population obtained in Plot 1 with the Plot 2 sample population.

In 2001, the NO_3^--N concentration of the drainage water in Plot 2 (7.60 mg/L) ($n = 25$) was significantly greater ($p = 0.0009$) than in Plot 1 (2.38 mg/L) ($n = 56$). There was a difference in the sample numbers between the plots because there were fewer opportunities to sample the shallow subsurface drains in Plot 2, due to fewer days of flow. The difference in the mean concentration from the two drains in 2001 is well

illustrated in Figure 14a. The flow-weighted average NO_3^--N concentration ranged from 2.3-4.2 mg/L in Plot 1 and 7.0-15.9 mg/L in Plot 2. The flow-weighted average NO_3^--N concentration of drainage water from the center drain (the most isolated of the three drains in each plot) in Plot 1 and 2 was 4.2 and 14.4 mg/L respectively.

In 2002 the average concentration of NO_3^--N in the subsurface drainage water increased in both Plot 1 ($p < 0.0001$) and Plot 2 ($p = 0.0003$), as a result of the accumulating swine waste application events. Even though the average NO_3^--N concentrations of the shallow subsurface drains in Plot 2 (15.7mg/L) ($n = 43$) were greater than in Plot 1 (12.8 mg/L) ($n = 72$), there was no statistical difference between them ($p = 0.4134$). Figure 14b graphically shows the similarity of the NO_3^--N concentrations in Plots 1 and 2 in 2002. The 2002 flow-weighted average NO_3^--N concentration ranged from 10.0-14.3 mg/L in Plot 1 and 10.0-17.2 mg/L in Plot 2. The 2002 flow-weighted average NO_3^--N concentration of drainage water from the center drain in Plot 1 and 2 were 14.3 and 14.4 mg/L respectively.

Discussion of drainage water NO_3^--N concentrations

Differences in groundwater NO_3^--N concentrations observed between Plot 2, with the shallow subsurface drainage system, and Plot 1, with the deeper subsurface drainage system, are contrary to what was observed in the drainage NO_3^--N water concentrations. Despite the higher water tables and lower groundwater NO_3^--N concentrations observed in the shallow drainage plot (Plot 2), the NO_3^--N concentrations in the drainage water were higher than in Plot 1. Since denitrification rates from both plots were not measured, we can only speculate about the reasons for differences observed in the NO_3^--N

concentrations in the drainage water. The Kliewer and Gilliam (1995) study, described in the groundwater discussion, supports the hypothesis that more denitrification may occur in the *entire* soil profile with shallow drains since the water table remained consistently higher in this study. Gilliam et al. (1979) found that the greatest increases in denitrification are at the deeper soil depths. Therefore, during drainage, water entering the bottom sections of the shallow subsurface drains should have lower NO_3^--N concentrations than it would in the deeper drains. However, drainage water concentrations were actually higher in the shallow drains in 2001 and about the same in 2002 compared to the deeper drains. These higher than expected concentrations may have resulted from preferential flow from the surface directly to the drains. Because of the short distance from the surface to the shallow drains, this phenomena could have a larger effect on the NO_3^--N concentrations in the shallow than in the deeper drains. Such flow would dramatically reduce the potential for denitrification to occur before the water entered the drains. To make denitrification possible in the upper soil profile, there must be adequate time to remove oxygen from the soil pores (Gilliam and Gambrell, 1978).

Evidence of preferential flow was observed immediately following most swine wastewater irrigation events. The characteristic pink color of the lagoon waste water (due to the presence of purple sulfur-reducing bacteria that colonize healthy swine lagoons) was observed in the drainage water during these events. The flow from the shallow drains in Plot 2 following irrigation usually did not cause the water table to rise above the drains. On most occasions, it appeared that the wastewater was entering the drains directly from the surface. The drainage water from the Plot 2 was also darker in color than that from the deeper drains in Plot 1. This gave a visual indication of short-

circuiting of the irrigation water directly to the drains in Plot 2, with minimal treatment or dilution. There was also some evidence of short circuiting in Plot 1, but to a much lesser extent than in Plot 2. Figures 15 and 16 show the average NH_4^+-N and the NO_3^-- N concentrations of grab samples from the subsurface drains in both plots following swine waste irrigation events in 2002. Irrigation water reaching the soil surface averaged over 400 mg/L NH_4^+-N, and rarely did NO_3^-- N concentrations exceed 2 mg/L. Concentrations of NH_4^+-N in the drainage water were much less than those in the irrigation water, indicating some nitrification or dilution before reaching the drain. In most cases, average nitrogen concentrations in the Plot 2 drains, directly following irrigation, exceeded those in Plot 1, and drainage flow rates from each plot were generally low. Drainage water NH_4^+-N concentrations during non-irrigation events in 2002 averaged 1.1 mg/L and 0.6 mg/L in 2002 in Plot 1 and 2 respectively. Average export of NH_4^+-N 2002 was 1 kg/ha in Plot 1 and 0.9 kg/ha in Plot 2. Based on these observations, NH_4^+-N drainage water concentrations and export did not appear to be affected by drainage depth (See Appendix 1-H). Therefore, increased NH_4^+-N concentrations after irrigation events may indicate that short-circuiting may play a role in increasing the NO_3^-- N concentrations in the drainage water from Plot 2.

Shorter flow paths directly above the shallow drains could also account for increases in NO_3^--N concentrations in the shallow drainage water following rainfall. Comparisons of daily subsurface drainage flows (cm) from the middle drain in Plot 1, P1B, and the middle drain in Plot 2, P2B, are shown in Figure 17 for three months in 2002. During most of these flow events, peak flow is higher for the shallow drain, P2B, than for the deeper P1B drain. Flow in P2B also slows faster than the P1B drain. In

other words, peak drainage flow increased with decreased drain depth. During conditions when the surface is ponded, as much as 95% of the flow can originate from a region bounded by +/- 25% of the drain spacing (Kirkham, 1957; Skaggs, 1999a). Salem (2000) used simulations to illustrate the contribution of flow to the drains following a rainfall event during the formation of the elliptical water table. Flow in the unsaturated zone during this time is generally in the vertical direction because of the large vertical gradients that occur near the drain. In one example, 45% of the flow that occurred 8 hrs after a rainfall event was derived from the 14% of the profile closest to the drain. Therefore, the retention time of the water flowing to the drains during this period may be less in systems with shallow drains spaced closer together, than when drains are deeper and spaced further apart, because the flow lines from the surface to the shallow drains would be shorter. This would decrease time for denitrification and/or dilution of the soil water before entering the drain. In addition, during these flow periods, the soil pores surrounding the drains, which may be rich in NO_3^--N, may also be flushed into the shallow drains via shorter flow paths. The combination of reduced retention time, decreasing the potential for denitrification, and soil pore flushing near the shallow drains, may contribute to the increased NO_3^--N concentrations observed in the shallow subsurface drainage water.

Nitrate Export

The bottom line of this research is to evaluate whether installing subsurface drains at depths more shallow than typical reduces the mass of NO_3^--N that leaves in subsurface drainage water. It may be concluded from the results presented earlier that drains

installed at 0.75 m deep and 12.5 m spacing produce significantly less outflow compared to the drains 1.5 m deep and 25 m apart. However, the average NO_3^--N concentration in the drainage water from Plot 2 exceeded that in Plot 1 on average. Both of these factors contribute to mass NO_3^--N outflows. Table 7 shows the NO_3^--N exported, in kg/ha, in 2001, 2002, and over the entire study. There was very low NO_3^--N export from both plots in 2001, a result of below average precipitation, which reduced drainage outflows, and low NO_3^--N concentration in the drainage water because wastewater irrigation had just begun. Despite having smaller drainage volumes, the concentration of NO_3^--N in the drainage water in 2001 was significantly greater in Plot 2, and resulted in greater NO_3^--N kg/ha losses than observed in Plot 1. However, the difference was only about 2 kg/ha/yr, and was not significant at the 5% level. Figure 18 shows the trend of NO_3^--N export for Plot 1 and 2 in 2001. From this figure and Figure 14a, the majority of the difference in NO_3^--N export in 2001 between Plot 1 and 2 was a result of an August flow event where drainage water NO_3^--N concentrations in Plot 2 were nearly 3 times that measured in Plot 1.

Increased precipitation, though still below normal, resulted in higher drainage volumes from both plots in 2002. Continued swine waste irrigation increased the NO_3^--N concentration in the drainage water. The result was much higher NO_3^--N export from both plots. In this year, NO_3^--N export from the deeper subsurface drains in Plot 1 exceeded the export from Plot 2 by an average of 26%, or nearly 10 kg/ha, through September. The difference in NO_3^--N export between Plot 1 and Plot 2 was significant at the 10% level ($p = 0.087$). Figure 19 shows the trend of NO_3^--N export for Plot 1 and 2 in

2002, through September. The difference between the average NO_3^--N export between the two plots continued to increase throughout the year.

The mass of NO_3^--N exported from the P1A drain in Plot 1 in 2002 was about 10 kg/ha less than the other two replicate drains, P1B and P1C. Because of a perimeter fence adjacent to the P1A drain, the traveling irrigation gun could not move past the end of the field, and less swine waste was applied to the P1A drainage area. This may have resulted in the observed lower NO_3^--N concentrations in that drain (see Table 6 for 2002 drainage water NO_3^--N concentration data). Had the same amount of wastewater been applied to the P1A drainage area as was applied to the rest of the field, more NO_3^--N export would probably have occurred, and the differences between total export from Plots 1 and 2 would have been greater. If the P1A drain had exported only 2 kg/ha more NO_3^--N, average losses from Plot 1 would have been over 27% greater than from Plot 2. In that case, differences in NO_3^--N export between the two plots would have been significant at the 5% level ($p = 0.0498$).

The shallow subsurface drainage system in Plot 2 reduced NO_3^--N losses by nearly 18% when compared to the deeper subsurface drainage system in Plot 1, for the entire 21-month study. This difference is equivalent to a reduction of 7.5 kg/ha. However, this overall difference was not significant at the 5 or 10% level ($p = 0.17$).

CONCLUSIONS

A 21-month field study was implemented to study the impacts of shallow subsurface drainage systems on reducing NO_3^--N losses and improving shallow groundwater quality. Two drainage systems, designed to provide adequate drainage for the site, were evaluated. The average depth of the drain tile installed in the deep drainage plot (Plot 1) was approximately 1.44 m, with a drain spacing of 25 m. The average depth of the drain tile installed in the shallow drainage plot (Plot 2) was approximately 0.70 m, with a drain spacing of 12.5 m. Decreased drain depth reduced drainage outflows by 42%. NO_3^--N concentrations in groundwater at the 90-120 cm and the 150-180 cm depth were significantly lower in Plot 2 (22.9 and 0.1 mg/L respectively) than in Plot 1 (39.1 and 15.5 mg/L respectively) in 2002. This difference was most likely a result of higher water tables and a larger reduced zone formed with the shallow drainage system, which increased denitrification potential. However the average NO_3^--N concentration in the drainage water from the Plot 2 drains (7.6 mg/L) was significantly higher than in the Plot 1 drains (2.4 mg/L) in 2001. In 2002, there was no significant difference in the average NO_3^--N concentrations in the drainage water from the two plots. On average, nitrate export from the shallow subsurface drains was about 8 kg/ha in 2001 and 27 kg/ha in 2002. Nitrate exports from the deeper drains were about 6 kg/ha in 2001 and 37 kg/ha in 2002. Overall, an average of nearly 8 kg/ha less nitrate was exported from the shallow subsurface drainage system over the 21-month study.

While the results of this study indicate that shallow subsurface drains will export less NO_3^--N losses from agricultural fields than will deeper drains placed further apart,

variability in the field observations reduced the certainty of this conclusion. Drainage system studies must be conducted on a field-scale, so a large number of replications are prohibitively expensive. Observations need to be conducted over a longer period of time to determine the response over a wider range of weather conditions. Other factors such as the uneven distribution of wastewater in one part of Plot 1 need to be corrected in future research on these systems.

The potential of the use of shallow drains to reduce NO_3^--N loads as an alternative to controlled drainage warrants more research. The implications of this research were not meant to just include animal wastewater fields. It is also applicable, and may be more beneficial, on agricultural fields where inorganic fertilizers are used. Effects of soil type, fertilization rates and type, topography, and preferential flow on NO_3^--N reduction should be evaluated. Long-term field studies are needed to further evaluate effects of various climatological effects on NO_3^--N reductions from shallow subsurface drainage systems.

Table 2. Observed and average precipitation for the research site in Plymouth, N.C.

Month	2001 (mm)	2002 (mm)	Research Site Average[1] (mm)
January	36.1 (-68.5)[2]	138.2 (+33.6)	104.6
February	59.5 (-34.0)	49.5 (-44.0)	93.5
March	70.9 (-37.8)	195.3 (+86.6)	108.7
April	31.2 (-51.4)	49.8 (-32.8)	82.6
May	100.1 (-11.4)	51.3 (-60.2)	111.5
June	141.7 (+15.0)	82.3 (-44.4)	126.7
July	152.7 (+2.1)	147.8 (-2.8)	150.6
August	104.6 (-45.5)	214.1 (+64.0)	150.1
September	29.5 (-100.8)	75.7 (-54.6)	130.3
October	11.9 (-75.2)	-	87.1
November	14.5 (-68.3)	-	82.8
December	17.8 (-63.7)	-	81.5
Total	**770.5** (-539.6)	**1004.0**[3] (-54.7)[3]	**1310.1** (1058.7)[3]

1 – Average of Plymouth, NC from 1948-2000 (Southeast Regional Climate Center)
2 – Departure from monthly average
3 – Through September

Table 3. Observed subsurface drainage in **a)** Plot 1 and **b)** Plot 2

a) Plot 1 - Drain depth = 1.5 m, Spacing = 25 m

Drain	2001 Drainage (cm)	2002 Drainage[1] (cm)	Total Drainage (cm)
P1A	17.9	30.0	47.9
P1B	15.4	28.6	44.0
P1C	18.4	31.9	50.3
Avg	17.2	30.2	47.4
Std Dev	1.6	1.7	3.2

b) Plot 2 - Drain depth = 0.75 m, Spacing = 12.5 m

Drain	2001 Drainage (cm)	2002 Drainage[1] (cm)	Total Drainage (cm)
P2A	3.6	15.9	19.5
P2B	6.5	21.9	28.4
P2C	11.3	23.1	34.4
Avg	7.1*	20.3*	27.4*
Std Dev	3.9	3.9	7.5

1 – Through September
Note: Significant decreases in drainage flow as a result of shallower drainage depths in Plot 2 indicated by * for each time period (p = 0.05)

Table 4. NO_3^--N levels (mg/L) in shallow groundwater beneath each plot in 2001 in **a)** Plot 1 and **b)** Plot 2.

a) Plot 1 - Drain depth = 1.5 m, Spacing = 25 m

Well Nest	Depth of Well Screen (cm)		
	90-120	150-180	210-240
W1A	1.9	< 0.1	<0.1
W1B	3.7	0.1	<0.1
W1C	1.7	<0.1	<0.1
Plot 1 Avg	2.4	0.1	<0.1
Std Dev	3.7	<0.1	<0.1

b) Plot 2 - Drain depth = 0.75 m, Spacing = 12.5 m

Well Nest	Depth of Well Screen (cm)		
	90-120	150-180	210-240
W2A	6.1	<0.1	<0.1
W2B	0.6	<0.1	<0.1
W2C	0.1	<0.1	<0.1
Plot 2 Avg	2.3	<0.1*	<0.1
Std Dev	4.2	<0.1	<0.1

Note: Significant differences in groundwater concentrations in Plot 2 indicated by * ($p = 0.05$)

Table 5. NO_3^--N levels (mg/L) in shallow groundwater beneath each plot in 2002 in **a)** Plot 1 and **b)** Plot 2.

a) Plot 1 - Drain depth = 1.5 m, Spacing = 25 m

Well Nest	Depth of Well Screen (cm)		
	90-120	150-180	210-240
W1A	42.5	5.2	<0.1
W1B	48.5	18.6	<0.1
W1C	26.3	22.7	<0.1
Plot 1 Avg	39.1	15.5	<0.1
Std Dev	15.4	11.1	<0.1

b) Plot 2 - Drain depth = 0.75 m, Spacing = 12.5 m

Well Nest	Depth of Well Screen (cm)		
	90-120	150-180	210-240
W2A	33.6	<0.1	<0.1
W2B	23.3	0.1	<0.1
W2C	12.0	<0.1	<0.1
Plot 2 Avg	22.9*	0.1*	<0.1
Std Dev	15.3	<0.1	<0.1

Note: Significant differences in groundwater concentrations in Plot 2 indicated by * ($p = 0.05$)

Table 6. Average drainage water NO_3^--N concentrations and ranges in **a)** Plot 1 and **b)** Plot 2.

a) Plot 1 - Drain depth = 1.5 m, Spacing = 25 m

Drain	2001 (mg/L)	2002 [2] (mg/L)
P1A	2.5 (0.2-7.7)[1]	10.0 (1.6-26.1)
P1B	3.0 (0.4-9.2)	14.9 (7.0-30.7)
P1C	1.5 (0.1-5.0)	13.6 (5.5-25.2)
Avg	2.4	12.8
Std Dev	2.4	5.4

b) Plot 2 - Drain depth = 0.75 m, Spacing = 12.5 m

Drain	2001 (mg/L)	2002 [2] (mg/L)
P2A	9.4 (0.1-28.1)	20.1 (9.6-54.6)
P2B	10.1 (0.7-23.6)	16.3 (7.7-44.8)
P2C	4.8 (0.4-12.6)	11.6 (3.3-33.9)
Avg	7.6*	15.7*
Std Dev	7.5	10.6

1 - Concentration range of flow proportional samples
2 - Through September
Note: Significant differences in groundwater concentrations in Plot 2 indicated by * ($p = 0.05$)

Table 7. Average NO_3^--N export from **a)** Plot 1 and **b)** Plot 2.

a) Plot 1 - Drain depth = 1.5 m, Spacing = 25 m

Drain	2001 NO_3^--N kg/ha	2002[1] NO_3^--N kg/ha	Study NO_3^--N kg/ha
P1A	5.9	29.9	35.9
P1B	6.5	40.9	47.4
P1C	4.3	39.8	44.1
Avg	5.5	36.9	42.4
Std Dev	1.2	6.1	5.9

b) Plot 2 - Drain depth = 0.75 m, Spacing = 12.5 m

Drain	2001 NO_3^--N kg/ha	2002[1] NO_3^--N kg/ha	Study NO_3^--N kg/ha
P2A	5.7	27.3	33
P2B	9.4	31.5	40.9
P2C	7.9	23.1	31
Avg	7.7	27.3*	34.9
Std Dev	1.9	4.2	5.2

1 - Through September
Note: Significant differences in groundwater concentrations in Plot 2 indicated by * ($p = 0.10$)

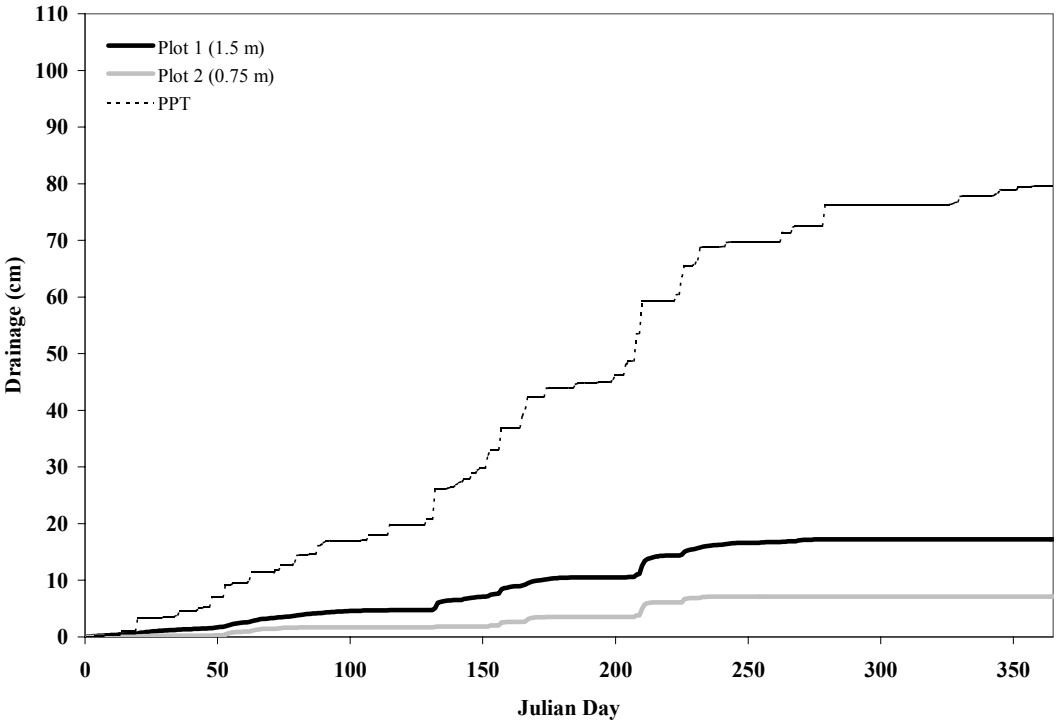

Figure 5a. Average cumulative subsurface drainage from Plot 1 and Plot 2 in 2001

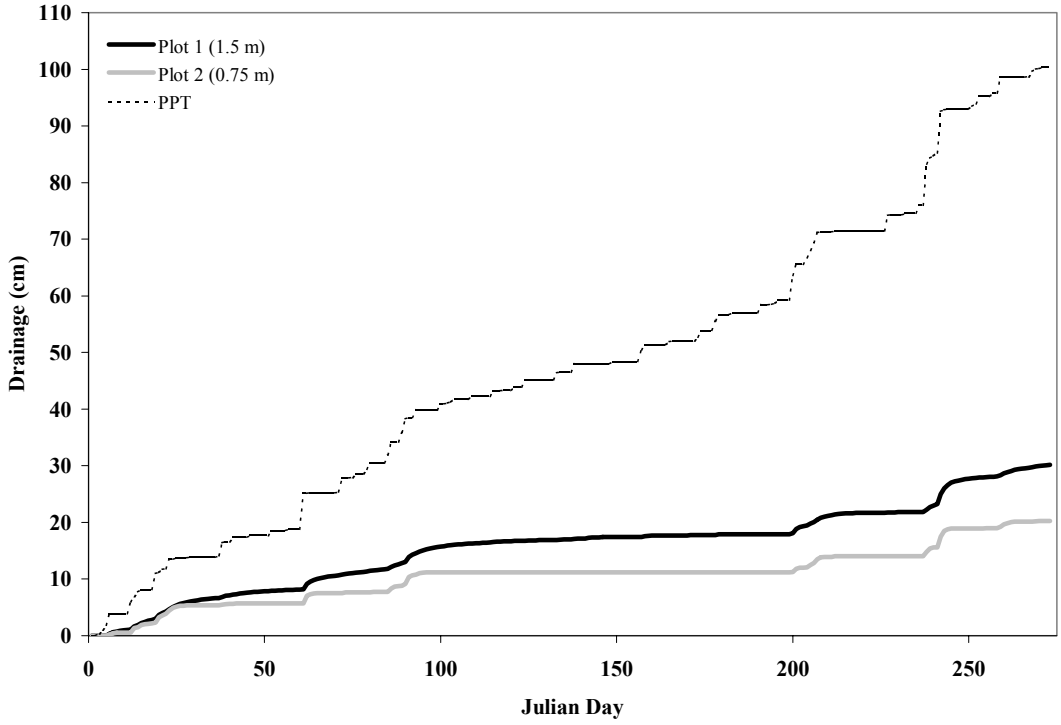

Figure 5b. Average cumulative subsurface drainage from Plot 1 and Plot 2 in 2002

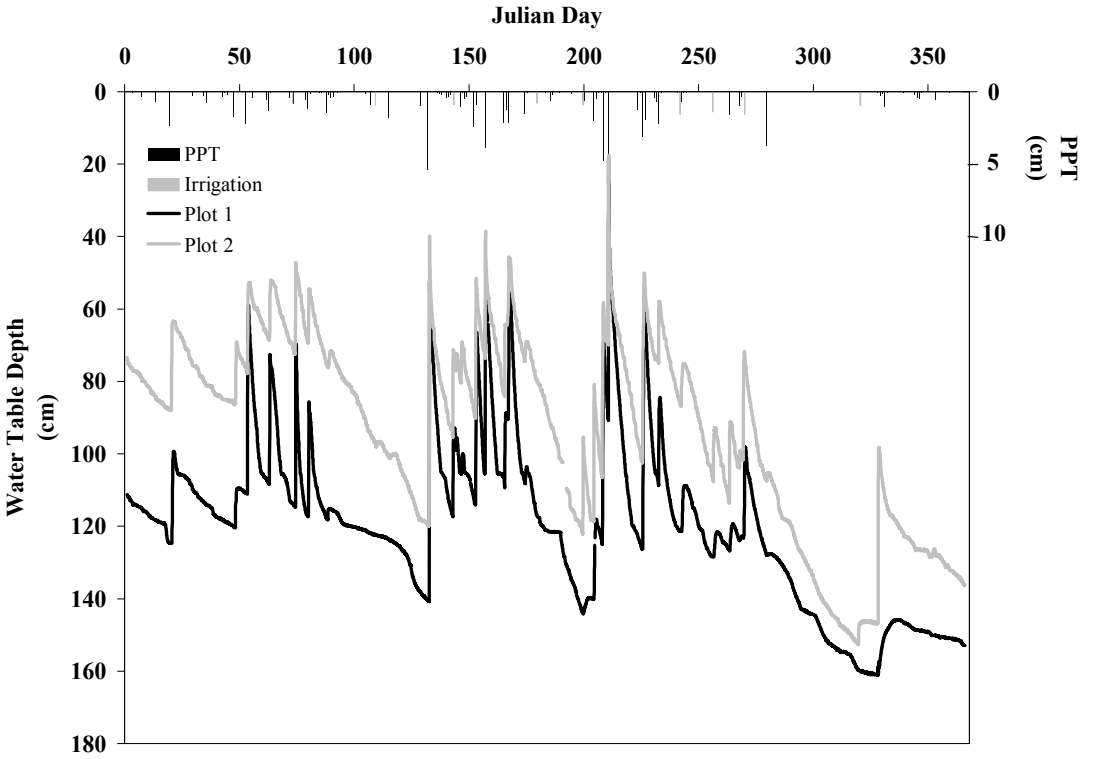

Figure 6a. Water table elevations in Plot 1 and Plot 2 in 2001

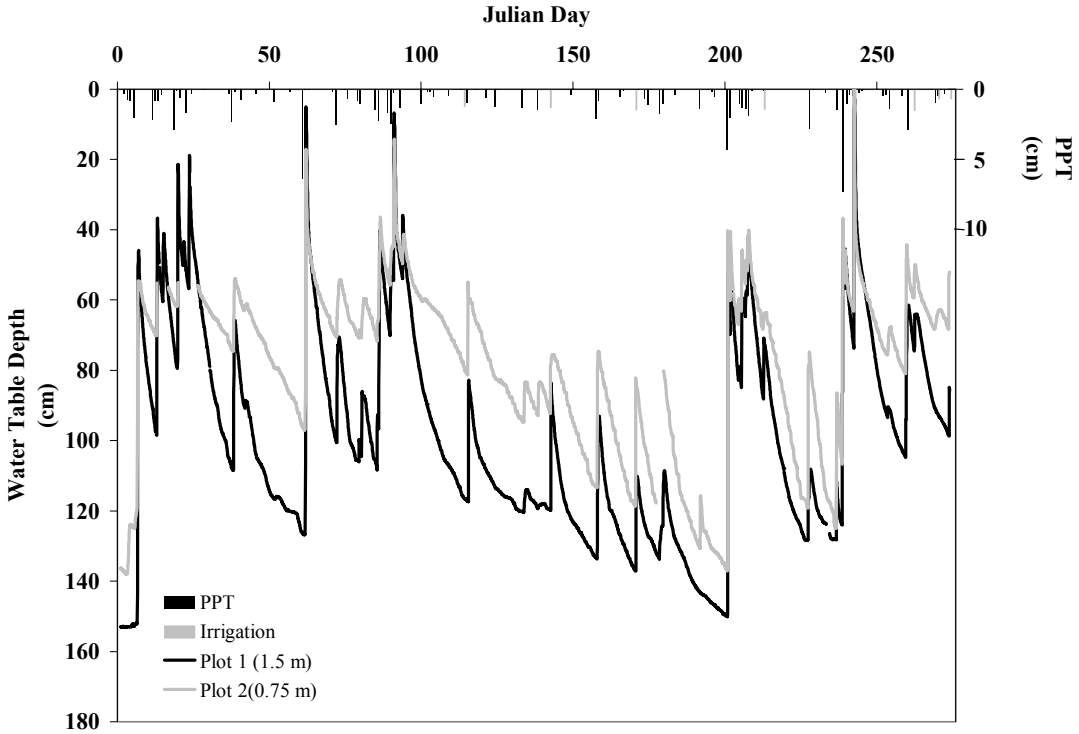

Figure 6b. Water table elevations in Plot 1 and Plot 2 in 2002

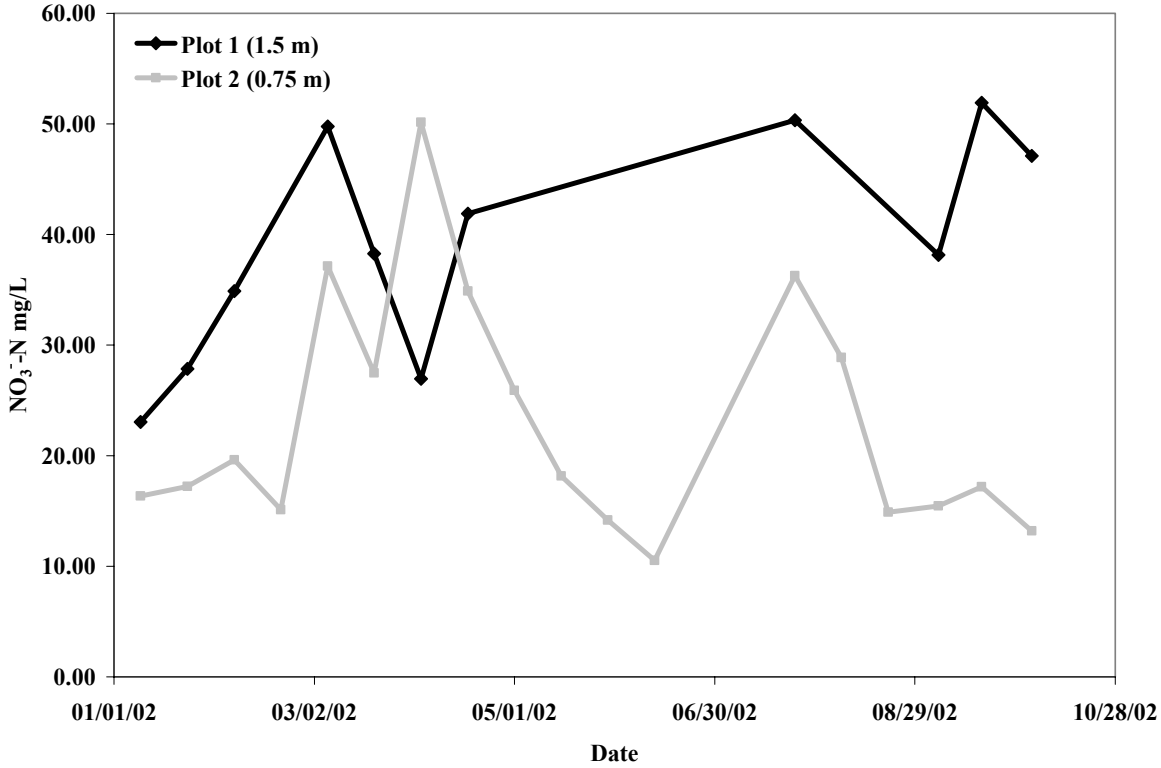

Figure 7a. Average groundwater NO_3^- -N concentrations at 90-120 cm in 2002

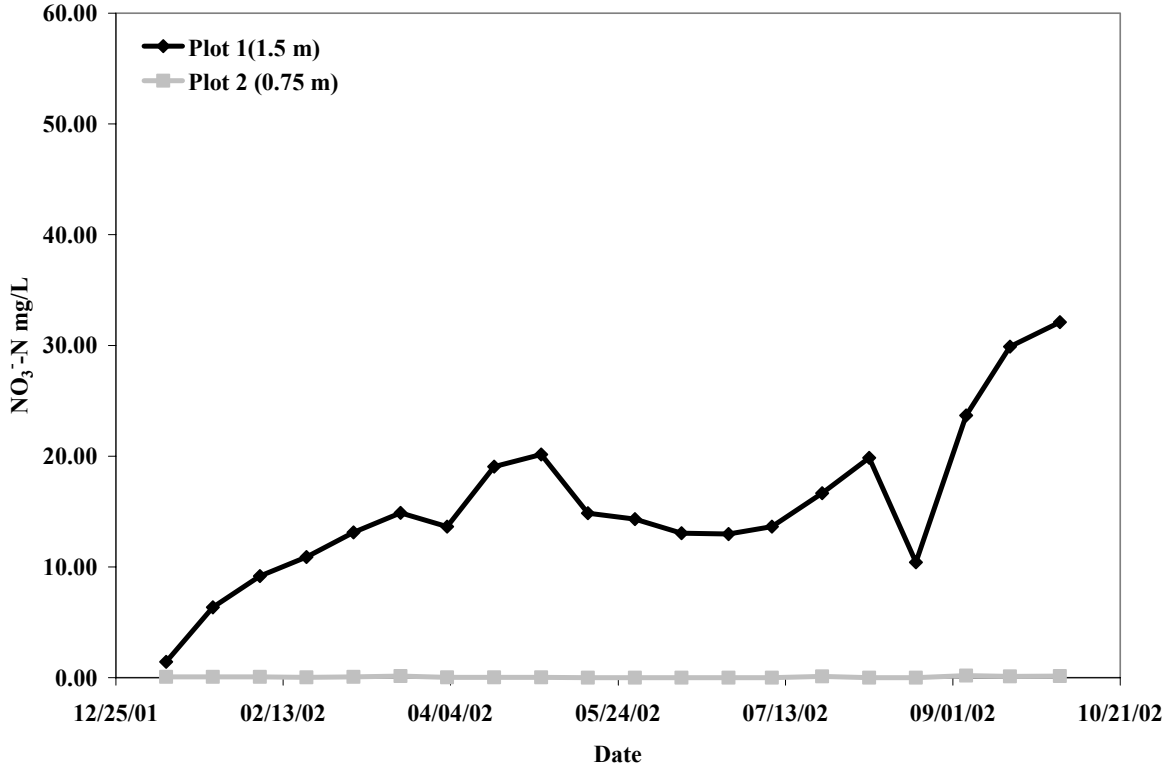

Figure 7b. Average groundwater NO_3^- -N concentrations at 150-180 cm in 2002

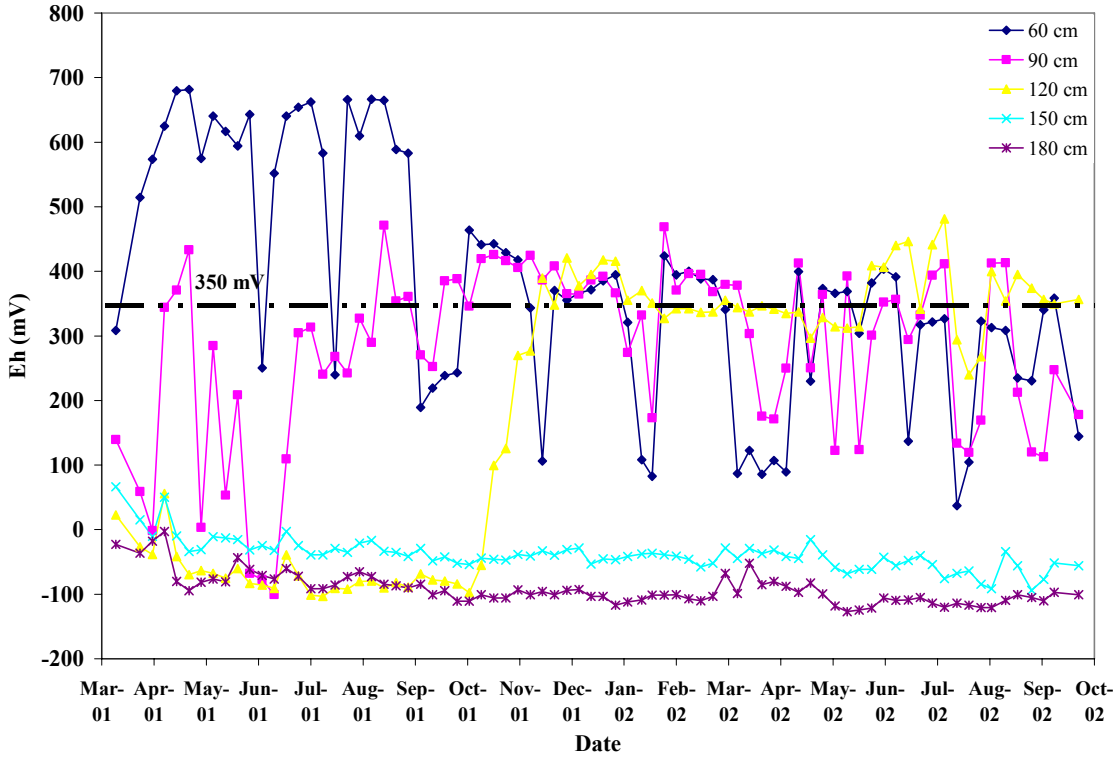

Figure 8a. Average soil redox (Eh) readings from Plot 1 (*Note*: line indicates 350 mV – the approximate Eh level required for denitrification to begin)

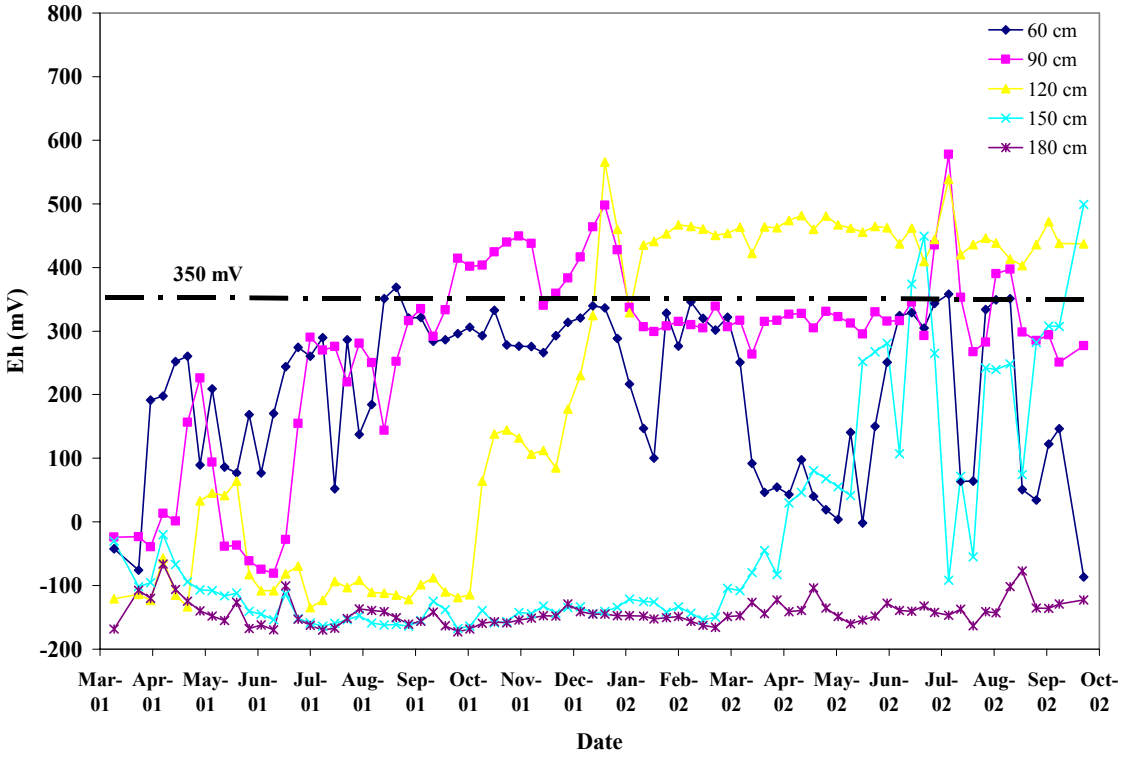

Figure 8b. Average soil redox (Eh) readings from Plot 2 (*Note:* line indicates 350 mV – the approximate Eh level required for denitrification to begin)

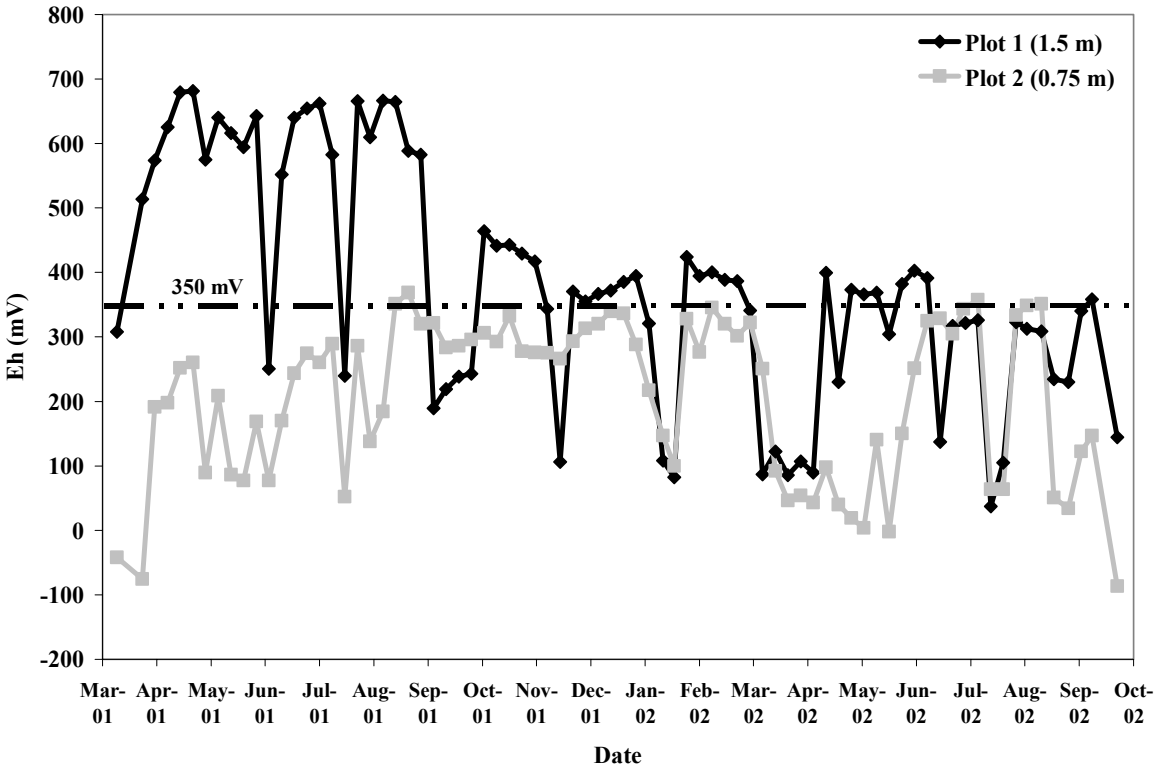

Figure 9. Average soil redox (Eh) readings at the 60 cm depth for Plot 1 and 2

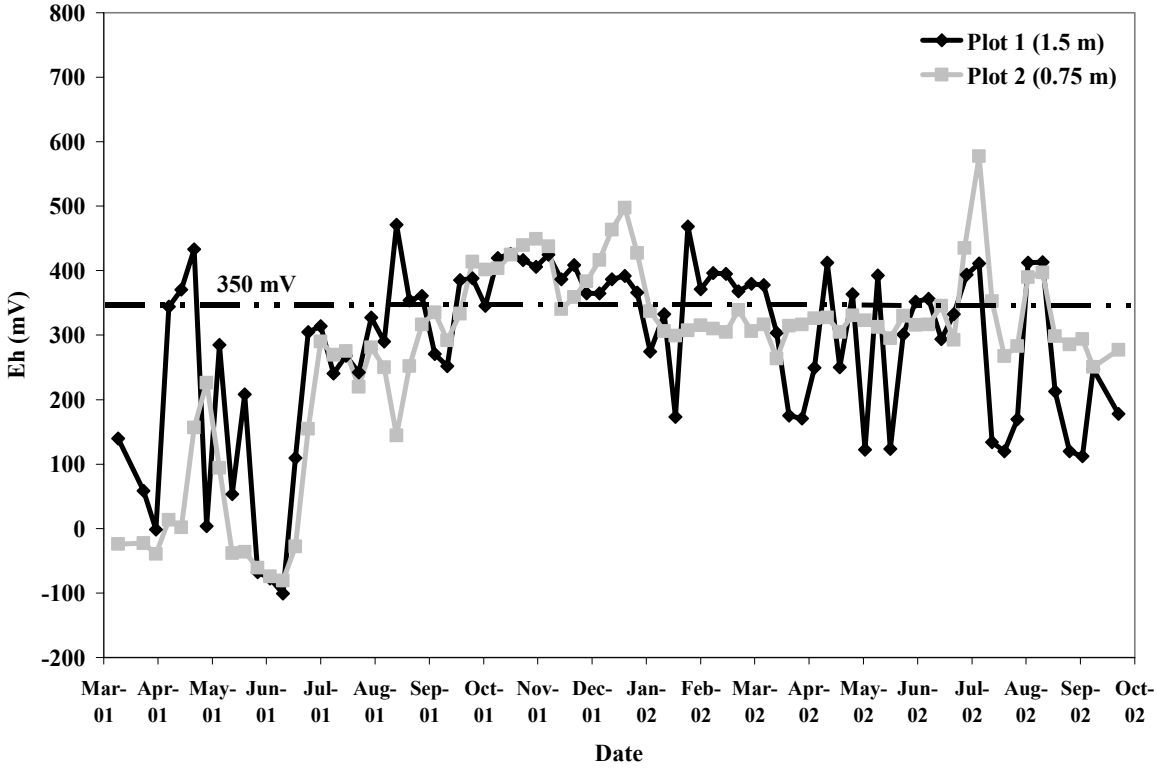

Figure 10. Average soil redox (Eh) readings at the 90 cm depth for Plot 1 and 2

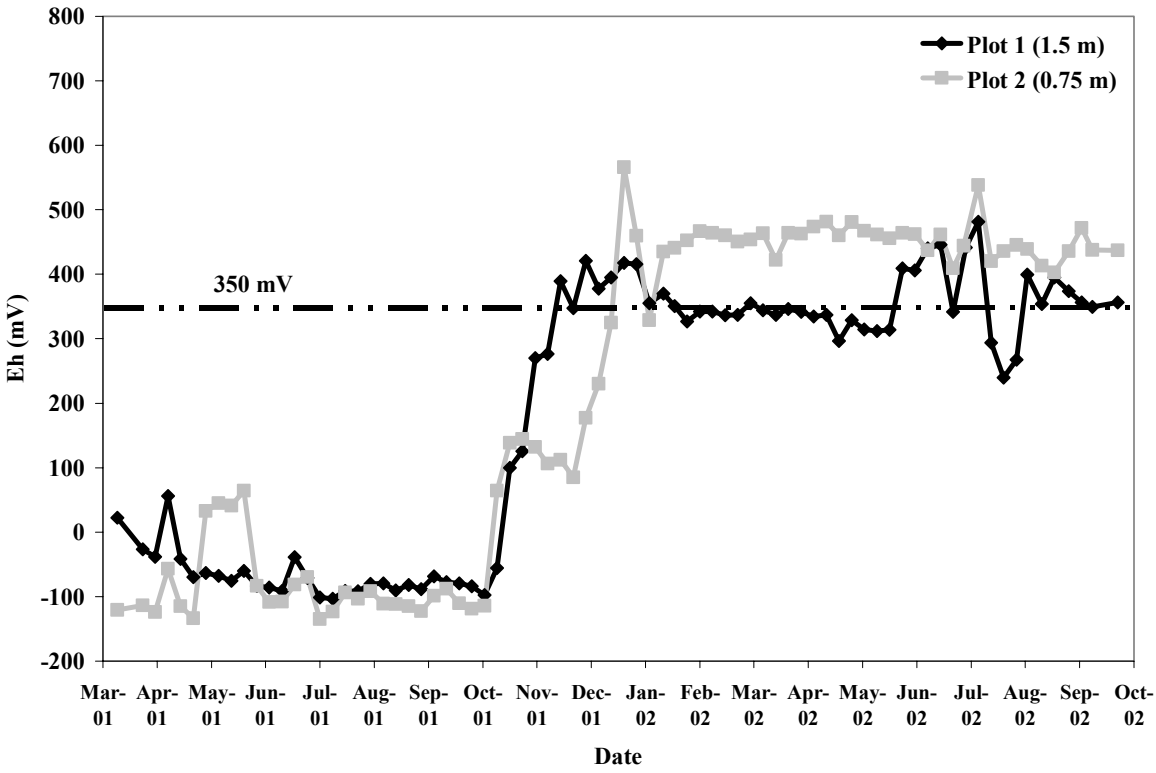

Figure 11. Average soil redox (Eh) readings at the 120 cm depth for Plot 1 and 2

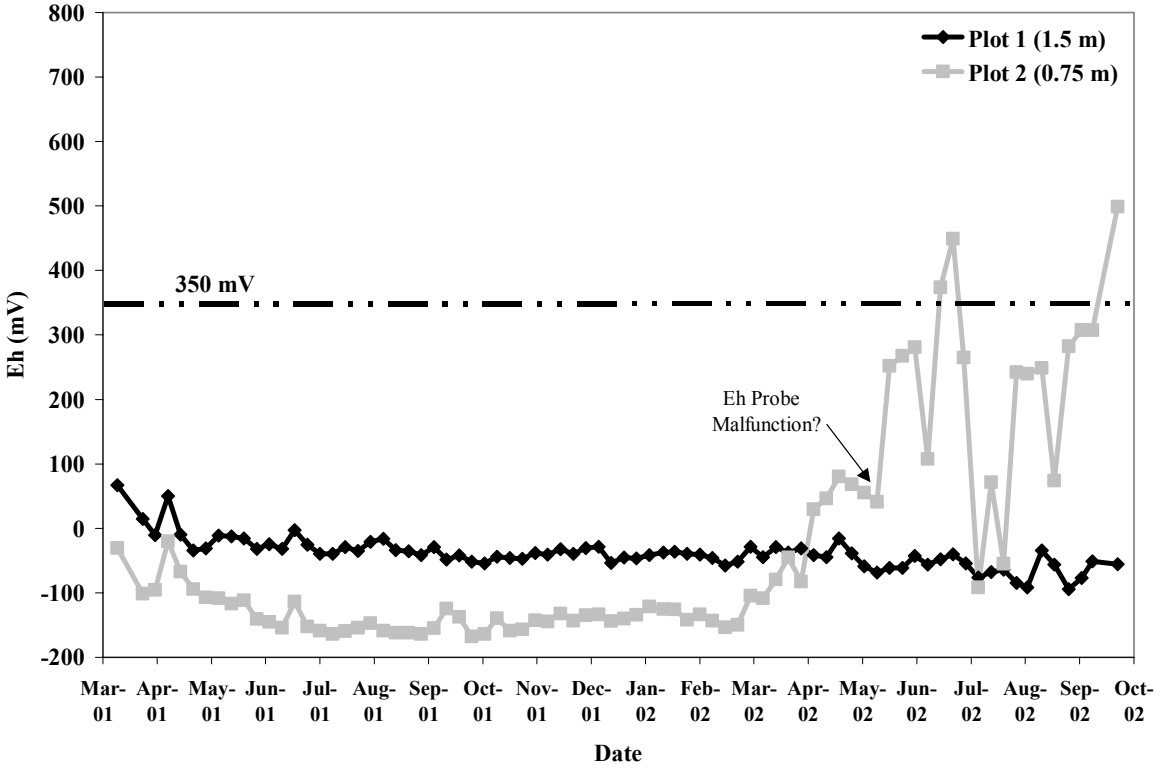

Figure 12. Average soil redox (Eh) readings at the 150 cm depth for Plot 1 and 2

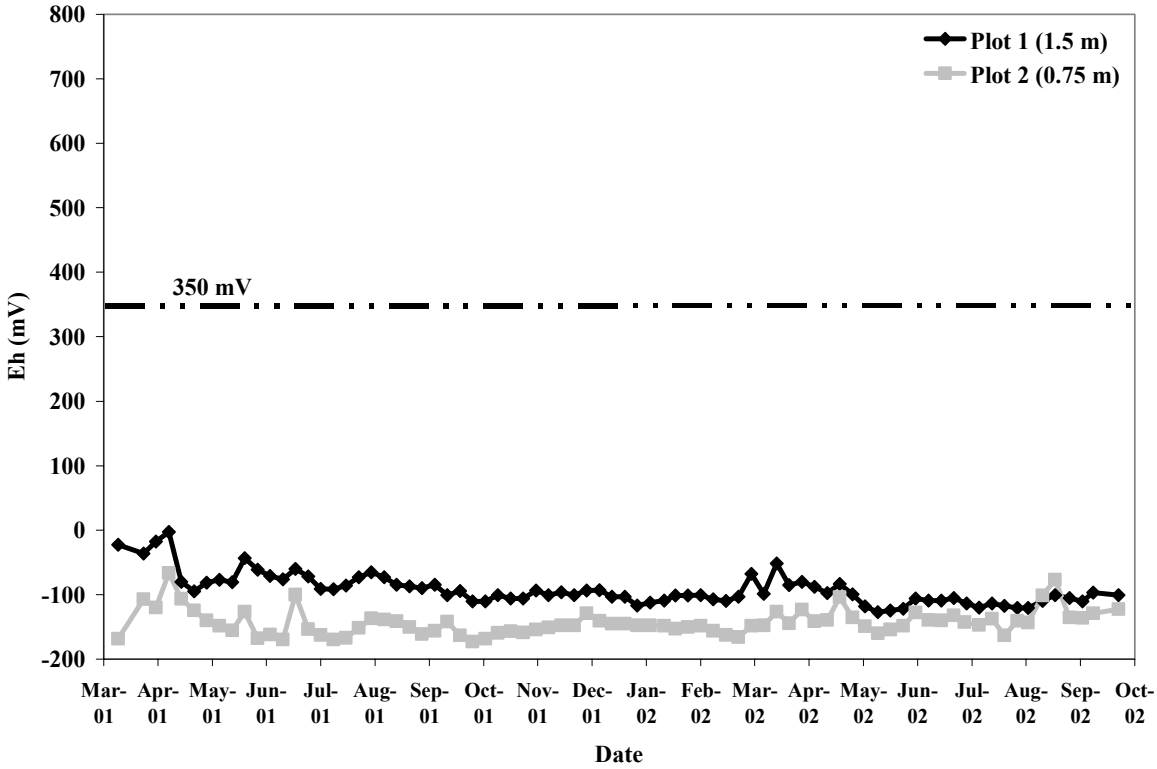

Figure 13. Average soil redox (Eh) readings at the 180 cm depth for Plot 1 and 2

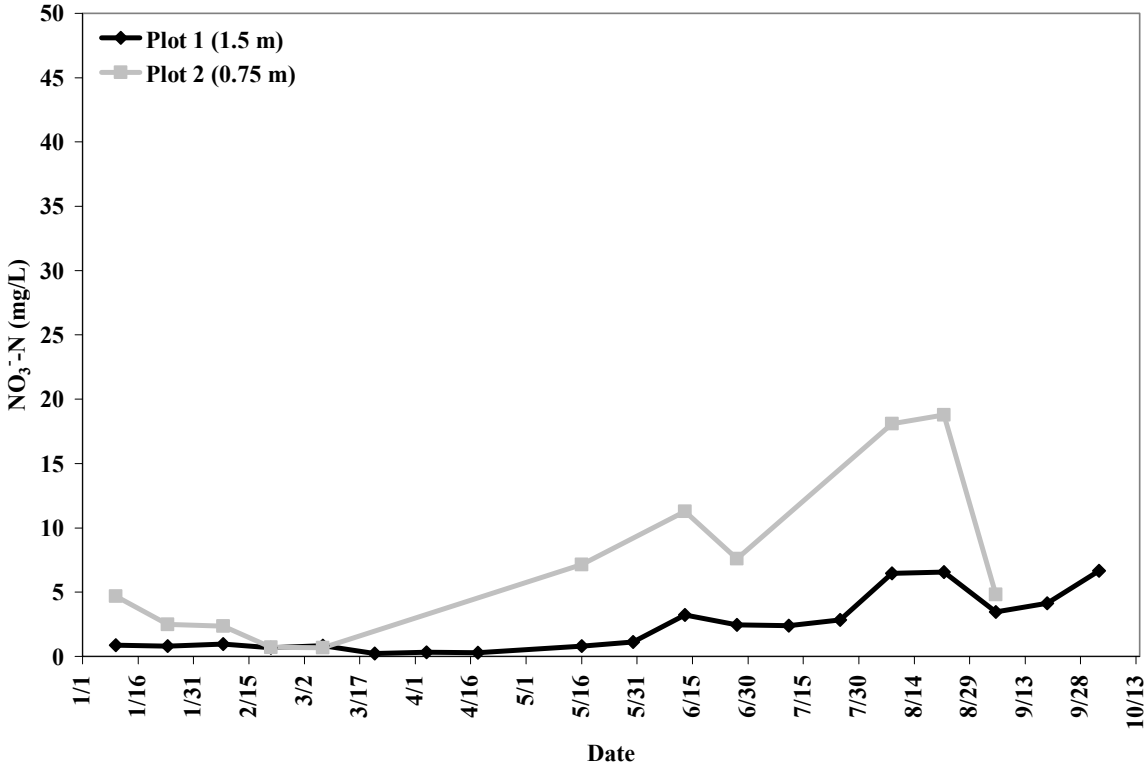

Figure 14a. Average drainage water NO_3^--N concentrations from Plot 1 and Plot 2 in 2001 (*Note:* No samples collected late in the year due to no subsurface flow)

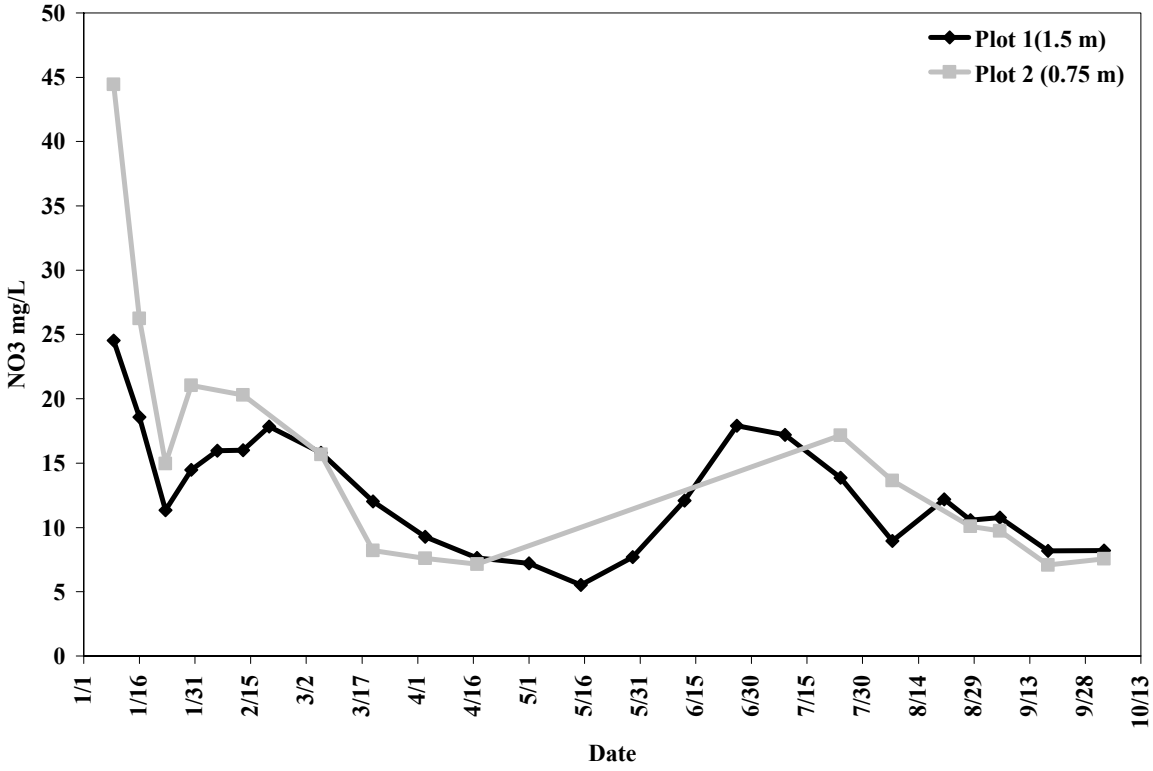

Figure 14b. Average drainage water NO_3^--N concentrations from Plot 1 and Plot 2 in 2002 through September

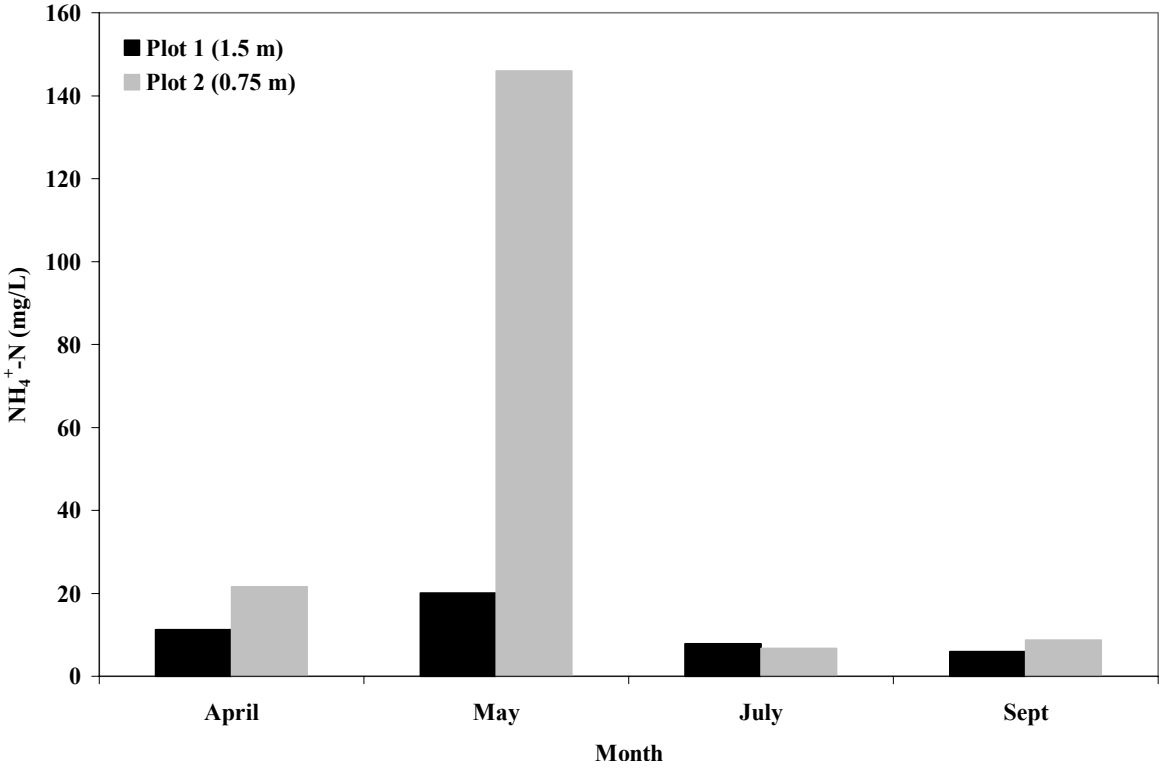

Figure 15. NH_4^+-N concentrations in drainage water grab samples following swine waste irrigation in 2002, possibly indicating preferential flow in Plot 2.

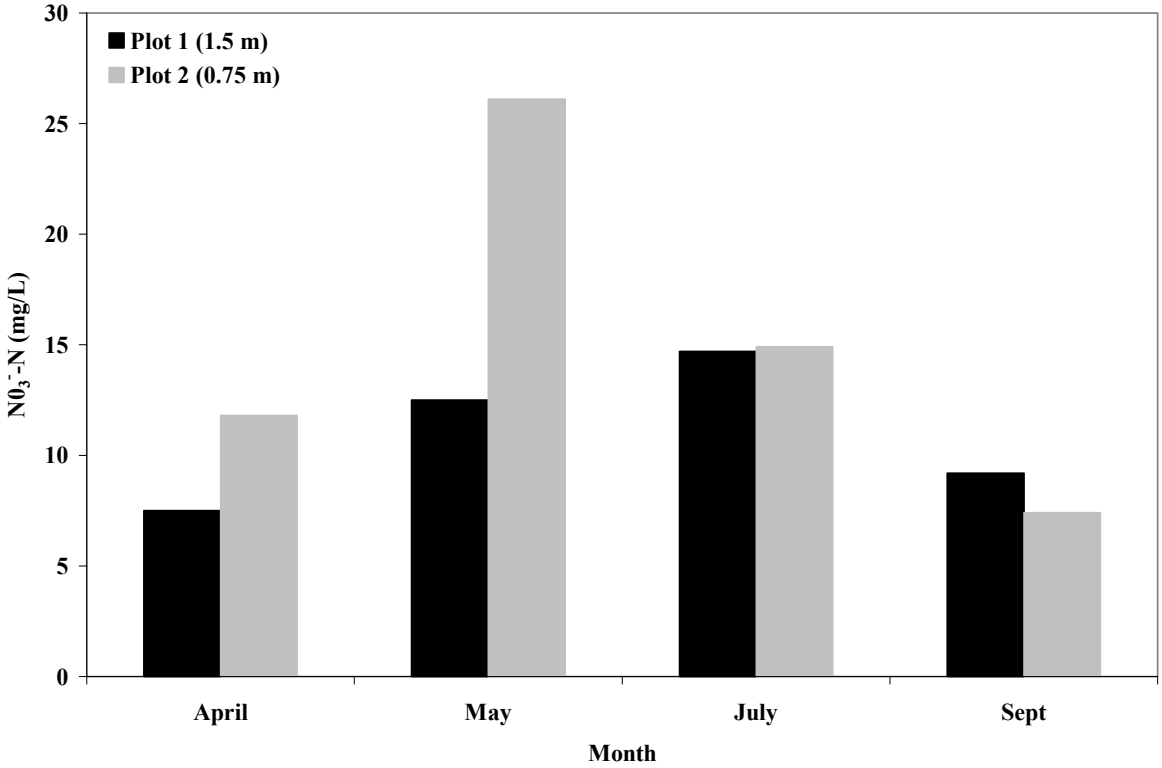

Figure 16. $N0_3^-$-N concentrations in drainage water grab samples following swine waste irrigation in 2002. Preferential flow may have contributed to increases in $N0_3^-$-N concentrations in Plot 2 drainage

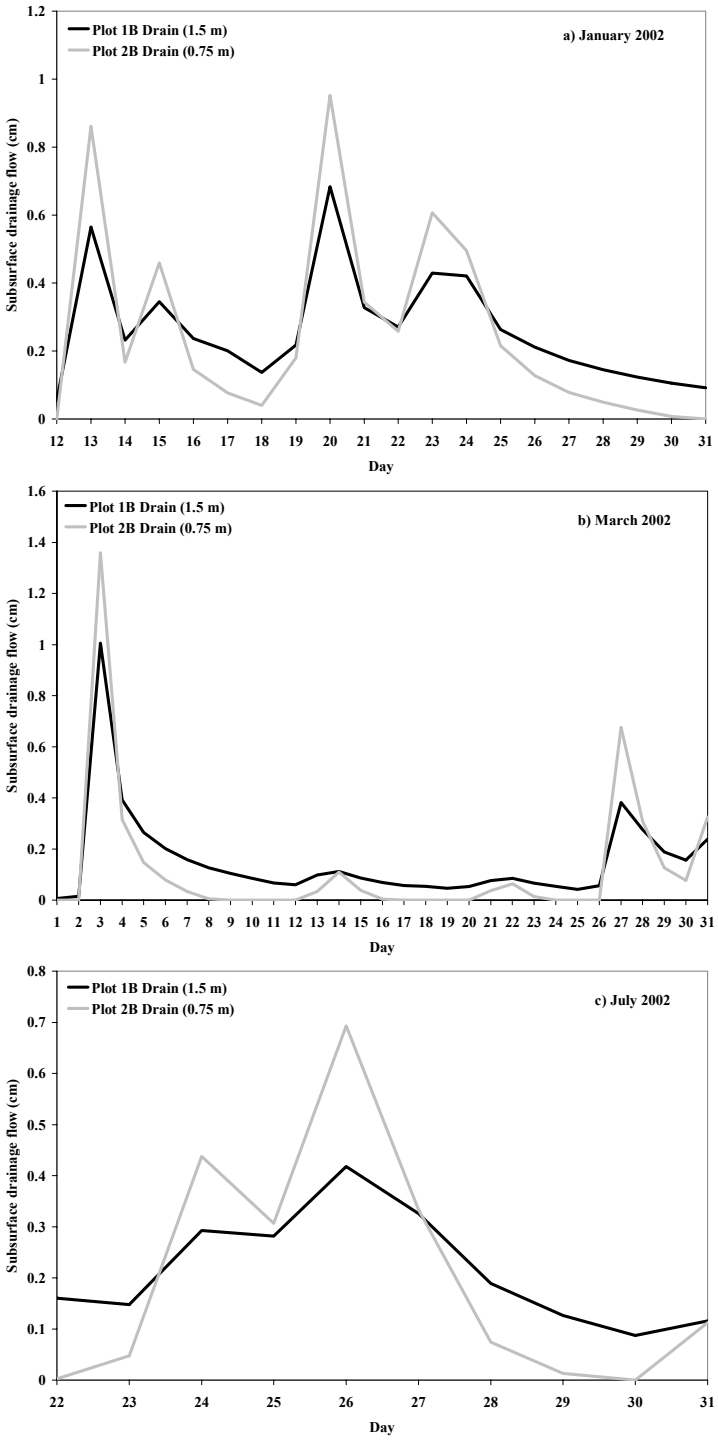

Figure 17. Subsurface flow signatures between the center drains in Plot 1 and Plot 2 for selected flow events from **a)** January 2002**, b)** March 2002**,** and **c)** July 2002

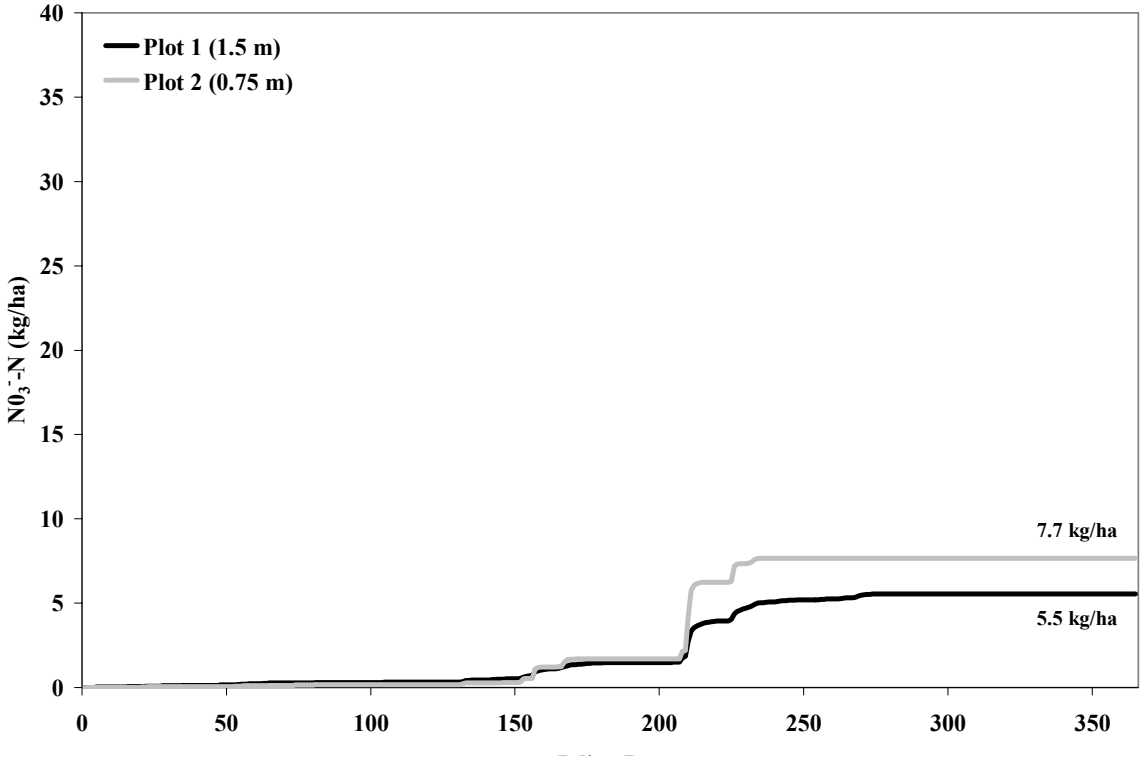

Figure 18. Average NO_3^--N export from Plot 1 and Plot 2 in 2001

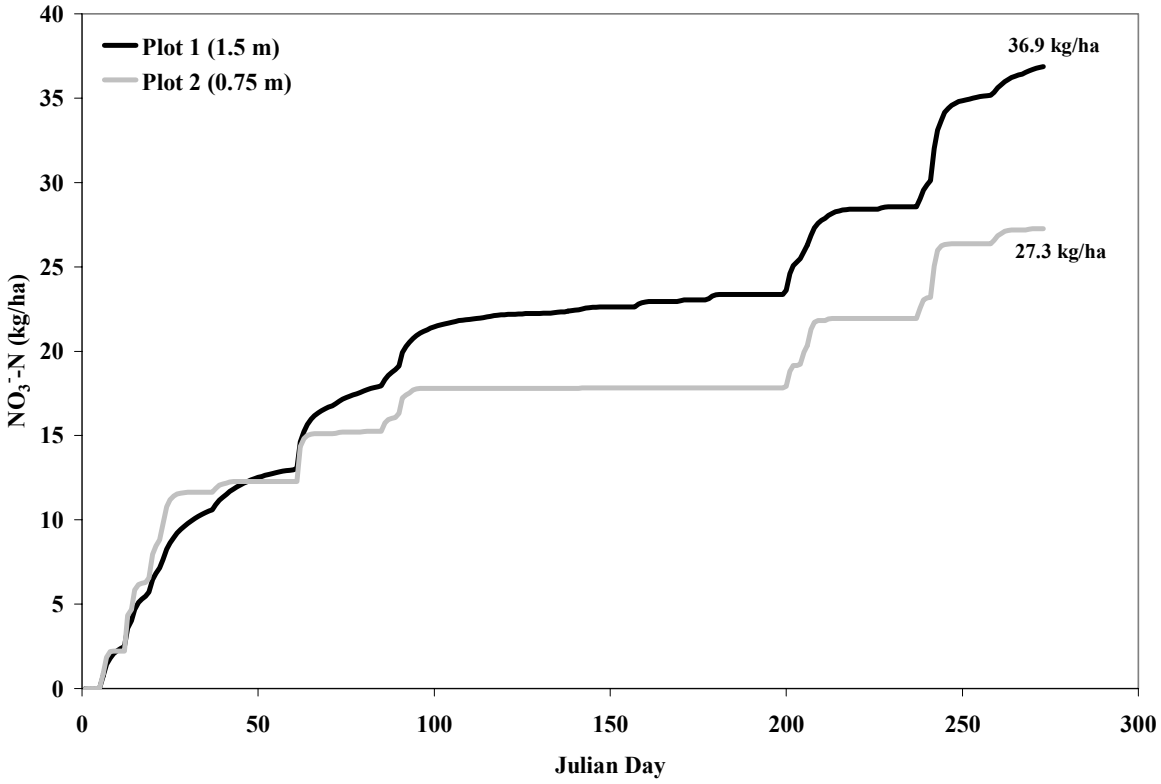

Figure 19. Average NO_3^--N export from Plot 1 and Plot 2 in 2002

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CHAPTER 2

LONG TERM SIMULATION OF THE IMPACT OF SHALLOW SUBSURFACE DRAINAGE ON NITRATE LOSS

INTRODUCTION

A complete understanding of the impacts of installing subsurface drainage at shallower depths on hydrologic and nutrient losses for a wide range of climatic conditions would require many years of observation and data collection. Though not as perfect as decades of observations, hydrologic modeling provides a faster, more cost-effective alternative. Short-term research plot data including climatological events, water table fluctuations, drainage volumes, site soil properties and crop data can be combined with historical rainfall data in a hydrologic model to simulate hydrologic responses over many years. Combine this output with short-term observations of drainage water quality, and the effects on nutrient losses can also be estimated.

The model DRAINMOD, described in detail by Skaggs (1978 and 1999), has been used extensively to simulate long term effects of drainage on water table fluctuations at the field scale (Skaggs and Gilliam, 1981; Skaggs and Nassehzadeh-Rabrizi, 1982; Jacobs and Gilliam, 1985; Skaggs and Nassehzadeh-Rabrizi, 1986; Fouss et al., 1987; Konyha et al., 1992). It was developed for shallow water table soils containing a network of parallel drainage ditches or subsurface drains. In basic terms, the model computes a water balance on a thin section of soil of unit cross-sectional area at the midpoint between the drains, extending from the impermeable layer to the surface (Skaggs, 1982). This water balance is determined on an hourly and daily basis, and the

water table depth (WTD) at the midpoint between the drains is then calculated for each time step.

Figure 1 shows a schematic of the inputs required and processes considered in DRAINMOD when simulating subsurface drainage with tile drains. Inputs required for DRAINMOD include:

Soil properties - saturated hydraulic conductivity and soil water characteristic of the various layers, and wilting point.

Crop parameters - seasonal rooting depth.

Drainage system parameters - drain depth, spacing, effective radius and surface storage.

Weather data - precipitation, temperature, potential evapotranspiration.

Irrigation data - timing and intensity.

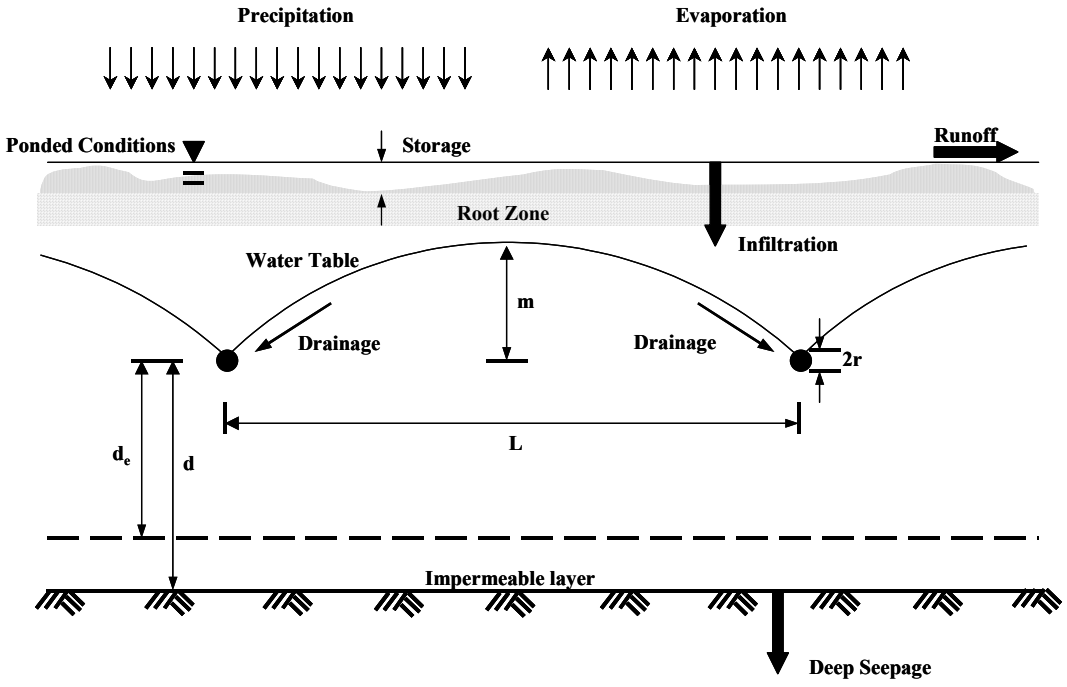

Figure 1. Schematic of subsurface drainage and principal processes considered in DRAINMOD (from Skaggs, 1999).

The water balance in the soil profile, used in calculating the water table depth at the midpoint between the drains in DRAINMOD, may be expressed, for any time increment Δt, as

$$\Delta V_a = D + ET + DS - F \quad \text{(Skaggs, 1999)}$$

where

ΔV_a = change in water free pore space (cm)

D = drainage from the section (cm)

ET = evapotranspiration (cm)

DS = deep seepage from the section (cm)

F = infiltration entering the section (cm) based on an approximation of the Green-Ampt equation (1911).

Similarly, the water balance at the soil surface is computed using the equation

$$P = F + \Delta S + RO \quad \text{(Skaggs, 1999)}$$

where

P = precipitation (cm)

F = infiltration (cm)

ΔS = change of volume of water stored in surface depressions (cm)

RO = surface runoff (cm).

Drainage rates in DRAINMOD are estimated using the steady-state Hooghoudt equation when the water table is below the soil surface (Skaggs, 1999). The water table is assumed to be elliptical in shape, as shown in Figure 1. Using the notation in Figure 1, the equation can be written as

$$q = \frac{8Kd_em + 4Km^2}{L^2}$$

where

q = drainage flux (cm/hr)

d_e = the equivalent depth from the drain to the impermeable layer (cm)

m = the midpoint elevation of the water table above the drain (cm)

K = the effective lateral hydraulic conductivity of the soil (cm/hr)

L = drain spacing (cm).

The equivalent depth of the drain to the impervious layer, d_e, is required to correct for convergence head losses as water moves radially into small openings in the drain. The theory and methods for calculating d_e in terms of d, L, and the drain radius can be found in van der Ploeg et al. (1999). Dierickx (1999) also describes how convergence near the drains can be considered using an effective drain radius r_e, which is much smaller than the actual radius of the drain, and represents a completely open drain tube with the same resistance to inflow (Skaggs, 1999). DRAINMOD calculates d_e automatically with drainage system inputs of L, d, and r_e.

When the water table rises to the soil surface, equations presented by Kirkham (1957) for subsurface drain tubes are used in DRAINMOD. The flow regime is significantly different in this case when compared to flow during water table drawdown, because most of the streamlines are concentrated near the drains. In other words, a high percentage of the flow to the drains when the water table is at the surface originates from the surface region close to the drain (Skaggs, 1999). Use of the steady-state Hooghoudt equation under these conditions would tend to underestimate flow because it does not take into account the high gradients and removal of water from around the drains as the characteristic elliptical water table profile develops (Salem, 2000).

The effect of shallow subsurface drainage on nitrate (NO_3^--N) loss was modeled by Skaggs and Chescheir (2003) using the nitrogen version of DRAINMOD (Breve et al., 1997). They found that installing subsurface drains 0.75 m deep and 28 m spacing reduced NO_3^--N losses by 60% when compared to a drainage system with drains at 1.5 m deep and 56 m apart. This 40-year simulation was based on a corn field near Plymouth, NC with a Portsmouth sandy loam soil which received inorganic fertilizer additions. The authors acknowledged that the practice of installing shallow subsurface drains to reduce nitrogen loads could not be recommended with confidence until there was field research to test the hypothesis. They recommended that research studies should be developed to specifically address this hypothesis on a wide range of soils, crops, and climatological conditions. They also suggested that the depths and spacings of the drains for the studies should be chosen to satisfy drainage requirements that would provide similar agricultural benefits.

This hypothesis was tested by Burchell (2003) by collecting 21 months of flow, water table, and drainage water quality data from a pasture at the NCDA-Tidewater Research Station near Plymouth, N.C. Two different drainage systems were considered. The drainage system in Plot 1 consisted of 10 cm corrugated plastic perforated drains installed at 1.5 m deep and 25 m apart, while the drains in Plot 2 were installed at 0.75 m deep and 12.5 m apart. The site soil was a Cape Fear Loam soil with a bermuda / rye grass rotation. The plots were grazed by beef cows and received organic fertilizer in the form of liquid swine waste. Drainage volumes were 42% less in the shallow drainage system over 21 months. Nitrate-nitrogen export was 7.5 kg/ha less from the shallow subsurface drainage plot, an 18% reduction when compared to the deeper drainage system. Uneven distribution of swine wastewater and relatively dry conditions caused variability in the results from each drainage plot. Reduced NO_3^--N export from the shallow drains was significant in at the 10% level in the wetter of the two calendar years studied, but not overall. Several more years of data collection, to incorporate variablity in weather conditions, would be needed before conclusions on the effect of shallow subsurface drains on NO_3^--N losses could be drawn with certainty.

Objectives

The objective of this study was to use observed data and the site parameters from the field study described above as inputs to the model DRAINMOD to estimate the long-term effect of a shallow subsurface drainage system on drainage volumes. Then, observed drainage water quality data from the site was used to estimate the effect on NO_3^--N export.

MATERIALS AND METHODS

Site Description

The study site is located in the lower coastal plain of North Carolina at the North Carolina Department of Agriculture – Tidewater Research Station's Swine Research Unit in Plymouth, NC. The two drainage systems were installed on a 2.5 ha pasture, which has historically been used for grazing beef cattle. The pasture was on a bermudagrass (May-October)/ ryegrass (November-April) rotation, and received swine lagoon irrigation water. Each drainage plot consisted of five - 125 m drain lines of 10 cm corrugated, slotted polyethylene tubing with a knitted fabric envelope. The average depth of the drain tubes installed in the deep drainage plot (Plot 1) was approximately 1.44 m, with a drain spacing of 25 m. The average depth of the drain tubes installed in the shallow drainage plot (Plot 2) was approximately 0.72 m, with a drain spacing of 12.5 m. During the field study, conducted from January 2001 – September 2002, the middle three drains in each plot were monitored for flow and drainage water quality. One water table recorder in each plot collected water table elevation data on an hourly basis. A more detailed description of the drainage plots is given in Burchell (2003).

The soil of the research plot was classified as Cape Fear Loam (fine, mixed, semiactive, Typic Umbraquualt). This is a very poorly drained soil with slow permeability and a seasonal high water table of 0- 30 cm typically occurring during the winter or early spring.

Determination of Soil, Crop and Weather Parameters

Soil samples were collected in May 1999 from auger holes and analyzed for particle size distribution using the hydrometer method (Gee and Bauder, 1986). Two soil pits in each plot were dug using a backhoe to a depth of 2 m in November 2001 to identify soil layers and collect samples for laboratory soil property analysis. Three undisturbed soil cores (7.6 cm diameter by 7.6 cm long) were collected from the center of each of the following depths: 0-40 cm, 40-100 cm, 100-135 cm, and 135-200 cm. The soil water characteristic, which describes the volumetric water content (θ) of a soil at various soil water potentials, was determined from each core using the standard pressure plate method (Klute, 1986). Three field measurements of the lateral saturated hydraulic conductivity (K_{sat}) of the site soil at various depths were made using the auger hole method (van Beers, 1970).

Once the soil water characteristic for each of the soil layers was determined, a soil file was generated from a DRAINMOD soil preparation subprogram (Soilprep). The final soil water characteristic for each layer was obtained from an average of the replicates from each layer in each plot. The Soilprep program takes the soil water characteristic data and estimates for vertical saturated hydraulic conductivity, and creates a soil input file for DRAINMOD simulations. Two separate soil files were generated for Plot 1 and 2. The soil input file includes the soil water characteristic of the A horizon, a volume drained (cm) versus water table depth (cm) relationship, an upward flux (cm/hr) versus water table (cm) relationship, and Green-Ampt infiltration parameters.

The auger hole method resulted in a large range of values for K_{sat}, and the depths measured were not consistent with the depths of the soil layers observed. Therefore, K_{sat}

was estimated using a relationship between observed hourly flow, *q* (cm/hr) and the observed height of the water table above the drains at the midpoint between the drains, *m* (cm) (Mohammad, 1997). Data collected from the center drain of each plot was chosen as the most representative observed hourly flow because each would have the least outside hydrologic influence. Values for m for each plot were obtained by subtracting the observed hourly water table depth from the average drain depth from each plot. Plot 1, with an average drain depth of 144 cm, has a possible range of *m* values from 0-144 cm. Observed data from two rainfall events in January and March 2002, and one low-flow period in August 2002, resulted in a range of values for *m* from 15 – 133 cm for Plot 1. Plot 2, with an average drain depth of 70 cm, has a possible range of m values from 0-70 cm. Observed data from two rainfall events in March and April 2002, and one low-flow period in April 2002, resulted in a range of values for *m* from 0.5 – 54 cm for Plot 2. The general form of the Hooghoudt equation was modified to reflect the various layers in the soil profile in order to solve for the K_{sat} of each of the four soil layers observed:

$$q = \frac{4m^2\left(\frac{K_1d_1 + K_2d_2 + K_3d_3 + K_4d_4}{d_1 + d_2 + d_3 + d_4}\right) + 8K_4d_em}{L^2}$$

where

q = drainage flux (cm/hr)

d_e = the equivalent depth from the drain to the impermeable layer (cm)

m = the midpoint elevation of the water table above the drain (cm)

L = drain spacing (cm)

d_1 = thickness of layer 1 (0-40 cm) contributing to flow

d_2 = thickness of layer 2 (40-100 cm) contributing to flow

d_3 = thickness of layer 3 (100-135 cm) contributing to flow

d_4 = thickness of layer 4 (135-300 cm) contributing to flow

K_1……K_4 = represent the saturated hydraulic conductivity of layers 1-4.

The values obtained from the auger hole method served as the starting point to iteratively determine the values of K_{sat} that produced a *q* vs. *m* relationship that most closely matched the observed *q* vs. *m* relationship in each plot. Appendix 2-A illustrates the method in more detail.

Surface storage capacity relates to the average depth of depressions in a field that must be filled before surface runoff occurs. For this site, depressional storage parameters were determined visually, according to the topography of the plots (He et al., 2002). These plots were situated in a relatively flat landscape setting. The perimeter of the plots was slightly elevated, which, in combination with the limited slope of the plots, limited surface runoff.

Determination of the effective rooting depths for the ryegrass/bermudagrass rotation were complicated by having overlap in their growing seasons, and by grazing. Rooting depth is very important in DRAINMOD simulations because of its effect on predicted evapotranspiration (ET). The maximum effective rooting depth for DRAINMOD simulations was defined as 50-60% of the maximum rooting depth of the vegetation. Root depths observed in the soil pits averaged 80 cm, so the maximum effective root depth for this site was chosen as 40 cm. The change in the effective rooting depth of the grasses over the growing season was estimated using crop growth stage coefficients (K_c) available in the USDA-SCS NEH-623-2 release "Irrigation Water

Requirements" (USDA-SCS, 1993). An example of this calculation is described by Skaggs (1980). K_c curves for pasture grasses and winter wheat were used to represent bermudagrass and ryegrass respectively in this study as an initial estimate for rooting depths. The calculation for this initial estimate is given in Appendix 2-B. Rooting depths for the 1st and 15th of each month were used as the inputs for DRAINMOD.

Weather inputs for the calibration of the model were based on data collected from a Campbell Scientific CR-10® weather station located approximately 1.5 km southwest of the study site. The station records air temperature, relative humidity, wind direction and speed, net radiation, and solar radiation. These parameters are all used to estimate potential evapotranspiration (PET) by the method employed by Amatya et al. (1995) using the Penman-Montieth Combination equation (Jensen et al. 1990). The daily estimates were then input directly into the model for the calibration procedure. For the long-term simulations, historical weather data were limited, making the use of the above method impossible. However, maximum and minimum daily temperatures for the simulation period were available. Therefore, the daily PET was estimated using the Thornthwaite (1948) method, which only requires the above temperature data. Monthly correction factors obtained from Amatya et al. (1995) were used to adjust Thornthwaite PET values for use in DRAINMOD.

Rainfall data measured using the Campbell Scientific CR-10® during the study period were entered into the model in ½ hour increments for model calibration. Irrigation amounts were included in this rainfall file. Irrigation at the site was accomplished with two passes on the field perpendicular to the lateral drains using a travelling gun system, resulting in half of each drainage plot being irrigated per pass. The depth of water was

distributed over a 1-2 hour period in the rainfall input file, depending on the duration of each event, or if both irrigation passes were accomplished on the same day. DRAINMOD distributes daily ET from 6:00 am to 6:00 pm and sets ET for any hour in which rainfall occurs to zero. In order to avoid the irrigation events in the rainfall file from affecting ET calculations in DRAINMOD, irrigation events were entered into the file as beginning at 7:00 pm.

Model Calibration

DRAINMOD was calibrated using the 21 months of observed water table and drainage data for the deep and shallow drainage plots. Initial inputs were based on field and laboratory measurements, all of which were averages of several determinations. Uncertainties in the values resulted from the variability in the measurements and the assumptions that were made in their determinations. The model was calibrated by adjusting the inputs within the range of measured or reasonable values for each case. Inputs were calibrated or adjusted until the observed and simulated water table and drainage responses were within acceptable limits. The agreement between the observed and predicted water table depths was determined using the average absolute deviation:

$$\alpha = \frac{\sum_{i=1}^{n} \left| Y_o - Y_p \right|}{n}$$

where

α = average absolute deviation

Y_o = observed end of day water table depth

Y_p = predicted end of day water table depth

n = number of days in the calibration period (Skaggs, 1982).

In addition, differences in observed and predicted annual cumulative drainage were used to determine agreement during the calibration procedure.

Long-Term Simulations

Once DRAINMOD was calibrated with the observed data, long-term hydrologic simulations were conducted. Rainfall and temperature data collected from the Tidewater Research Station from 1933-1999 were used to simulate 67 years of drainage data from the deep and shallow subsurface drainage systems. The means of the yearly drainage volume from each drainage system were calculated and analyzed for differences using ANOVA and t-Test procedures at the P=0.05 level. The average NO_3^--N concentration measured in the drainage water from the center drains in each of the two plots during the 21-month field study was then used to estimate the yearly NO_3^--N exported from each drainage system (Skaggs and Gilliam, 1981; Jacobs and Gilliam, 1985).

RESULTS AND DISCUSSION

Summary of Field Results

Observed data for drainage flow and water quality were based on the center drains in Plot 1 (drain depth = 1.5 m, spacing = 25 m) and Plot 2 (drain depth = 0.75 m, spacing = 12.5 m). These drains were the most representative of each plot because they were the most isolated from outside hydrological influences, received the same amount of nitrogen during land application, and the flow and water quality data from these drains were the most reliable during the course of the field study. During the 21-month field study, the flow from the center drain in Plot 1 was 44 cm. Flow from the center drain in Plot 2 was 28.4 cm, 35% less than in Plot 1. Average NO_3^--N concentrations in the drainage water for the center drain in Plot 1 and 2 were 14.9 and 16.3 mg/L respectively. The center drain in Plot 1 exported 47.4 kg/ha NO_3^--N, while the center drain in Plot 2 exported 40.9 kg/ha NO_3^--N, a 14% reduction as a result of the shallow drain depths.

Soil Properties

The various horizons, particle size distributions, and textural classes of the soil in each of the plots are shown in Table 1. The soil horizons in each plot are similar, but there appears to be an increase in the percentage of sand in the lower horizons of Plot 2, especially below the Btg2 horizon. An average of the soil water characteristic (SWC) for each plot was calculated to create a soil file for each plot. The saturated water content (θ_s) for Plot 2 was greater for each of the four layers. Table 2 shows the range of θ_s for each of the layers. The SWC curves for each layer are found in Figure 2a-d.

An iterative method based on the Hooghoudt equation was used to estimate K_{sat} for each plot. This resulted in two different sets of K_{sat} in the Plot 1 and Plot 2. Table 3 shows the results that most closely matched the observed *q* vs. *m* relationship in each plot. Estimates conducted with a 4 layer profile in Plot 1 resulted in an estimated *q* vs. *m* curve that was not as smooth as the observed *q* vs. *m* curve. To match the observed data, an additional layer (40-65 cm) was added to reduce the dramatic decrease in K_{sat} in the top two layers, making the estimated curve as smooth as the observed curve. Plot 2 was modeled in a similar manner, except an equivalent depth, D', was chosen to reflect the layer that the shallow drains were located (65-100 cm) with a K_{sat} = 1.1 cm/hr. However, this created the overestimates of *q* in the range of *m* from 0-20 cm, so the K_{sat} for that layer was lowered to 0.1 cm/hr. The upper layers of the Plot 2 K_{sat} estimate were much greater than in Plot 1 in order to match the Plot 2 observed data. Figures 3a and b show the *q* vs. *m* relationships from observed data and with the estimated values of K_{sat}. Appendix 2-A describes this method in more detail.

Model Calibration

Plot 1

DRAINMOD was first calibrated to simulate observed water table and drainage data from Plot 1. Original inputs to the model were based on measured or estimated site parameters, and then the inputs were modified to better match observed data. The input for drain depth was 1.44 m depth, which represents an average depth of the drain along its length with a slope of 0.07%. The input for drain spacing was 25 m. Depth to the impervious layer was chosen as 300 cm, based on site observations and observations in prior studies near the

site by Evans (1991). Input data for the surface storage parameters, Kirkhams depth for flow to drains, $S_{i,}$, and maximum surface storage, S_m were 1.5 cm and 10 cm respectively to represent the surface conditions observed at the site. The values for K_{sat} for Plot 1, listed previously in Table 3, were used in the original calibration with good results, and did not need to be modified initially. After calibration of Plot 2, K_{sat} for the 0-40 cm layer was increased to 20 cm to keep the soil inputs for both plots the same. This increase had little effect on the average absolute deviation (AAD) between the observed and simulated water table levels.

The original estimate for the effective rooting depths of the ryegrass- bermudagrass rotation, based on crop growth stage coefficient curves, provided a starting point for inputs to the model. However, modifications were needed to adequately model the water table depths in the Plot 1, because of the effect of rooting depth on ET, which affects water table drawdown. Table 4 shows both the original estimate and the final input for effective rooting depth in Plot 1. The rooting depths ranged from 4-40 cm in the first estimate and 5-40 cm in the final model inputs. Modifications were needed to account for the overlap of the growing seasons for the two grasses, and grazing of the plots. Of particular interest is the time period from 1 April to 1 June, where simulated water table levels were much lower than the observed levels when the first estimate was used. This time period reflected the die-back of the winter annual ryegrass and the beginning growth of the bermudagrass. Grazing was particularly intense during this period as well, with 11 grazing days in 2001 and 10 in 2002 (see Appendix 2-B). Both of these factors would potentially reduce root depths. Reduction of the root depths successfully improved the agreement between the simulated and observed water table depths during this period. The lower limit for water extraction by the crop at

maximum rooting depth, θ_{ll}, was varied during calibration from 0.17 – 0.27 cm^3/cm^3. The value that produced the best results, with the final rooting depth inputs, was 0.20 cm^3/cm^3.

The initial estimate used in calibrating the model for Plot 1 was based on the volume drained (V_d, cm) and upward flux (UPFLUX, cm/hr) versus water table depth (WTD, cm) relationship generated from the average soil water characteristic data from each layer measured from the pits in Plot 1. Table 5 shows the original and final modified versions of these two relationships entered into DRAINMOD. The slope of the curve, V_d vs. WTD, is the drainable porosity, *f*. It represents the volume of water per unit area that is released per unit distance of water table drop, assuming a drained to equilibrium state above the water table. Drainable porosity values dictate the water table response as a volume of water is added or lost from the soil. Higher values result in smaller drops in the WT elevation for a given drainage amount, while lower values would cause the WT to fall more sharply. Values of *f* from the initial volume V_d vs. WTD curve were systematically altered to adequately reflect the observed water table responses to inputs and losses of water to the system, resulting in the best estimate shown in Table 5.

The original estimate of upward flux was nearly acceptable for DRAINMOD calibration for Plot 1. However, simulated water table levels were lower than the observed levels at deeper soil depths. Therefore, the initial upward flux values below 75 cm soil depth were reduced to improve the agreement of the observed and simulated water table levels at those depths.

The final parameter that was considered in calibration for Plot 1 was seepage losses. Manipulation of the other inputs mentioned earlier resulted in a average absolute deviation (AAD) between the observed and simulated WTDs of 12.4 cm across the study period.

However, simulated drainage volume was overestimated by over 14 cm. Minor seepage losses had been suspected in the Plot 1 drainage system, due to the system location and design. Seepage from Plot 1 was modeled as vertical seepage, and the inputs to DRAINMOD were varied to reduce simulated drainage, while maintaining acceptable agreement between the observed and simulated water table data. This was achieved by using the values for piezometric head of the aquifer, $H_v = 0$, the thickness of the restricting layer, $D_v = 1000$ cm, and the vertical saturated hydraulic conductivity of that layer, $K_{vs} = 0.0005$ cm/hr. Figure 4a and b show the effect of adding seepage in the DRAINMOD calibration of Plot 1. Even though there was a change in the water table due to the addition of seepage, the AAD remained constant at 12.4 cm. The major benefit to model calibration was reducing the difference between the observed and simulated drainage to 5.6 cm. A diagram for these vertical seepage components can be found in Appendix 2-C.

Plot 2

Plot 2 input for drain depth was 0.70 m depth, which represents an average depth of the drain along its length with a slope of 0.07%. The input for drain spacing was 12.5 m. Despite the differences observed in soil particle size, soil water characteristic, and estimated lateral saturated hydraulic conductivity in Plot 1 and 2, they were located immediately adjacent to each other, so the goal was to model Plot 1 and 2 with the same inputs. The K_{sat} values in the upper layers of Plot 2 were higher than in Plot 1 (Table 3). As mentioned earlier, K_{sat} for the 0-40 cm layer in Plot 1 was increased from 12 to 20 cm/hr. The K_{sat} for the 0-40 cm layer in Plot 2 was decreased from 30 to 20 cm/hr, to achieve consistency between Plot 1 and 2. K_{sat} values for the lower soil layers in Plot 2 were then modeled with

those estimated for use in Plot 1. Plot 1 values for depth to the impervious layer, surface storage parameters, V_d and UPFLUX - WTD relationships, effective rooting depth, and wilting point were all used for the Plot 2 calibration.

The Plot 1 V_d vs. WTD relationship was not an effective input for DRAINMOD water table prediction, and required modification. Table 6 shows the relationship from the original soil data, the Plot 1 estimate, and the estimate that produced the best results in predicting water table depths. Because it was preferable to have consistent soil inputs between Plots 1 and 2, simulations were run with an average of the best V_d vs. WTD curve from each plot. Some precision in water table prediction was lost in Plot 1 and 2, but it was minimal. Therefore this average V_d vs. WTD relationship was used for both Plot 1 and 2, and consistency in the soil inputs was maintained between the plots. Figure 5 shows the relationships graphically.

Seepage inputs for calibration of Plot 2 were considered next. Without a seepage component, simulated drainage totals in Plot 2 were two times higher than observed drainage losses, and WTDs were higher. This observation may be synonymous with those found in controlled drainage. When the water table is maintained at higher levels in controlled drainage, water losses are usually less than in conventional drainage systems. Gilliam et al. (1979) indicated that seepage losses may account for this difference. This rationale may be applicable to the Plot 2 system with shallower drains, because WTDs were maintained higher than with deeper drains (Burchell, 2003). The drainage systems in Plot 1 and Plot 2 were designed to provide similar drainage intensity, yet the observed flow from the center drain in Plot 2 was 35% less than in the center drain in Plot 1. Runoff on the site was limited due to

surface storage and crop growth, so this difference in drainage amounts was most likely due to increased seepage in Plot 2.

Because of increased potential for seepage, Plot 2 inputs for seepage required a different approach than in Plot 1. Plot 2 was modeled as lateral seepage. The thickness of the transmissive layer, H_d, was set at 0 cm, since there was no true highly permeable layer between the drain depth and the impermeable layer. The hydraulic head of the receiving waters, H_r, was estimated to be 83 cm, based on the difference between the canal depths in the area (122 cm) and the equivalent depth, d'(205 cm), of the 65-100 cm layer the shallow drains were located, with a K_{sat} = 1.1 cm/hr. This K_{sat} was then used as the hydraulic conductivity of the transmissive layer, K_t. The distance to the receiving waters parameter was modified until the AAD for the WTD and the drainage water totals were acceptable. A diagram for these lateral seepage components can be found in Appendix 2-C.

Figure 6a and b show the effects of seepage on the AAD between the observed and simulated WTDs and on the drainage amounts in Plot 2. Addition of the seepage component reduced the AAD of the observed and simulated water tables from 14.3 cm to 12.3 cm. More importantly, the difference between the simulated and observed drainage was reduced from 29.5 cm to 5.8 cm.

In summary, calibration of DRAINMOD for use in long-term simulations for the drainage systems resulted in an AAD of 12.4 and 12.3 cm between the observed and simulated water table depths for Plots 1 and 2, respectively. Calibration with respect to drainage amounts resulted in an over-prediction of 5.6 and 5.8 cm for Plot 1 and 2 respectively. A summary of the final DRAINMOD inputs for Plot 1 and 2 may be found in Tables 7 - 10.

Long-Term Simulations

DRAINMOD simulations based on the calibration of the model with the observed data from Plot 1 and Plot 2 allowed us to estimate the long-term effect of installing shallow subsurface drainage systems on reducing drainage outflows and nitrate losses. The simulations used 67 years (1933-1999) of weather observations near the study site in Plymouth, NC. Inputs for these long-term simulations can be found in Appendix 2-D (Plot 1) and Appendix 2-E (Plot 2).

Figure 7 shows the difference in drainage volumes from Plot 1 and Plot 2 over the 67-year simulation. The average flow was 45.3 cm/yr from Plot 1 and 34.9 cm/yr from Plot 2. This represents an average difference of 10.4 cm/yr, or a 23% reduction in drainage volume for the shallow drainage system as compared to the deeper drains. An analysis of variance showed that this reduction was significant (P=0.0002). Maximum flows in Plots 1 and 2 were 75.3 and 62.7 cm/yr, respectively. Minimum flows were 13.7 and 5.6 cm/yr in Plots 1 and 2, respectively. Predicted subsurface drainage from the shallow drains ranged from 6.5 cm to 14.2 cm less than flows from the deeper drains. DRAINMOD estimated drainage totals from both plots may be slightly high because during calibration, the drainage was overestimated in both plots by almost 6 cm over 21 months. Average seepage from Plot 1 was about 5 cm/yr, while average seepage in Plot 2 was nearly 15 cm/yr. Yearly DRAINMOD hydrology output may be found in Appendix 2-F.

Observed average NO_3^--N concentrations during 2002 from the center drain in Plot 1 (14.9 mg/L) and Plot 2 (16.3 mg/L) were used to estimate long term NO_3^--N losses from each drainage system. Based on the average predicted drainage flow from the DRAINMOD simulations, average annual predicted NO_3^--N export from Plot 1 would be 67.6 kg/ha, while

the average export would be 56.9 kg/ha from the shallow drains in Plot 2. This represents a long-term reduction in NO_3^--N export of 10.7 kg/ha-yr, or about 16%. Figure 8 shows the simulated yearly reductions of NO_3^--N using shallow subsurface drains. The maximum reduction of NO_3^--N was 15.6 kg/ha-yr, while the minimum reduction was 3.8 kg/ha-yr. Over the 67 year simulation, the use of shallow subsurface drains reduced NO_3^--N losses by over 714 kg/ha (Figure 9). This reduction in export, at this site, is correlated to the reduction in drainage flow from the shallow drains.

The results of the field test were different than those observed from Skaggs and Chescheir's (2003) simulations, because the sites modeled were so different. Their simulations produced a 60% reduction in NO_3^--N losses – much greater than the 16 % reduction produced in this study. The drain depths were the same in both studies, but the drain spacing in the study by Skaggs and Chescheir (2003) was greater - 55 m and 28 m for the 1.5 m and 0.75 m drain depth respectively. Lateral saturated hydraulic conductivities for the Cape Fear loam used in this study were different than those measured in the Portsmouth Sandy loam used in the simulation by Skaggs and Chescheir (2003). More surface runoff occurred in their simulations because the maximum surface storage input was 2.5 cm. In this study, surface storage was assumed to be 10 cm, and runoff occurred in only 2 out of 67 years in Plot 1 and 3 out of 67 years in Plot 2. Thus, a higher percentage of water exited via subsurface drainage in this study. Seepage was not considered in their study, but was a large component in this study. Addition of swine waste in this study as opposed to inorganic fertilizer in the study by Skaggs and Chescheir (2003) increased the concentration of NO_3^--N in the shallow subsurface drains in Plot 2, which decreased the percent reduction of NO_3^--N exported from Plot 2 (Burchell, 2003). Finally the crops considered in both studies were

different; corn in the Skaggs and Chescheir (2003) study and rye/bermudagrass in this study. The grasses in this study were not harvested from the site as the corn was. Grazing removed some N, but a significant amount was redeposited by the cattle.

The main factor that determines the effectiveness of shallow subsurface drains to reduce NO_3^--N losses is whether NO_3^--N concentrations in the shallow subsurface drainage water decreases, remains unchanged, or increases, when compared to a deeper drainage system. Drainage volumes will almost certainly be reduced using shallow subsurface drains (Gordon et al., 1998; Skaggs and Chescheir, 1999; and Cooke et al., 2002), and reducing drainage volumes can be correlated with reducing NO_3^--N losses (Gilliam et al., 1979). However, if NO_3^--N concentrations increase dramatically in the drainage water of these shallow drainage systems, the effect of volume reduction on NO_3^--N export may be cancelled. Theoretically, NO_3^--N concentrations in the drainage water from shallow drains should be lower in most cases. Like controlled drainage, water tables are maintained at higher levels, increasing the reduced zone in the soil matrix, and may increase the potential for denitrification (Kliewer and Gilliam, 1995). However, in this study, NO_3^--N concentrations in the drainage water were higher in the shallow drains than in the deeper drains, but groundwater concentrations were lower. Liquid swine waste was applied as the nitrogen source for the research plots. This may have resulted in the observed increase through preferential flow to the drains during application or the during the next rainfall event following application (Burchell, 2003). The result of an increase in NO_3^--N concentration in the drainage water from the shallow subsurface drainage system, was to decrease the percent reduction of NO_3^--N exported observed, when compared to the deeper drainage system, from 23% (if the drainage water concentrations in both systems had remained the same), to 16%.

CONCLUSIONS

The model DRAINMOD was used to simulate the long-term effects of drain depth on reducing NO_3^--N losses from agricultural fields. Twenty-one months of water table, drainage, and drainage water quality data were collected during a field study from the center drain of two drainage systems, and were used for calibrating DRAINMOD. The deeper drainage system, Plot 1, was designed with drains at 1.44 m deep and 25 m spacing. The shallow drainage system, Plot 2, was designed with drains at 0.70 m deep and 12.5 m spacing.. Simulations included 67-years of weather data collected near the research site in Plymouth, N.C. Simulated drainage flow from the shallow subsurface drains was 10.4 cm/yr, or 23% lower than flow from the deeper drains. Based on the average NO_3^--N concentrations observed in the field study from the center drain in Plot 1 (14.6 mg/L) and Plot 2 (16.3 mg/L) an estimate was made to the long term NO_3^--N losses from each drainage system. A estimated reduction of 10.7 kg/ha-yr, or nearly 16%, of NO_3^--N may be achieved from the use of a shallow subsurface drainage system at this site. Over the 67-year simulation, the use of shallow subsurface drains reduced NO_3^--N losses by over 714 kg/ha. Reductions in NO_3^--N losses were correlated to reduction in drainage volume. Higher reductions may be achieved if NO_3^--N concentrations in the drainage water from the shallow drainage systems are reduced through denitrification. More research into the impacts of fertilizer application (inorganic vs. animal waste) and in the area of the physical and biological factors that influence NO_3^--N concentrations in the drainage water, must be completed before the practice of installing shallow subsurface drains to reduce NO_3^--N losses can be recommended.

Table 1. Particle size distribution and textural class of each horizon in Plot 1 and Plot 2.
Note: Values for the Ap horizon were obtained from a composite sample form Plot 1 and 2.

Horizon	Depth cm	Sand %	Silt %	Clay %	Textural Class
		Plot 1			
Ap	0-20	39.8	39.5	20.7	Loam
A	20-35	25.2	29.3	45.5	Clay
Btg1	35-65	25.6	28.1	46.3	Clay
Btg2	65-90	24.1	25.9	50.0	Clay
Btg3	90-120	33.7	24.3	42.0	Clay
2C	120-130	52.7	21.5	25.9	Sandy Clay Loam
2Cg1	130-170	76.3	11.2	12.6	Sandy Loam
2Cg2	170-200	76.0	12.8	11.2	Sandy Loam
		Plot 2			
Ap	0-20	39.8	39.5	20.7	Loam
A	20-40	22.6	36.1	41.3	Clay
Btg1	40-70	30.0	31.0	39.0	Clay
Btg2	70-85	35.8	27.7	36.6	Clay
Btg3	85-100	61.0	16.4	22.6	Sandy Clay Loam
2C	100-120	82.5	6.8	10.8	Loamy Sand
2Cg1	120-160	82.7	6.9	10.4	Loamy Sand
2Cg2	160-200	67.7	19.6	12.7	Sandy Loam

Table 2. Average of saturated water content (θ_S) observed in Plot 1 and 2.

Layer	Plot 1	Plot 2
	θs	
0 - 40 cm	0.493	0.522
40 -100 cm	0.470	0.546
100 - 135 cm	0.335	0.353
135 - 200 cm	0.403	0.437

Table 3. Initial estimated saturated lateral hydraulic conductivity for each plot

Plot 1	
Layer (cm)	**K (cm/hr)**
0-40	12.0
40-65	5.5
65-100	1.1
100-135	1.6
135-300	0.1
Plot 2	
0-40	30.0
40-65	14.0
65-205	0.1

Note: The 40 –65 cm layer was added to help in curve fitting, and the Plot 2 last layer reflects the equivalent depth of the layer in which the drain is located

Table 4. Initial and final estimates of rooting depths used as inputs to DRAINMOD

Date	Rooting Depth		Date	Rooting Depth	
	First estimate (cm)	**Final Input (cm)**		**First estimate (cm)**	**Final Input (cm)**
01-Jan	40.0	40.0	01-Jul	40.0	30.0
15-Jan	40.0	40.0	15-Jul	40.0	35.0
01-Feb	40.0	40.0	01-Aug	40.0	32.0
15-Feb	40.0	40.0	15-Aug	37.3	30.0
01-Mar	38.7	40.0	01-Sep	29.3	20.0
15-Mar	34.7	20.0	15-Sep	22.7	20.0
01-Apr	20.0	10.0	01-Oct	8.0	25.0
15-Apr	6.7	5.0	15-Oct	4.0	25.0
01-May	26.7	5.0	01-Nov	10.7	25.0
15-May	33.3	5.0	15-Nov	18.7	30.0
01-Jun	37.3	5.0	01-Dec	28.0	35.0
15-Jun	40.0	20.0	15-Dec	34.7	40.0

Table 5. Volume drained and upward flux relationships for Plot 1 used in calibration of DRAINMOD

	Vd		Upward flux	
WTD (cm)	Initial Estimate (cm)	Best Estimate (cm)	Initial Estimate (cm/hr)	Best Estimate (cm/hr)
0	0	0	0.5000	0.5000
3	0.006	0.006	0.5000	0.5000
6	0.023	0.025	0.5000	0.5000
9	0.049	0.059	0.5000	0.5000
12	0.078	0.100	0.5000	0.5000
15	0.111	0.148	0.2949	0.2949
20	0.174	0.270	0.1218	0.1218
25	0.251	0.449	0.0612	0.0612
30	0.339	0.686	0.0323	0.0323
35	0.434	0.981	0.0182	0.0182
40	0.540	1.311	0.0101	0.0101
45	0.660	1.461	0.0059	0.0059
60	1.112	1.636	0.0016	0.0016
75	1.658	2.128	0.0012	0.0008
90	2.296	2.702	0.0009	0.0005
120	3.760	4.020	0.0006	0.0001
150	5.908	5.953	0.0003	0
200	12.902	12.248	0	0
500	78.280	71.088	0	0

Table 6. Volume drained vs. water table relationships for Plot 2 used in calibration of DRAINMOD

	Vd		
WTD (cm)	Initial Estimate (cm)	Plot 1 Estimate (cm)	Best Estimate (cm)
0	0	0	0.000
3	0.005	0.006	0.006
6	0.02	0.025	0.025
9	0.047	0.059	0.059
12	0.08	0.100	0.100
15	0.118	0.148	0.148
20	0.216	0.270	0.270
25	0.359	0.449	0.449
30	0.549	0.686	0.686
35	0.785	0.981	0.981
40	1.049	1.311	1.311
45	1.339	1.461	1.674
60	2.166	1.636	2.471
75	2.893	2.128	3.616
90	3.573	2.702	4.466
120	4.841	4.020	6.051
150	6.039	5.953	7.549
200	11.239	12.248	14.050
500	65.789	71.088	80.000

Table 7. Final DRAINMOD inputs for Plot 1 and Plot 2

Parameter	Plot 1	Plot 2
Drain depth	144 cm	70 cm
Drain spacing	2500 cm	1250 cm
Effective drain radius (r_e)	1.5 cm	1.5 cm
Distance to impervious layer	300 cm	300 cm
Drainage coefficient	2.5 cm/d	2.5 cm/d
Initial depth to water table	112 cm	112 cm
Max. surface storage (S_m)	10 cm	10 cm
Kirkhams depth (S_i)	1.5 cm	1.5 cm
Lateral Saturated Hydraulic Conductivity (K_{sat})		
Layer 1 (0 - 40 cm)	20 cm/hr	20 cm/hr
Layer 2 (40 - 65 cm)	6 cm/hr	6 cm/hr
Layer 3 (65 - 100 cm)	1.1 cm/hr	1.1 cm/hr
Layer 4 (100 -135 cm)	1.6 cm/hr	1.6 cm/hr
Layer 5 (135 - 300 cm)	0.1 cm/hr	0.1 cm/hr
Wilting point	0.2 cm^3/cm^3	0.2 cm^3/cm^3

Table 8. Final volume drained and upward flux relationships used as final DRAINMOD inputs for Plot 1 and Plot 2

WTD (cm)	Vd (cm)	Upward flux (cm/hr)
0	0.000	0.5000
3	0.006	0.5000
6	0.025	0.5000
9	0.059	0.5000
12	0.100	0.5000
15	0.148	0.2949
20	0.270	0.1218
25	0.449	0.0612
30	0.686	0.0323
35	0.981	0.0182
40	1.311	0.0101
45	1.568	0.0059
60	2.053	0.0016
75	2.872	0.0008
90	3.584	0.0005
120	5.036	0.0001
150	6.751	0
200	13.149	0
500	75.544	0

Table 9. Final DRAINMOD rooting depth inputs for Plot 1 and Plot 2

Date	Depth (cm)	Date	Depth (cm)
01-Jan	40.0	01-Jul	30.0
15-Jan	40.0	15-Jul	35.0
01-Feb	40.0	01-Aug	32.0
15-Feb	40.0	15-Aug	30.0
01-Mar	40.0	01-Sep	20.0
15-Mar	20.0	15-Sep	20.0
01-Apr	10.0	01-Oct	25.0
15-Apr	5.0	15-Oct	25.0
01-May	5.0	01-Nov	25.0
15-May	5.0	15-Nov	30.0
01-Jun	5.0	01-Dec	35.0
15-Jun	20.0	15-Dec	40.0

Table 10. Final DRAINMOD seepage inputs for Plot 1 and Plot 2

Parameter	Plot 1	Plot 2
Seepage type	Vertical	Lateral
Piezometric head of the aquifer (H_v)	0 cm	N/A
Thickness of restricting layer (D_v)	1000 cm	N/A
Vertical conductivity of restricting layer (K_{vs})	0.0005 cm/hr	N/A
Thickness of transmissive layer (H_d)	N/A	0 cm
Hydraulic head of receiving waters (H_r)	N/A	83 cm
Distance to receiving waters (L_r)	N/A	3500 cm
Lateral conductivity of transmissive layer (K_{ls})	N/A	1.1 cm/hr

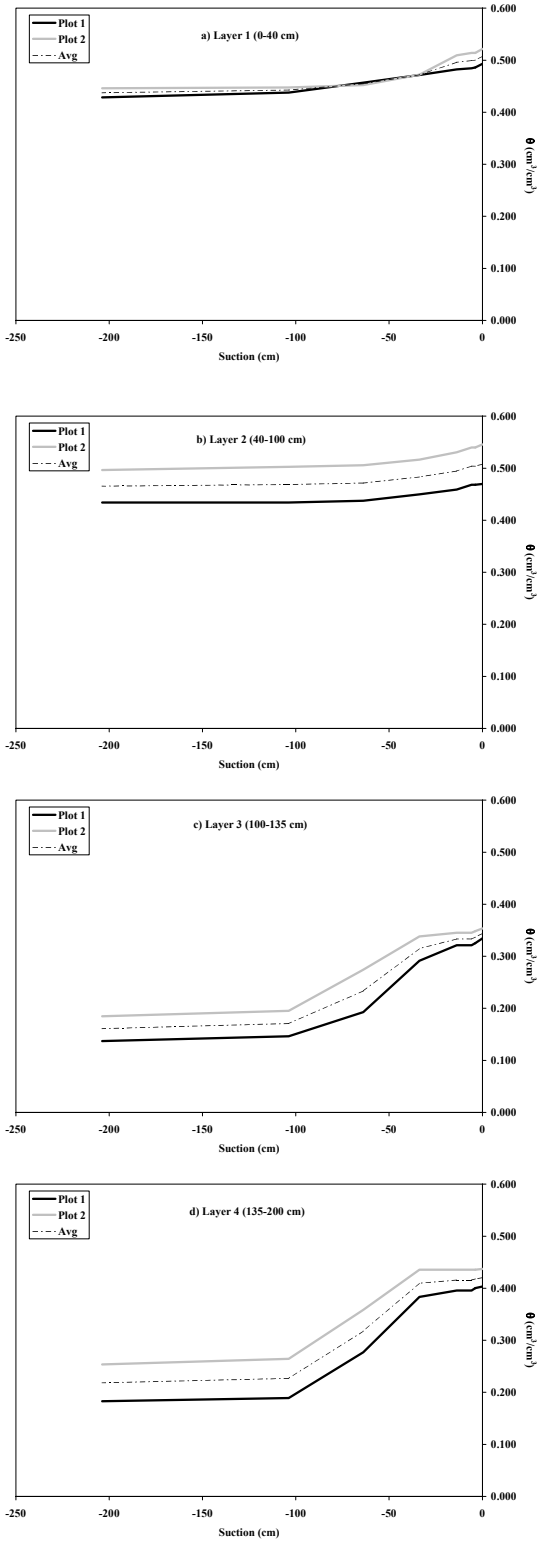

Figure 2. SWC curves for soils in Plot 1 and Plot 2 in Layers 1-4 **(a-d)**

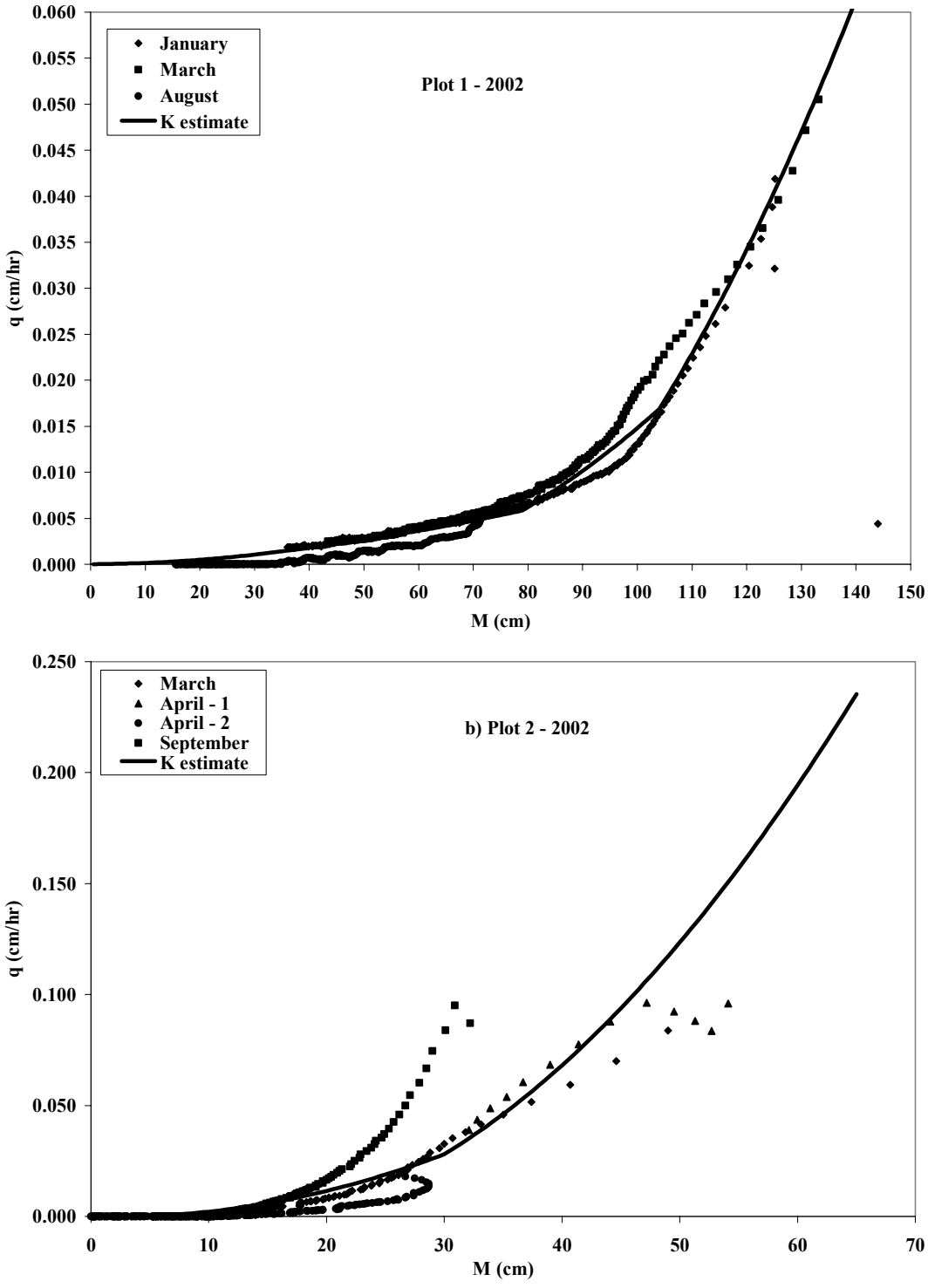

Figure 3. Drainage flux (q) versus height of the water table above the drains (m) for **a)** Plot 1 and **b)** Plot 2

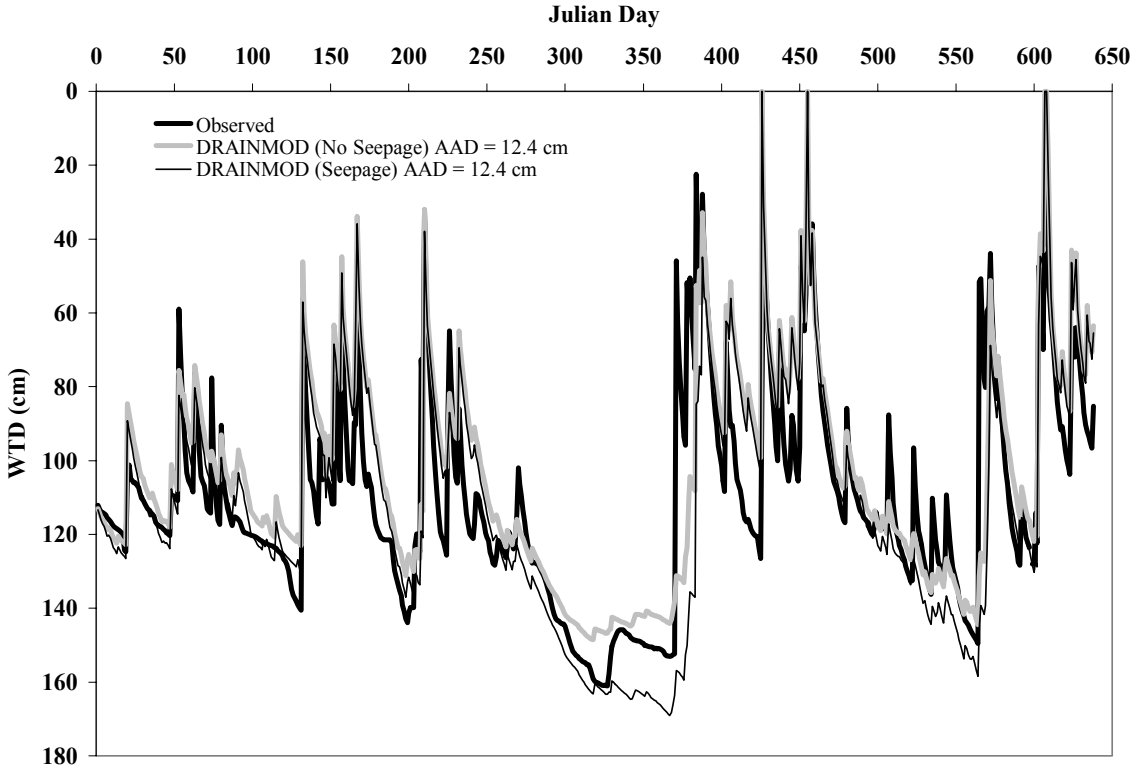

Figure 4a. Effect of seepage on calibration of DRAINMOD to observed WTDs in Plot 1

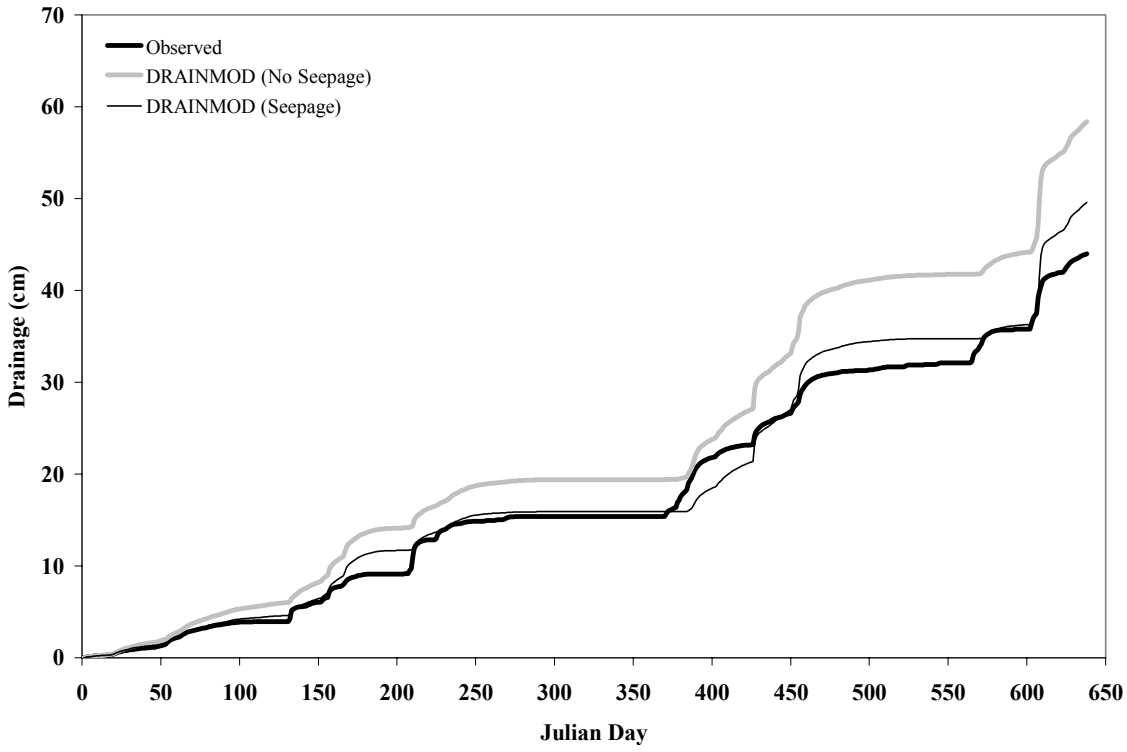

Figure 4b. Effect of seepage on calibration of DRAINMOD to observed drainage volume in Plot 1

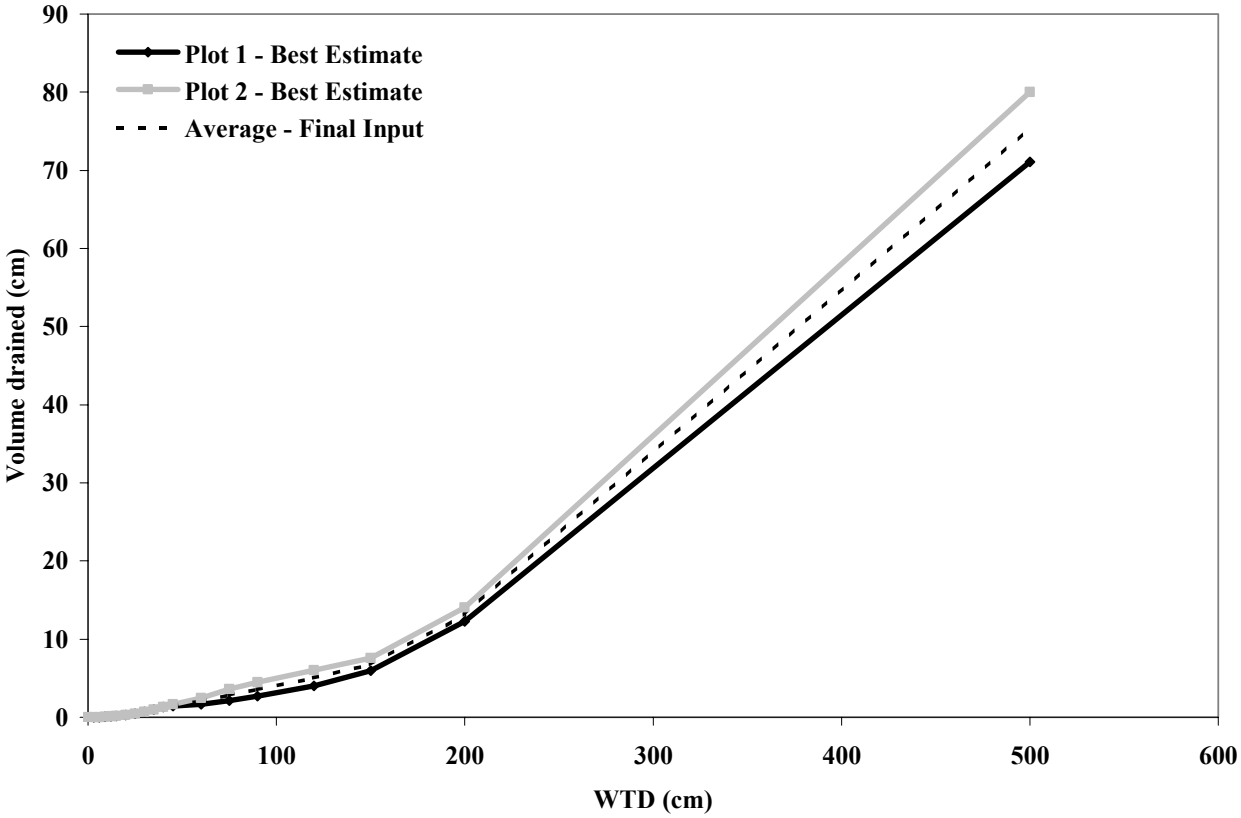

Figure 5. Estimates of the volume drained vs. water table depth relationship during calibration of DRAINMOD

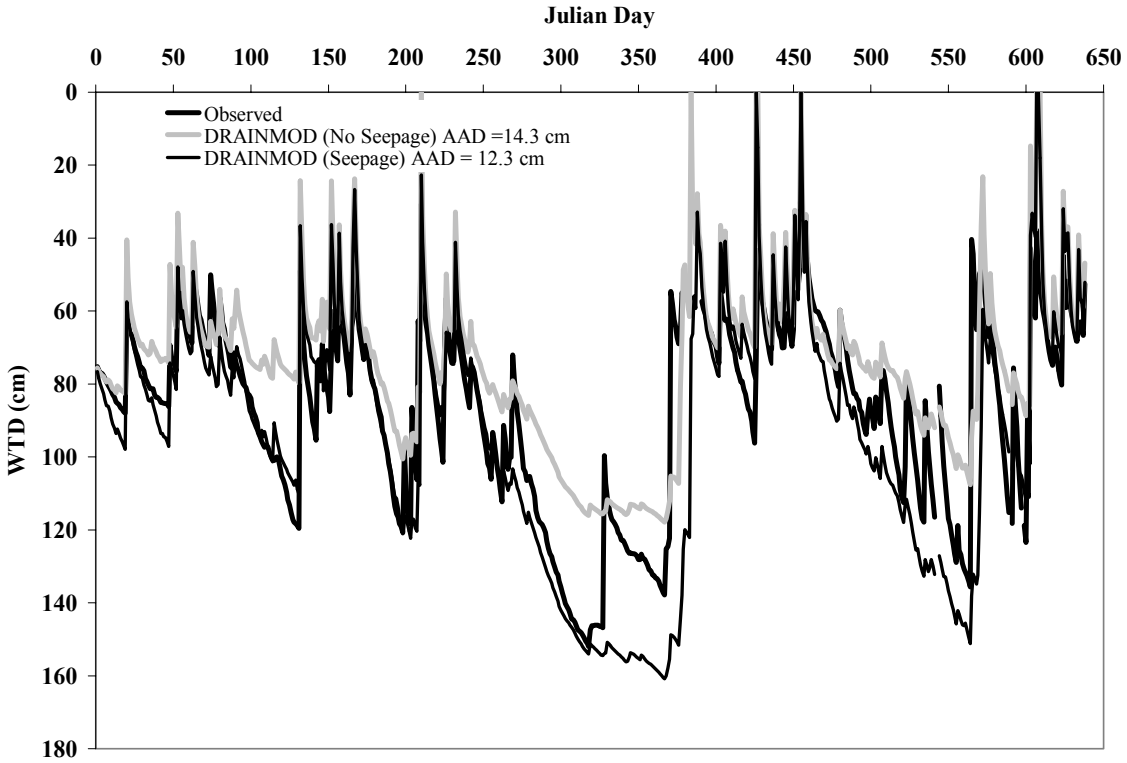

Figure 6a. Effect of seepage on calibration of DRAINMOD to observed WTDs in Plot 2

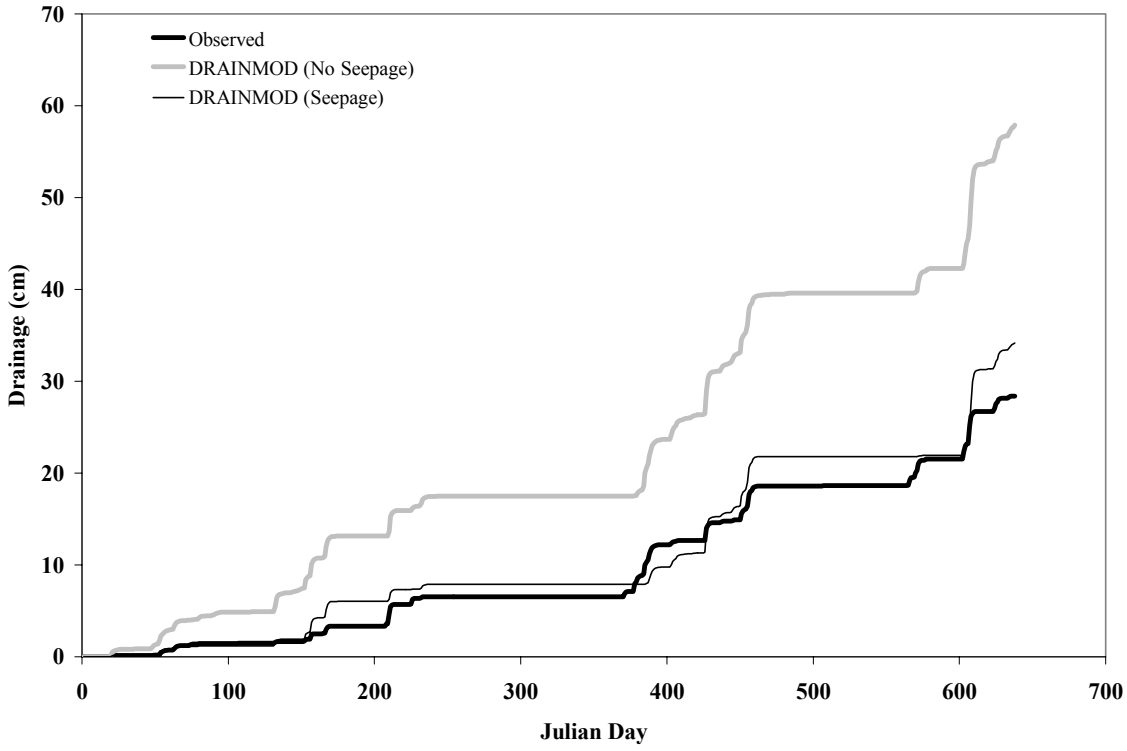

Figure 6b. Effect of seepage on calibration of DRAINMOD to observed drainage volume in Plot 2

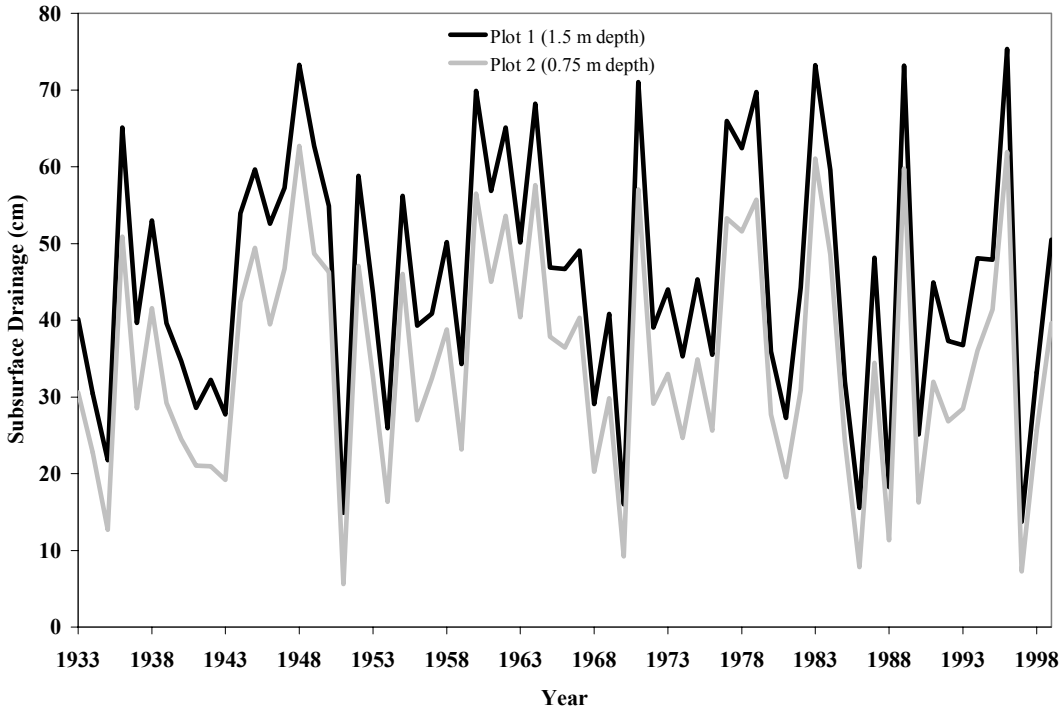

Figure 7. DRAINMOD simulated drainage volumes from Plot 1 and 2

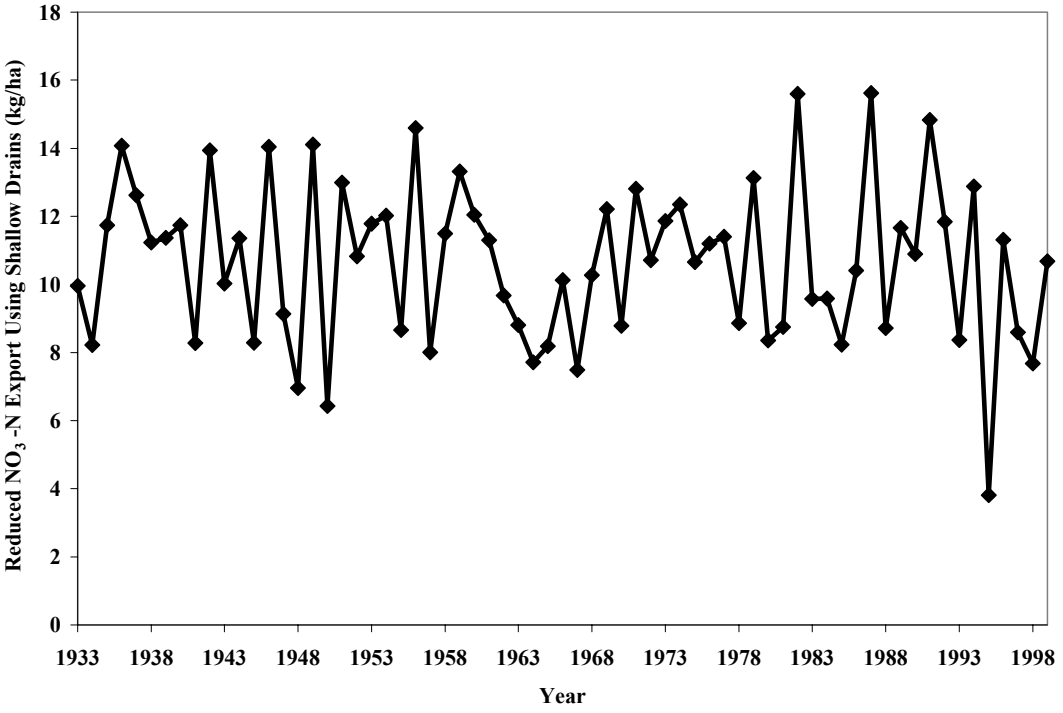

Figure 8. Yearly reductions of NO_3^--N exported from the shallow subsurface drainage system in Plot 2

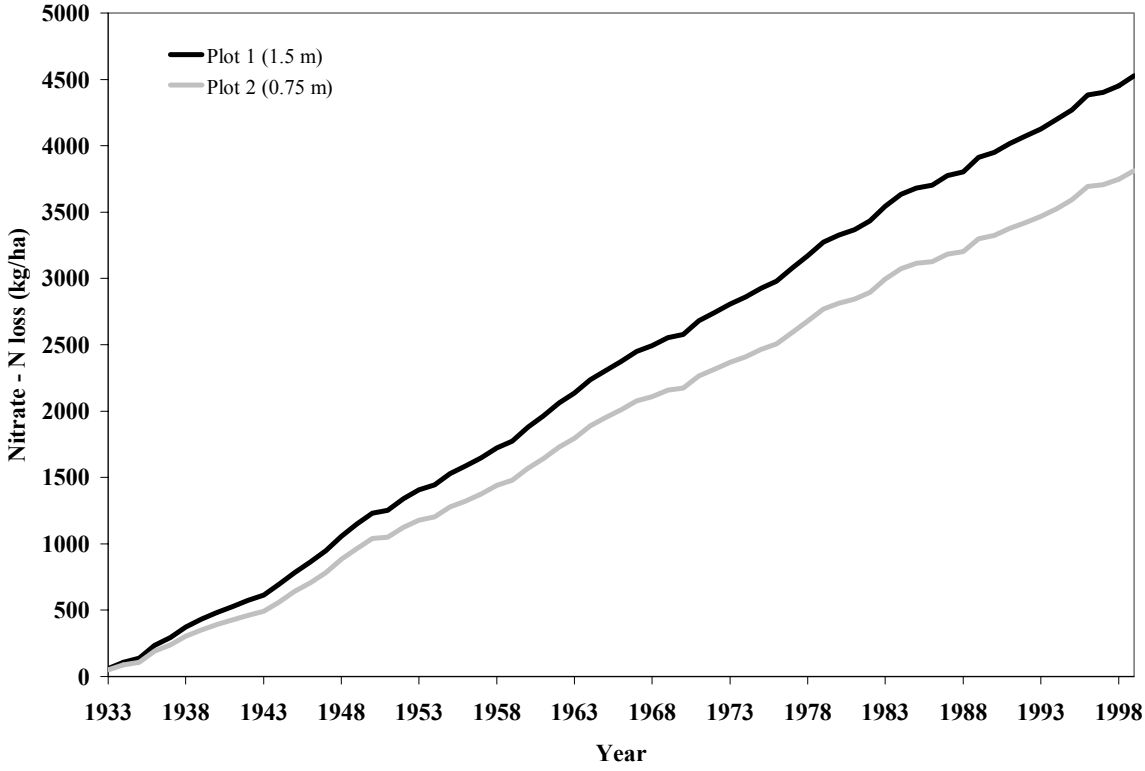

Figure 9. Cumulative nitrate losses from both drainage systems during the 67-year DRAINMOD simulation

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CHAPTER 3

THE ROLE OF SUBSTRATE ORGANIC MATTER IN IMPROVING NITRATE REMOVAL EFFICIENCY IN SURFACE-FLOW CONSTRUCTED WETLANDS

INTRODUCTION

Constructed Wetlands for Wastewater Treatment

Numerous studies in the early 1970's revealed the ability of natural wetlands to remove pollutants such as suspended solids and nutrients from domestic wastewater (Mitsch and Gosselink, 1993). Since then, scientists and engineers have been studying ways to optimize these natural wastewater treatment systems. These systems, when created for water treatment, are known as constructed wetlands. Constructed wetlands show promise in providing a low-cost, low maintenance solution for some wastewater treatment applications when compared to conventional wastewater treatment technologies.

A typical surface-flow constructed wetland (SFCW) is constructed similar to a natural fresh-water marsh. It is composed of three principal components - water, plants, and soil/substrate. Water transports substances both into and out of the wetland, and provides environmental conditions that allow unique plant and microbial biochemical processes to occur (Hammer and Bastian, 1989). Plants have many functions in the wetland, including increasing sedimentation of suspended solids, stabilizing wetland soil, light attenuation that reduces algal growth, uptake and storage of nutrients, oxygenation of the substrate around roots, and providing attachment sites for microorganisms (Brix, 1997; Reed et al., 1995). Wetzel (1993) states that the primary function of macrophytes in a wetland system is to photosynthetically supply large amounts of organic carbon that can be metabolized gradually

by wetland microbiota. Others agree that the accumulation of wetland plant litter provides a renewable source of organic matter to the system, but also add that it provides sites for material exchange and microbial attachment, while helping to provide low redox conditions that are crucial in many important biological transformation reactions (Kadlec and Knight, 1995; Davis, 2000). Wetland soil, often referred to as substrate, is another important component of SFCWs. Hammer and Bastian (1989) state that not only do substrates provide physical support for emergent wetland plants, but also provide large surface areas for microbial attachment and for complexing ions and other compounds. Reed et al. (1995) add that substrate supplies the majority of nutrients required for plant growth to wetland plants. In a SFCW, it is the water-substrate interface where most of the critical microbial transformations of pollutants occur (Steiner and Freeman, 1989).

Nitrogen Removal Using SFCWs

Constructed wetlands have shown much promise in nitrogen removal from wastewater, but with varying results. Numerous papers (Gersberg et al., 1983, 1984, 1986; Crumpton et al., 1993; Ingersoll and Baker, 1998; Bachand and Horne, 2000a, 2000b; etc.) and texts (Hammer, 1989; Kadlec and Knight, 1996; Moshiri, 1993; Reed et al, 1995) present laboratory and field studies indicating significant reduction of nitrogen in wastewaters treated with constructed wetlands.

There are several important mechanisms associated with nitrogen removal in SFCWs. Figure 1 shows a simplified schematic of the physio-chemical and biological transformations of nitrogen that may occur in a wetland, concentrating solely on ammonia (NH_4^+) and nitrate (NO_3^-). Nitrogen in the form of NH_4^+ entering a wetland may be removed from the system

only if pH conditions permit conversion to NH_3 to allow volatilization, or if wetland plants are harvested. However, if it is microbially converted to NO_3^- through nitrification in aerobic zones in the soil or around plant roots, that nitrogen can then be ultimately removed from the system through denitrification in anaerobic zones.

Denitrification

Denitrification is considered the major pathway of N removal from aquatic sediments since it can completely remove nitrogen from the system (Reddy et al., 1989). In the presence of nitrate and under anoxic conditions, certain bacteria utilize the nitrate as an electron acceptor instead of oxygen. Bacteria responsible for denitrification are biochemically and taxonomically very diverse, but most are heterotrophs (requiring carbon for a source of electrons for energy) and share the ability to utilize nitrogen oxides as electron acceptors in the absence of oxygen (Knowles, 1982; Metcalf and Eddy, Inc., 1991). Several genre of bacteria have been shown to be denitrifiers, including *Alcaligenes*, *Flavobacterium*, *Bacillus*, *Achromobacter*, and *Pseudomonas* (Metcalf and Eddy, Inc., 1991), with the genus *Pseudomonas* being the most commonly isolated denitrifying bacteria from both soils and aquatic environments (Knowles, 1982).

Complete denitrification occurs when nitrate (NO_3^-) is converted to nitrogen gas (N_2). Several enzymatic steps are required during this microbially mediated transformation. The first step is the conversion of NO_3^- to nitrite (NO_2^-). The nitrite is then further reduced to gaseous nitrogen end products, primarily nitrous oxide (N_2O) and dinitrogen gas (N_2) (Metcalf and Eddy, Inc. 1991, Sylvia et al., 1998). The steps of this reaction are

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$ (Metcalf and Eddy, Inc., 1991)

with the overall stoichiometry of the reaction being

$$C_6H_{12}O_6 + 4NO^-_3 \rightarrow 6CO_2 + 6H_20 + 2N_2 \text{ (Mitsch and Gosselink, 1993)}$$

For denitrification to proceed within a system such as a constructed wetland, certain conditions must exist: presence of NO_3^-, anoxic conditions, acceptable temperature and pH conditions, and an adequate carbon source (Knowles, 1982; Reed et al., 1995). In SFCWs, the combination of flowing water, plants, and sometimes man-made baffles, help provide mixing that increases the probability of water encountering microsites on sediment or detrital matter where all of these conditions exist, ultimately leading to nitrate reduction as the water passes though the system.

Low dissolved oxygen (DO) conditions are critical to denitrification. Dissolved oxygen limits denitrification rates because it represses the microbial production and activity of enzymes, such as nitrate, nitrite, and nitrous oxide reductases, which are responsible for the series of reductions that ultimately produce N_2 (Knowels, 1982; Sylvia et al., 1998). Knowles (1982) cites studies that reported 0.35% - 5% O_2 (0.03 – 0.45 mg/L at 20°C) completely repressed nitrate reductase (the first enzyme required to begin denitrification) in cultures of different bacteria, while a review by Beachamp et al. (1989) indicates DO exceeding 0.2 mg/L in soil water can inhibit denitrification. Theoretically, denitrification should not occur in the presence of oxygen, but it is possible that it may occur in low DO waters in anoxic microsites that may form in bacterial films on wetland plants, litter, or soil (Kadlec and Knight, 1996). The picture is not quite clear how low the oxygen concentration must be in the water just above the sediment in a SFCW before denitrification can occur, but

it seems clear that the level is somewhere below 1 mg/L based on the wastewater engineering equation presented by Metcalf and Eddy, Inc. (1991):

$$U'_{DN} = U_{DN} \times 1.09^{(T-20)} (1\text{-}DO)$$

where

U'_{DN} = overall denitrification rate

U_{DN} = specific denitrification rate

T = water temperature (°C)

DO = dissolved oxygen content in the water, mg/L.

This equation suggests that denitrification rates go to zero at DO ≥ 1 mg/L. In flooded soils such as those found in SFCWs, there is no pore space for O_2 to reside. Therefore, an O_2 gradient is established in the upper millimeters of the wetland substrate. At sites where nitrate-laden water contacts these layers with very low DO, denitrification can occur, provided that all of the other requirements for denitrification have been met.

Redox potential (Eh) is an important parameter in evaluating the potential biological transformations in systems, and denitrification is no exception. Nitrate reduction generally begins at Eh values below 350 mV, with complete nitrate disappearance below 220 mV (Ponnamperuma, 1972; Engler and Patrick, 1974; Kadlec and Knight, 1996).

As with most biological systems, temperature and pH affect denitrification. Denitrification rates increase with temperature up to a maximum, decreasing rapidly thereafter. Low temperatures decrease denitrification rapidly, but some activity has been

measured at 0-5 ºC (Knowles 1982). Denitrification is positively correlated with pH, with optimum pH in the range of 7-8 (Knowles, 1982; Kadlec and Knight, 1996).

Effect of carbon on denitrification rates

Carbon is important for optimizing denitrification rates, because it supports requirements for both energy and cellular synthesis for heterotrophic bacteria (Knowles, 1982). Stoichiometrically, 2.47 g of methanol (commonly used in conventional wastewater treatment systems - CH_3OH), or equivalent, is required to reduce 1 g of nitrate to nitrogen gas, including cellular synthesis (Kadlec and Knight, 1996). However, reduction of nitrate in aquatic systems is usually enhanced when carbon to nitrogen ratios exceed these theoretical levels, due in part to small levels of dissolved oxygen that allow some aerobic degradation of the carbon source. McCarty et al. (1969) expressed the carbon requirement as methanol, C_m, based on the concentrations of nitrate, nitrite, and dissolved oxygen,

$$C_m = 2.47\ (NO_3^- - N) + 1.53\ (NO_2^- - N) + 0.87\ (DO)$$

implying a C:N ratio greater than 2.47:1 when DO is present. Since constructed wetlands are open to the atmosphere and have some amount of DO as well as aerobic decomposition of OM, carbon supplies in these systems will need to be higher than theoretical levels, as well as those used in anaerobic reactors, to obtain optimum denitrification rates (Gersberg et al., 1983).

Several researchers have attempted to quantify the effect of organic matter (OM) in the enhancement of nitrate removal from water. In a two-part study, Engler and Patrick (1974), found that nitrate removal in a submerged salt water marsh soil with between 20-25% OM was greater than that in a swamp soil with 7% OM. In the second part of that study, a

positive correlation in nitrate removal was found with the addition of varying amounts of rice straw to the surface of a mineral soil that originally contained less than 1% OM. They argued that the rice additions decreased the distance of nitrate diffusion to an anaerobic layer, and increased the availability of a microbial energy source, both of which would enhance denitrification. Davidsson and Ståhl (2000) found a weak correlation between nitrate loss and OM in cores studied with 5 - 64 % OM, but also stated that all of the cores were suitable for removal of nitrate. On the other hand, a microcosm study by Phipps and Crumpton (1994) found no significance in OM additions to nitrate loss in sediment cores they were studying, but the cores contained between 9 and 28% OM before the additions. Studies on constructed wetlands by Gersberg (1984), Baker (1998), and Ingersoll and Baker (1998) found C:N ratios of 4:1 to 5:1 may maximize nitrate removal in those treatment systems. In their text, Reed et al. (1995) support these findings, using an example that describes how plant litter within a constructed wetland could support denitrification, assuming a desired C:N ratio of 5:1.

SFCWs receiving nitrified influent waters that are low in dissolved carbon or biological oxygen demand (BOD), will require a carbon supply from outside additions or from within the wetland itself to maximize its denitrification potential. In a survey of the substrate of several natural wetlands, Faulkner and Richardson (1989) reported organic matter levels between 17 and 77%, the result of a gradual buildup of detrital matter from decaying wetland plants. Mineral soils used as substrate in constructed wetlands can often limit denitrification due to low levels of OM (Nichols, 1983), a limitation much more prevalent in constructed wetlands than in older natural marshes (Bachand and Horne, 2000b). Constructed wetlands often take years to mature and accumulate levels of organic matter

comparable to natural marsh systems. Supplementing the wetlands with an external carbon source such as methanol can stimulate denitrification, but it can substantially increase operating costs. Additions of alternative carbon sources that are easily degraded such as mulch, grass clippings, or harvested wetland plants have been shown to be an effective substitute to methanol in wetlands. However, as stated earlier, additions should be higher than the methanol to nitrogen ratios due to losses of the carbon fraction to aerobic decomposition, as well as resistance to degradation of the biomass lignin fraction (Gersberg et al., 1983, 1984).

Manipulation of Wetland Substrate to Enhance Denitrification

Despite the evidence that OM enhances denitrification rates in constructed wetlands, the importance of the substrate is often overlooked in the design of these systems. Addition of OM and nutrients to mineral substrate to be used in a SFCW may serve to enhance denitrification in the first few years of the wetland by providing a head-start in the accumulation of available carbon. The increase in OM will essentially age the SFCWs, so that they more quickly reach the OM levels found in natural marshes. Abundance of nutrients, particularly nitrogen, in the substrate may also serve to increase the overall production of biomass (Broome et al., 1973; Allen et al., 1989), which will later become the major source of renewable carbon to the SFCW.

Enhancement of the substrate in a SFCW can be accomplished using Recycled Soil Manufacturing Technology (RSMT), an innovative approach in using contaminated or non - contaminated soils and/or sediments to engineer inexpensive soils with increased stability, fertility and functionality. The soil or sediment is mixed with cellulose (originating from

sawdust, yard waste, waste paper products, etc.) and biosolids (such as BIONSOIL™ reconditioned animal manure) to provide a fertile soil that has many beneficial uses (Lee et al., 1996; Lee et al., 1998; Sturgis et al., 2001). Some of these uses have included topsoil used in landscaping, as well as landfill, Superfund and mining site covers.

Objectives

The main objectives of this study, conducted at the North Carolina Department of Agriculture – Tidewater Research Station's Swine Research Unit, were to quantify and compare NO_3^--N reductions in mesocosm-scale constructed wetlands receiving nitrified drainage water, based on various OM additions blended into two mineral soils. The two soils, a Cape Fear loam from Plymouth, NC (5% OM) and dredged material from the Eagle Island Confined Disposal Facility in Wilmington, NC (12% OM), were blended with various amounts of wheat straw or *Phragmites australis* compost. The Cape Fear loam and straw represented what a farmer would have available to use as a substrate if, for example, construction of a wetland in an outlet drainage canal was desired as a final polishing step before water exited the facility (Figure 2). The dredged material and *Phragmites* represents what would be available for constructing a wetland near a coastal region. The dredged material is being tested as part of the U.S. Army Corps of Engineers Dredging Operations Environmental Research Program (DOER) initiative to evaluate alternative dredged material management strategies.

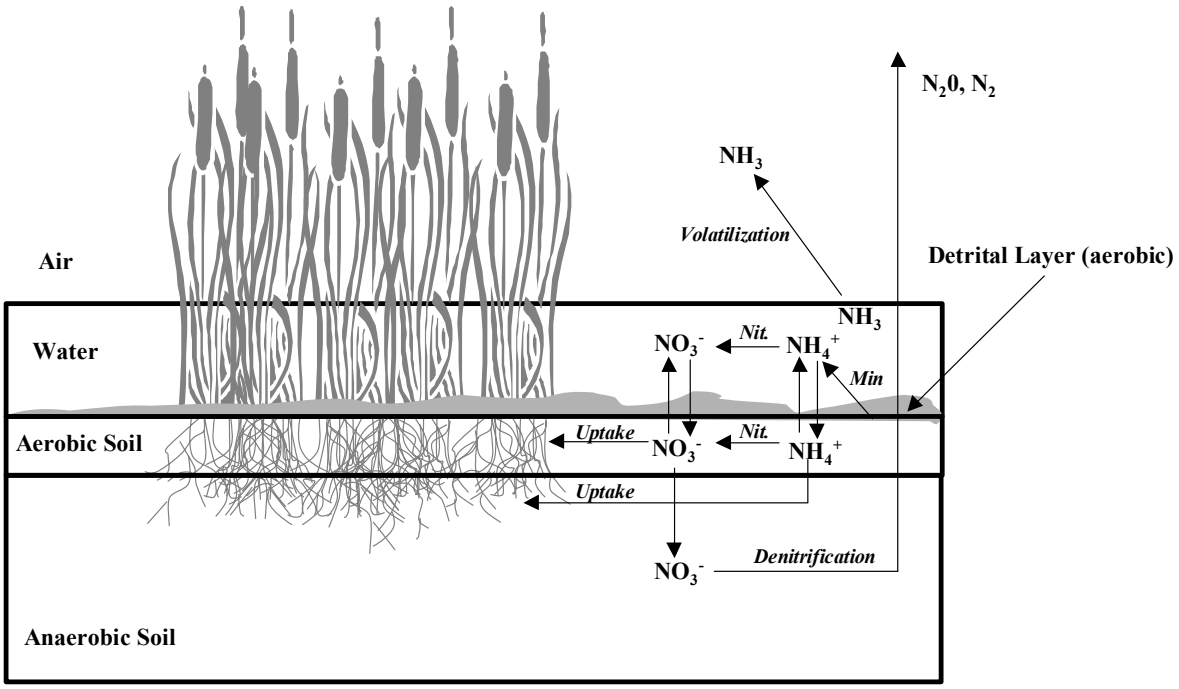


Figure 1. Simplified nitrogen cycle within a constructed wetland, considering only NH_4^+ and NO_3^-. Note: *Nit.* = Nitrification (from Mitsch and Gosselink, 1993)

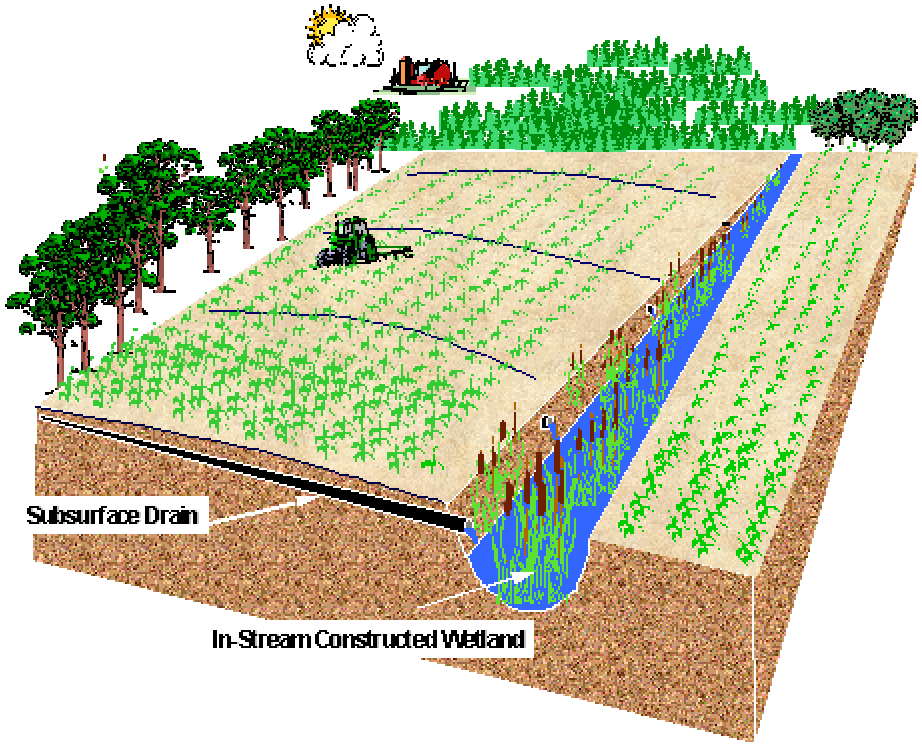


Figure 2. In-stream constructed wetlands used in drainage canals to treat NO_3^--N from drainage water as it exits the facility

MATERIALS AND METHODS

Site and Wetland Mesocosm Description

The study site is located in the upper coastal plain of North Carolina at the North Carolina Department of Agriculture – Tidewater Research Station's Swine Research Unit in Plymouth, NC. Twenty - one 2 m long x 1 m wide x 1 m deep above -ground wetland mesocosms were constructed of 16 gauge steel. These tanks were lined with a 7 mil protective liner. The tanks were sprayed with 2.5 cm of urethane insulation (donated by Coastal Refrigeration Company, Greenville, N.C.) and painted white to protect against diurnal variations in temperature. Since the metal tanks were flexible the outsides of the tanks were supported with a wooden frame to help maintain their rectangular shape once substrate and water were added. The tanks were placed in three rows of seven. Each mesocosm was accompanied by a 132 L evapotranspiration (ET) tank (AgriSupply Co., Garner, N.C.), which supplied each mesocosm with fresh water to replace water lost to ET during each batch study. These ET tanks, painted to protect against algal buildup inside, rested on a steel drum rack at the end of each mesocosm, and the water supplied to the mesocosm was controlled by a DARE – o – Matic float valve (AgriSupply Company, Garner, N.C.) commonly used in watering animals. The water recirculation system in each mesocosm consisted of a Rio90 aquarium pump (FishPros, Raleigh, N.C.) connected to 1.25 cm PVC pipe. The pump rested near the substrate/water interface at one end of the mesocosm, and the redistribution manifold (a 1.25 cm pipe with six – 7 mm holes) rested just above the substrate/water interface at the other end of the mesocosm. A 1.25 cm PVC ball valve was installed in the recirculation system for water quality sampling. Two – 11.4 m^3 polyethylene

tanks (AgriSupply Co., Garner, NC), were placed on site to store drainage water from an adjoining land application field receiving swine waste. These tanks supplied water to the wetland mesocosms during the study. Electrical power was installed at the site, and each mesocosm was supplied with two 115 V electrical outlets. Figure 3 shows a schematic of the entire wetland study site and Figure 4 shows the wetland mesocosm schematic. Figure 5 is a photograph of the site.

Wetland Substrate Blending

The ingredients of the blends to be tested were based on what would be available to the farmer at this site, and what would be available near where dredged material would be used. Therefore, the site soil was blended with straw and BIONSOIL™ reconditioned swine manure, and the dredged material was blended with *Phragmites australis* (an invasive plant that grows proliferously on dredged material sites) compost and the BIONSOIL™ reconditioned swine manure. In early April 2000, excavation of the soils for the substrate blends was begun. The U.S. Army Corps of Engineers Wilmington District granted clearance to excavate from the Eagle Island Confined Disposal Facility (CDF) in Wilmington, NC. Approximately 36 cubic meters of dredged material was excavated, and the material was passed though a 1.25 cm screen at a local materials handling company, to remove *Phragmites* rhizomes, rocks and clods. About 12 cubic meters of this screened dredged material, along with 4 cubic meters of *Phragmites* compost also collected from the CDF, were transported by dump truck to the study site. The *Phragmites* is described as compost because it was obtained from a pile of above-ground shoots that had begun to decompose. The other mineral soil to be tested was excavated at the study site, and was a

mixture of the A and B horizons of a Cape Fear Loam (fine, mixed, semiactive, Typic Umbraquualt).

Six substrate conditions and a control were created in wetland mesocosms, in triplicate, for a total of 21 wetland mesocosms. The treatments were placed in a randomized complete – block design, with each row (A, B, and C) containing one replicate of each of the substrate conditions. Substrate depth in each mesocosm was to be 46 cm, corresponding to a volume of approximately 0.91 m^3 of substrate in each mesocosm. For the substrate blends, additions of cellulose and BIONSOIL™ to each of the mineral soils were calculated on a volume basis, to increase the organic matter content in the soils to approximately 5 and 10% above its original content. The substrate in each mesocosm was blended individually using a custom-made 220V pug-mill (Advanced Remediation Mixing, Inc, New Orleans, LA). Soil substrate was shoveled out of a front-end loader and into the blender to remove large clods, before being added to the mesocosms. The components of each of the blended substrate was layered into the front-end loader, and then shoveled into blender before being added to the mesocosms. Organic matter percentage was controlled by the addition of straw and *Phragmites* compost to the Cape Fear Loam and dredged material, respectively. Addition of the BIONSOIL™ to the blended substrate was constant, and comprised only 5 % of the total volume of the blend. Addition of the substrates to the mesocosms was completed at the end of April 2000.

Samples of each of the substrates were collected during addition to the mesocosms, and were analyzed by the Biological and Agricultural Environmental Analysis Laboratory at North Carolina State University for total kjeldahl nitrogen (TKN), total phosphorous (TP), ammonia nitrogen (NH_3 – N), nitrate nitrogen (NO_3^-- N), pH, % carbon, % nitrogen, moisture

content, % organic matter, and bulk density. Substrate analysis for TKN and TP included digestion according to methods described by Schuman et al. (1973) followed by automated analysis using a Bran + Leubbe Autoanalyzer 3 (EPA Method 351.2 for TKN (USEPA, 1983) and Standard Method 4500-P B for TP (APHA, 1995)). NH_3 - N and NO_3^-- N were and analyzed using the same autoanalyzer (Standard Method 4500 -NH_3^+ G for NH_3 - N (APHA, 1995) and Standard Method 4500 -NO_3^- F for NO_3^-- N (APHA, 1995)). Substrate pH was analyzed using a glass electrode (Standard Method 4500-H (APHA, 1995). Percent carbon and nitrogen were analyzed with a Leco CN-2000 Carbon, Protein and Elemental analyzer (Method 990.03, Journal AOAC, 1989). Moisture content of the substrate was measured after oven drying at 105 °C for 24 hours. After oven drying, percent organic matter in the substrate was measured as the residue lost from ignition at 550 °C in a muffle furnace (Standard Method 2540 (APHA, 1995)). Bulk density of the substrate was measured on a wet-weight basis in a 450 cm^3 container, to reflect the weight per volume of the substrate as added to the wetland mesocosms. All analyses were adjusted to a dry-weight basis.

Wetland Planting and Establishment

In early May 2000, the mesocosms, except for the control treatment, were planted with a monoculture of soft – stemmed bulrush (*Scirpus validus*), obtained from a greenhouse (Naturescapes, Suffolk, Va.). Each bulrush plug contained 3 – 6 shoots that ranged between 30 – 50 cm in height. Before planting, each mesocosm was flooded with water to approximately 2.5 cm above the wetland substrate. The bulrush was planted on 15 cm

centers, or 72 plants per mesocosm. During the remainder of 2000, and into the Spring of 2001, the plants were allowed to establish, using well water to maintain flooded conditions.

Batch Studies

2001 Wetland batch studies

Batch studies were conducted in May (Batch 1), July (Batch 2), August (Batch 3), and September 2001 (Batch 4), each continuing for 10 to 22 days. Stored drainage water was added to a depth of approximately 30 cm in each mesocosm. Because of the variations on the substrate surfaces in each mesocosm, as well as variances in plant density, the volume added to each mesocosm to achieve a 30 cm depth also varied. Therefore, volume added to each mesocosm was measured using a flowmeter and recorded. Drainage water stored for the studies contained NO_3^-- N concentrations < 2 mg/L, so technical grade calcium nitrate decahydrate ($Ca(NO_3)_2 \times 10\ H_2O$ purchased from Fisher Scientific) was used to amend the feed water to various NO_3^-- N concentrations for each batch. Before loading, each mesocosm was drained to a depth of 1-2 cm. Based on the amount of water added to each mesocosm to increase the water depth to 30 cm, calcium nitrate was added to achieve NO_3^-- N concentrations of 12 mg/L in Batch 1, 25 mg/L in Batch 2, and 50 mg/L in Batch 3 and 4. The calcium nitrate was dissolved in 5L of feed water and poured into the each mesocosm. A 1/6 hp submersible pump (TEEL Model No. 1P914 GRAINGER, Raleigh, N.C.) with a 1 m outlet hose was placed in the mesocosm for 2 minutes to mix the calcium nitrate evenly through the wetland. After loading of all of the mesocosms, well water was added to the ET tanks and the batch study began.

During each batch study, each wetland mesocosm was sampled for water quality analysis from the water recirculation system on day 1, 3, 5, 7, 10, 15 and 22 (if needed). Samples were collected in 500 mL plastic bottles, acidified with H_2SO_4 to pH 2-3, and then frozen until analyzed. Water was analyzed by the Soil Science Analysis Laboratory at North Carolina State University using a LACHAT Quickchem 8000 instrument for NO_3^-- N (Cadmium Reduction Method, Standard Method 4500 -NO_3^- F (APHA, 1995)) , ammonium (NH_4^+-N) (Automated Phenol Method, Standard Method 4500 -NH_3^+ G with salicylate substituted for phenol (APHA, 1995)), ortho-phosphate (o-PO_4^-) (Ascorbic Acid Method, Standard Method 4500 –PF (APHA, 1995)). Dissolved organic carbon (DOC) was measured using a combustion-infrared method on a Shimadzu® analyzer (Standard Method 5310 B (APHA, 1995)). Rainfall was measured using a manual rain gage at the site, so that the nutrient data could be adjusted to account for dilution. No adjustments had to be made thanks to numerous dry periods and rainfall followed by high ET that maintained the volume of water within the wetlands during the batch studies of 2001.

During each batch study, water temperature was monitored continuously on an hourly basis, using HOBO® temperature loggers (Model H08-001-02) in watertight enclosures. Temperature was monitored in a control mesocosm from one of the rows, and in a treatment mesocosm from each of the other two rows, for a total of three measurements during each batch. Measurements were made at the substrate/water interface, and were downloaded at the completion of each batch study.

On water quality sampling days, Eh, water temperature, salinity, dissolved oxygen (DO), and pH, measurements were taken from each wetland mesocosm. Platinum redox (Eh) electrodes were constructed using methods described by Kunickus (2000). Two Eh probes

were installed in each mesocosm; one at a depth of 2 cm and one at 15 cm. Eh was measured with an Accumet pH/mV meter (Model No. AP63 – Fisher Scientific) connected to a Ag/AgCl reference electrode (Jensen Instruments, Tacoma, WA). Water temperature, salinity, conductivity DO, and pH were measured using a YSI – 600 multiparameter water quality probe (Model 600R-25-C-T-pH-DO, Yellow Springs International) connected to a YSI –610D hand held microcomputer (Model 610D, Yellow Springs International), at 2.5 cm above the substrate/water interface in each wetland mesocosm.

The purpose of the ET tanks was to provide fresh water to the wetland mesocosms to prevent them from drying up during the high ET periods during the summer. More importantly, this water maintained a constant water level throughout the batch so that nutrients would not be concentrated as the volume of water decreased within each wetland, making analysis of removal more accurate. The ET tanks also provided an easy way to estimate ET from each of the wetland mesocosms. ET was measured on water quality sampling days. ET that occurred between sampling days was calculated for each mesocosm based on the volume of water remaining in each ET tank, taking into consideration any rainfall that occurred during the period. Rainfall measured minus depth of water above the original depth in the wetland mesocosm was added to the ET measured from the ET tank. Estimated ET loss per 2.5 cm change in water depth equaled approximately 42 L, based on the size of the mesocosms. Occasionally, ET in the wetland mesocosms exceeded the capacity of the ET tank. The difference in the depth of water from the original depth at the beginning of the batch was used to calculate the additional ET (again 2.5 cm change = 42 L ET). After measurements, the ET tanks were refilled to capacity.

2002 Wetland batch studies

Batch 5 (February), 6 (May), 7 (June), and 8 (July) were conducted in 2002. Initial NO_3^-- N concentrations in Batch 5 and Batch 6 were 30 mg/L, 60 mg/L in Batch 7, and 120 mg/L in Batch 8. Mixing procedures used in 2001 were used in Batch 5, but were altered for Batches 6-8, because inadequate mixing was believed to result in inconsistent initial NO_3^-- N concentrations of the 2001 batches. Instead of mixing the calcium nitrate within the wetland mesocosm based on 30 cm of water in each tank, drainage water and calcium nitrate was added to a 470 L tank and mixed for 5 minutes prior to loading. This simplified the loading, because equal volumes of drainage water and calcium nitrate were added to each wetland mesocosm during each batch study, and produced very consistent initial NO_3^-- N concentrations in each of these batches. A drawback was that the float valves controlling the ET tanks on some of the mesocosms needed adjustments from the original setting 30 cm above the substrate.

Wetland Biomass Sampling

At the conclusion of the 2000, 2001, and 2002 growing season, a sample of the emergent vegetation was taken from each mesocosm and analyzed for nutrient content (TKN, TP, %C, %N) on a dry weight basis, with methods described above for substrate analysis. After senescence of the emergent vegetation, the entire stand of bulrush was harvested from each mesocosm at 5 cm above the substrate surface. This biomass was transported back to the lab where it was dried and weighed to estimate the biomass production of each treatment. Nutrient removal from the system by the wetland plants could then be estimated. After analysis of the biomass was complete, 30% of the dry weight of the biomass from each

wetland mesocosm was transported back to the study site and added back to its respective mesocosm. This was done to simulate natural litter accumulation. Only 30% was added back to prevent the entire mesocosm from being filled with litter during the course of the study, limiting the amount of drainage water that could be added.

Final Substrate Sampling

At the conclusion of 2002, substrate from each wetland mesocosm was sampled to compare the %C and %N to the values measured at the beginning of the study. Water was pumped from each of the mesocosms prior to sampling. Cores taken from the wetland mesocosms were approximately 40 cm in length. Each core was separated into four layers; layer 1 (dense rhizome layer from 0- 5 cm), layer 2 (5-15 cm), layer 3 (15-25 cm) and layer 4 (25-40 cm). Each layer was oven dried at 50 °C and ground with mortar and pestle. The samples were then further ground mechanically and passed through a 1 mm sieve. Each layer was then analyzed for %C, %N and moisture content with the same methods employed in the analysis at the beginning of the study.

Data Analysis

Statistical analysis on the NO_3^-- N removal of each of the wetland treatments included regression analysis of the treatment curves, followed by univariate and multivariate ANOVA of the estimated coefficients from the regressions, to test for treatment effects. For biomass production, a randomized complete block design was used and multiple comparisons of treatment means were conducted using Tukey's procedure. Both of these analyses were conducted using SAS statistical software (SAS Institute, 1989).

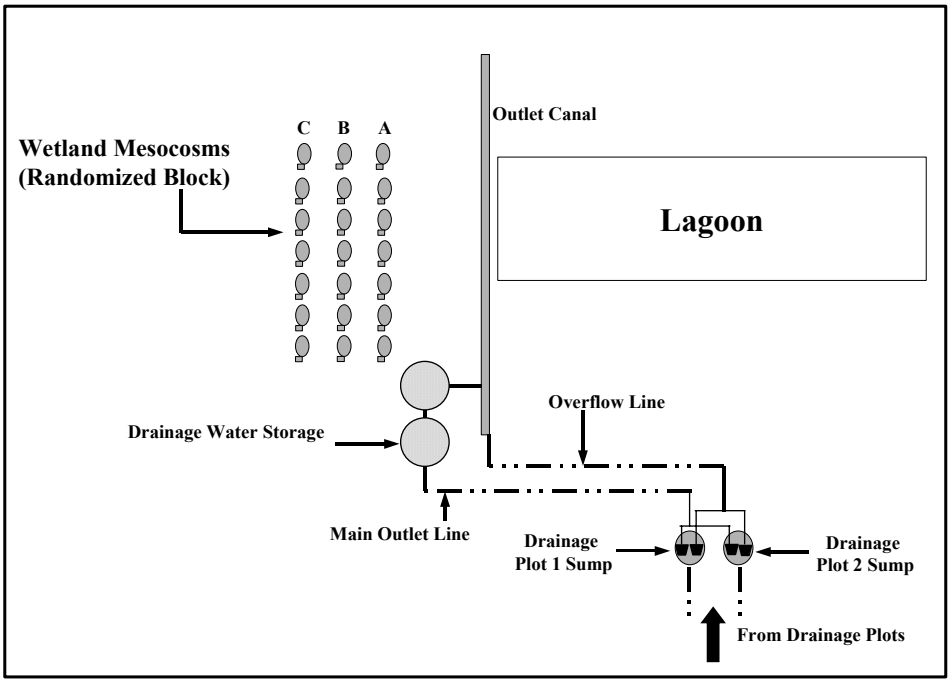


Figure 3. Wetland site setup

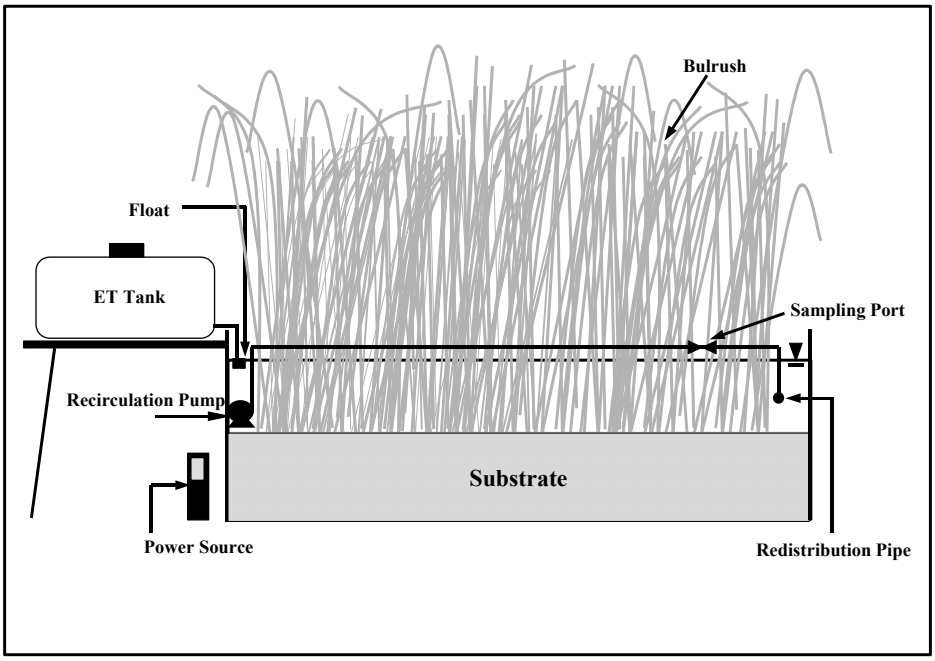


Figure 4. Wetland mesocosm schematic

Figure 5. Wetland study site

RESULTS AND DISCUSSION

Initial Wetland Substrate Conditions

The physiochemical parameters of each of the substrates are shown in Table 1. The control in this experiment was the flooded site soil; the Cape Fear Loam soil alone with no plants, which effectively represents an outlet canal from an agricultural facility. The Cape Fear Loam with plants (represented as "Site Soil Only"- ***SS***) represents a SFCW constructed with just the soil available to the farmer at the site. The soil was a blend of the A and B horizons, contained around 5% OM, and had an average particle size distribution of 25% sand, 28% silt, and 46 % clay. The Cape Fear Loam soils were blended with biosolids and low and high additions of straw, which increased the OM to around 11% ("Site Soil Blend – 11% OM"-***SSB11%***) and 16% ("Site Soil Blend – 16% OM"-***SSB16%***). These two blends represent substrates that could be manufactured with materials available at the agricultural facility.

The dredged material (represented as "Dredged Material Only" - ***DM***) treatment represent wetlands constructed near a CDF such as Eagle Island in Wilmington, NC, with the dredged material alone as the substrate. It contained about 12% OM, and exhibited a particle size distribution of 15% sand, 38% silt, and 47% clay. The dredged material was blended with biosolids and low and high additions of *Phragmites* plant organic matter to produce wetlands substrate blends with 18% ("Dredged Material Blend – 18% OM" - ***DMB18%***) and 22% ("Dredged Material Blend – 22% OM" – ***DMB22%***) organic matter. These blends represent wetlands that could be constructed with manufactured substrate with materials available from a CDF.

As shown in Table 1, the dredged material contained more organic matter, total nitrogen, and total phosphorous than the Cape Fear Loam, but because it was screened after excavation, its bulk density as added to the wetland mesocosms was less. Additions of the cellulose and BIONSOIL™ to the Cape Fear Loam increased the OM%, total nitrogen, and the total phosphorous in these wetland substrates. The additions of the straw significantly decreased the bulk density of the substrates. This may increase the flow of water through the wetland substrate, but it also makes it more difficult to establish plants initially. It was very difficult to keep the plants upright and stable in the SSB16% treatment substrate shortly after planting, and required the water level in each of the three replicates of this treatment to be kept lower during establishment. The additions of the cellulose and BIONSOIL™ to the dredged material also increased the OM%, total nitrogen, and the total phosphorous in these wetland substrates. Little change in the bulk densities of the dredged material blends was observed because the *Phragmites* compost added was similar to the original bulk density of the dredged material.

Nitrate Removal Studies

Wetland batch studies 1-4 were performed in 2001, and batch studies 5-8 were performed in 2002. Batch studies were scheduled to measure NO_3^- - N removal in the various seasons to incorporate various water temperatures and wetland plant growth stages. Batches 1 and 6 evaluated the wetland performance during the spring. Batches 2, 3, 7 and 8 evaluated wetland performance in the summer. Batch 4 evaluated wetland performance in the fall, while Batch 5 was conducted during the winter. Statistical analyses were performed

to determine if the differences in these removal curves were significant. NO_3^- - N treatment curves from the site soil based wetlands were compared only to the control and other site soil based wetlands. Similarly, NO_3^- - N treatment curves from the dredged material based wetlands were compared only to the control and other dredged material based wetlands. To test for treatment effects, NO_3^- - N concentration data from each of the wetlands was transformed to percent NO_3^- - N removal to normalize the data within each batch. A multiple regression model, which took the percent NO_3^- - N removal to be quadratic in time (Engler and Patrick, 1974) was fit using least squares. The full quadratic model was such that the models for the wetland treatments were nested within the full model, and the linear and quadratic coefficients were allowed to vary between the treatments (Rao, 1998). Comparisons of the nested models with the full model were tested for equality using univariant and multivariate ANOVA procedures. Due to the limited number of treatment comparisons, these comparisons were not adjusted for multiplicity.

Batch 1 – May 14th-29th, 2001

The initial 15-day wetland study was conducted in the Spring of 2001, from May 14th-29th. The wetland plants had one growing season to establish, and had been growing in this season for approximately 2 ½ months. The goal for initial NO_3^- - N concentration in this study was 12 mg/L. Average water temperature during this study was 19.7 °C. NO_3^- - N treatment in this batch was slower than anticipated. High DO levels at the onset of the study may have contributed to lower denitrification rates.

Figure 6a shows the average NO_3^- - N concentrations for the site soil based wetlands (SSWs) and the control during this study. The wetland treatment SSB11%, reduced NO_3^- - N

concentrations on average below 1 mg/L in 12 days. All of the treatments except the control reduced NO_3^- - N concentrations on average below 1 mg/L in 15 days. However, all of the treatments did not start with equal concentrations of NO_3^- - N. The initial NO_3^- - N concentration in the controls ranged between 15-16 mg/L and between 12-15 mg/L in the SSWs. In fact, NO_3^- - N concentrations in most of the replicates did not seem to reach equilibrium until 1-3 days after the study began. In other words, NO_3^- - N concentrations increased in the first few days after the study began in some of the wetland mesocosms. To normalize the data for statistical analysis, the wetlands were evaluated on a % NO_3^- - N removal basis. Day 1 of the study was taken as day 0 for the % NO_3^- - N removal curves, to allow for an extra day to achieve equilibrium NO_3^- - N concentrations within each of the wetland mesocosms. Subsequently, days 3, 5, 7, and 10 of the study were converted to day 2, 4, 6, 9, and 14. Percent removal was recorded as zero for any day there was an increase in NO_3^- - N concentration within a wetland treatment. Figure 6b shows the resulting average % NO_3^- - N removal curves. Table 2 lists the probability (P) values generated from the statistical tests for equality of the treatments in Batch 1. All of the SSW treatments significantly outperformed the control in NO_3^- - N removal. The SSB11% wetlands removed NO_3^- - N slightly more quickly than did the substrate with site soil alone, SS ($P<0.0116$). There was no difference in treatment in the SSB16% wetlands and the SS and SSB11% wetland treatments.

Figure 7a shows the average NO_3^- - N concentrations for the dredged material based wetlands (DMWs) during this study. The initial NO_3^- - N concentration in the DMWs replicates ranged from approximately 9 mg/L to 18 mg/L. The DMB18% and DMB22% wetland treatments reduced the NO_3^- - N concentrations below 1 mg/L in <10 days. All of the

DMWs reduced NO_3^- - N concentrations below 1 mg/L in <14 days. The data were normalized to % NO_3^- - N removal as in the SSW treatments, and is shown in Figure 7b. The P values for these treatments are listed in Table 2. Differences in the treatment curves between the control and the DMWs were strongly significant. A slight difference between DM and DMB22%, was observed (*P<0.0252*).

Batch 2 – July 3rd -13th, 2001

This 10-day summer batch study was conducted from July 3rd – 13th, 2001. Biomass had fully established within the wetlands. The goal for initial NO_3^- - N concentration in this batch was 25 mg/L. Average water temperature in the wetland treatments during this study was 23.6 °C , much warmer than was observed in Batch 1. The control mesocosms were nearly 3 °C warmer than the wetland treatments due to lack of shading by bulrush shoots. DO levels within the wetlands were low early in the study, and generally the wetlands removed NO_3^- - N rapidly.

Figure 8a shows the NO_3^- - N treatment curves, on the basis of concentration, for the SSWs. Problems in initial NO_3^- - N concentration in the wetland mesocosms were more pronounced in this batch study than in Batch 1. The control initial concentration ranged from 32-44 mg/L, while initial concentrations in the SSWs ranged from 9-23 mg/L. Residual NO_3^- - N in the substrate, redispersed during loading, was later blamed for the higher concentrations observed in the control. NO_3^- - N concentrations were reduced below 5 mg/L in approximately 8.5, 4.5, and 5 days in the SS, SSB11%, and SSB 16% wetlands, respectively. However, variations in the initial concentrations made it difficult to evaluate differences in treatment efficiency. Although there was only a 7 mg/L maximum difference

between the average initial NO_3^- - N concentration in the SSWs, this was equivalent to a 32% difference. The data were again normalized and described as % NO_3^- - N removal, as shown in Figure 8b. Statistical analysis revealed that all of the SSWs outperformed the control in NO_3^- - N removal. The wetlands with blended substrate, SSB11% and SSB16%, removed NO_3^- - N more rapidly than the SS treatment, but were not different from each other. Table 3 shows the probability values generated during the analysis in testing for equality between the treatments.

Figure 9a shows the average NO_3^- - N concentrations for the DMWs during this batch study. An even larger range of initial NO_3^- - N concentration, 5 – 26 mg/L, was observed in the DMWs replicates. NO_3^- - N concentrations were reduced below 5 mg/L in approximately 5.5, 2.5, and just over 3 days in the DM, DMB18%, and DMB22% wetlands, respectively. However, it must be noted that because it started with an average of only 8 mg/L NO_3^- - N, the DMB18% treatment needed to only remove 3 mg/L NO_3^- - N to achieve that level. There was also a 47% difference in the starting concentrations in these wetlands. Again, this was another example why the variations in the initial concentrations made it difficult to evaluate differences in treatment efficiency. Figure 9b shows the data normalized and described as % NO_3^- - N removal. Under these conditions, statistical analysis revealed that all of the DMWs outperformed the control, as shown in Table 3. DMB22% displayed the fastest treatment and there were no treatment differences between DM and DMB18%.

Despite normalization of the data, these results should still be regarded as estimates due to the large differences in starting concentrations during this batch.

Batch 3 - August 14th-29th, 2001

Batch 3, conducted August 14th-29th, 2001, was the second summer study. The initial NO_3^- - N concentration goal in this study was 50 mg/L. Average water temperature during this study was 23.8 °C, slightly higher than in Batch 2. The control tank water temperature averaged 2.5 °C higher due to a lack of shading by bulrush. All of the wetland treatments performed well in removal of these relatively high NO_3^- - N concentrations.

The average NO_3^- - N concentrations observed in the SSW mesocosms are shown in Figure 10a. The cause of the initial NO_3^- - N concentration problem in the wetlands had not been pinpointed by Batch 3. The NO_3^- - N concentrations in the control treatments far exceeded the 50 mg/L goal. Initial concentrations ranged between 86-93 mg/L on day 1 (day 0 data was ignored to allow for more mixing); this was later attributed to redispersion from the soil during loading. The initial concentration range in the SSWs was 34-70 mg/L on day 1. However, the average concentrations on day 1 only ranged from 50-58 mg/L, which allowed for more reliable comparisons between the SSW treatments, but not against the control. The maximum difference in the average initial concentrations was only 16% in this batch. The SS wetland treatment reduced the NO_3^- - N concentrations to 10 mg/L in just over 15 days (projected), while the SSB11% and SSB16% wetland treatments reached this concentration in just over 8.5 days. Normalizing these data was a much more reliable tool to compare the wetland treatments in this batch than in Batch 2 because of the lower percent difference in average NO_3^- - N initially. Figure 10b shows the resulting normalized curves. The differences observed between the SSWs and the control should probably be ignored due to the large initial concentration in the control. There was an observed increase in treatment efficiency in the SSW blends (SSB11% and SSB22%) when compared to the SS treatment,

but no significant difference between them. Table 4 lists the probabilities generated to test for equality of these treatments.

Figure 11a shows the NO_3^- - N concentrations measured in the DMW treatments. Replicate A of the DMB22% wetlands was taken off-line due to severe leaking, so only two replicates were used its treatment calculations. Day 0 data were ignored as in the SSW treatments. The initial NO_3^- - N concentration range in all of the DMW treatments was between 26-52 mg/L, but the average concentrations on day 1 only ranged from 38-43 mg/L, for an average difference of 12%. As mentioned in the analysis of the SSW treatments, this reduced initial percent difference made analysis of this batch more reliable than in Batch 2. Treatment to below 10 mg/L NO_3^- - N occurred on average in just under 8 days in DM and DMB18%, while it took only an average of just under 6 days in DMB22%. Normalization of the data (Figure 11b) followed by statistical analysis, revealed no treatment differences between DM and DMB18%. However, NO_3^- - N treatment in the DMB22% wetlands was significantly faster than in the other DMWs. Table 4 lists the probabilities generated to test for equality of these treatments.

Though more reliable than the Batch 2 results, these statistical results still lack the reliability that could be obtained if the initial NO_3^- - N concentrations were more uniform across the treatments. Comparisons to the control should be ignored in the analysis of this batch because of the high initial concentrations. However, these results for this batch are still useful in observing treatment trends within the SSWs and the DMWs.

Batch 4 – September 18- October 3, 2001

Batch 4, conducted September 18th – October 3rd, 2001 was the lone wetland study conducted in the Fall. The goal for initial NO_3^- - N concentration for this batch was 50 mg/L. The growing season for the bulrush was essentially at its end, and some senescence had begun. The cooler daily temperatures resulted in decreased average water temperature of 18.1 °C, over 5 °C cooler than the summer batches. The control mesocosms were on average 2 °C warmer. The wetland treatments did not perform as well in NO_3^- - N removal when compared to the Batch 3 initiated in the summer during warmer temperatures.

The average NO_3^- - N concentrations observed in the SSW mesocosms are shown in Figure 12a. The cause of the initial NO_3^- - N concentration problem in the wetlands still had not been identified by Batch 4. Problems in the NO_3^- - N concentrations in the control treatments reduced by thoroughly flushing the soil in these tanks with clean water before beginning the study. Initial concentrations ranged between 43 - 44 mg/L on day 1 (day 0 data was ignored once again to allow NO_3^- - N concentrations to reach equilibrium in all treatments). The initial concentration range in the SSWs was 13.5 - 46 mg/L on day 1 (Note: this range was observed within the SS wetland treatment). The average concentrations on day 1 only ranged from 31-39 mg/L, for a 20% maximum difference. This difference was similar to what was observed in Batch 3. Treatment was noticeably slower in than in Batch 3. The SS wetland treatment reduced the NO_3^- - N concentration to 10 mg/L in just over 15 days (projected) on average. The SSB11% treatments reached this concentration in 13 days average, while the SSB16% wetland treatments reached this concentration in 15 days. Normalization of the concentration data from day 1 to day 0 and to % removal, as in the previous batches, is shown in Figure 12b. Statistical comparisons to the control were

once again relevant, and revealed significant increases in NO_3^- - N treatment in the SSWs when compared to the control. Increased treatment efficiency observed in the SSB11% over the SS wetlands was only slightly significant (P=0.0474). No differences were observed between the SSB16% and the SS or the SSB11% wetland treatment. Table 5 lists the probability values generated during the tests for equality for the SSW treatments.

Figure 13a shows the NO_3^- - N concentration data for the DMWs. As in Batch 3, the DMB22% treatment was made up of only 2 replicates. The initial NO_3^- - N concentration range for the DMWs on day 1 was between 27-51 mg/L. The average initial concentrations on day 1 ranged from 36 - 41 mg/L, a maximum difference of 12%. On average, NO_3^- - N was reduced below 10 mg/L in 14 days in the DM treatment, 14.5 days in the DMB18%, and 10 days in DMB22%. Analysis of the normalized data to % NO_3^- - N removal is shown in Figure 13b. The DMWs all had % NO_3^- - N removal efficiencies greater than the control. Treatment in the DMB22% wetlands was significantly greater than in the DM treatments, but there were no differences in the treatment observed between the DM and the DMB18% wetlands. Table 5 shows the probability values produced in statistical analysis of the DMWs.

Batch 5 – February 12th - March 6th, 2002

Batch 5, conducted February 12th – March 6th, 2002 was the first batch conducted in 2002, and was the only winter batch in the study. The goal for initial NO_3^- - N concentration in this study was 30 mg/L. The wetland mesocosms had remained saturated since the last study in October of 2001 (Batch 4). Above-ground biomass had been harvested in all of the wetland treatments, and 30% of the biomass dry weight from each mesocosm had been added back prior to start-up to simulate litter accumulation. During the study, the biomass tended

to float in the mesocosms. A small number of new shoots in some of the wetland mesocosms were observed, but they were very sparse. The average temperature in the wetland treatments was 7.5°C, much lower than in the previous batches. The water temperature in the control mesocosms averaged 8.5 °C. The wetland treatments were cooler because the biomass that was floating near the surface reduced heating in the lower depths of the water column. Treatment efficiency of all of the wetlands were severely hindered by the cooler temperatures and the lack of actively growing biomass.

Figure 14a shows the NO_3^- - N treatment curves for the SSWs based on the average concentrations within each treatment. Immediately evident is a tightness of the data on day 1 of the batch study, not observed in the previous batches. Lack of standing biomass allowed for better mixing and dispersion of the NO_3^- - N in the mesocosms. The range of the control replicates was 39-40 mg/L, while the range of the SSW replicates was between 35-39 mg/L. The maximum % difference between the SSWs average initial NO_3^- - N concentration was less than 2%. The difference between the average initial NO_3^- - N concentrations between the SSWs and the control was about 6%. Therefore analysis of difference in treatment was more reliable. Treatment in this batch was very slow. It took over three weeks for NO_3^- - N to be reduced below 20 mg/L. Normalization of these data to account for the slight differences in starting NO_3^- - N concentrations is shown in Figure 14b. Again, day 1 data were represented by day 0 in these % NO_3^- - N removal curves. All of the SSWs performed better than the control in removing NO_3^- - N, but there were no differences between them, as described by the P values in Table 6.

NO_3^- - N concentration data for the DMWs are shown in Figure 15a. All of the DMB22% replicates were included in this batch and those thereafter. The initial

concentration range of all replicates on day 1, 32-41 mg/L, and the range of the average initial concentrations, 34-37 mg/L (8% maximum difference), was slightly greater than what was observed in the SSWs, but still better than in the previous batches. The DMB22% reduced the NO_3^- - N to below 20 mg/L in 19 days, while the DM and DMB18% treatments took 21 days to reach this level. Normalization of the concentration data to % removal as with the SSW data is shown in Figure 15b. All of the DMWs treated the NO_3^- - N more effectively than the control. There was no difference in treatment between the DM treatment and the DMB18% and DMB22% treatments. However, the DMB22% treatment slightly outperformed the DMB18% treatment (P=0.0181). Table 6 lists the P values generated during analysis of this data.

Change of wetland batch study mixing protocol

After investigating the various reasons for the inconsistent initial NO_3^- - N concentrations in the batches (i.e. quality of calcium nitrate used, calculation errors, errors in measurement of the volume of drainage water added), the problem was finally traced to a poor mixing protocol during the start-up of each of the batches in 2001. This conclusion was based mainly on the improved success in initializing more consistent NO_3^- - N concentrations in Batch 5, where there was no standing bulrush in any of the treatments. The original protocol appeared to be adequate for the control treatment (aside from the problem of redispersion of NO_3^- - N), but inadequate for the other treatments, due to the density of the biomass that restricted mixing.

A lab test showed that consistent concentrations could be obtained by pre-mixing the water with NO_3^- - N in a 470L tank prior to addition to the wetlands. The calcium nitrate

decahydrate ($Ca(NO_3)_2$ x 10 H_20) needed to achieve initial NO_3^- - N concentration goals was also evaluated more closely. The reported moles of H_20 attached to the $Ca(NO_3)_2$ is an estimate, and may vary from bottle to bottle or if it is exposed to air. Based on chemical analysis of the water during the mixing test, a more exact correlation between NO_3^- - N concentrations and calcium nitrate additions was obtained.

The new mixing protocol and the new calcium nitrate addition relationship was utilized in Batches 6-8. The result was highly satisfactory initial NO_3^- - N concentrations for each of these batches. Even though the initial NO_3^- - N percent differences between the replicates were very small, the data were still normalized to % NO_3^- - N removal for statistical analysis. The data were analyzed from the actual day 0 concentration, which was measured directly from the mixing tank prior to loading of each wetland mesocosm. Very little difference was observed between the graphical representation of the data as NO_3^- - N concentration or % NO_3^- - N removal in Batches 6-8.

Batch 6 – May 7th-22nd, 2002

Batch 6 was conducted from May 7th-22nd, 2002, with a target initial NO_3^- - N concentration of 30 mg/L. Actual initial NO_3^- - N concentrations averaged 32 ± 1 mg/L across all treatments. Biomass growth had started a few weeks later than in 2001, and freezing temperatures had slowed growth early in the season. Well over 50% of the bulrush above-ground biomass for the growing season was present at the onset of the batch. Water temperature averaged 17.8°C in the wetland treatments during Batch 6. Despite slightly cooler water temperatures, and less than 100% of the bulrush stand established, the wetlands performed well in NO_3^- - N treatment.

Figures 16a and b show the NO_3^- - N concentration and percent removal data for the SSWs. Concentrations of NO_3^- - N were reduced to 5 mg/L in 10, 7, and just over 8, days in the SS, SSB11%, and SSB16% respectively. Analysis of % NO_3^- - N reduction data revealed significant increases in NO_3^- - N treatment in all of the SSWs when compared to the control. The site soil blends (SSB11% and SSB16%) outperformed the SS wetlands. However, the SSB11% and SSB16% wetland treatment curves were not significantly different. Probability values for equality between the treatments are given in Table 7.

Figures 17a and b show the NO_3^- - N concentration and percent removal curves for the DMWs. Reduction of NO_3^- - N to an average of 5 mg/L took 8.5 days in the DM treatment, 10 days in the DMB18% treatment, and 5.5 days in the DMB22% treatment. The P values, generated during the analysis for equality between the DMWs treatments, based on the % NO_3^- - N removal curves are shown in Table 7. Significantly greater NO_3^- - N removal was observed in all of the DMWs when compared to the control. Reduction of NO_3^- - N was significantly greater in the DMB22% when compared to the other DMWs, but there was no difference in removal observed between the DM and the DMB18% wetlands.

Batch 7 – June 11-26, 2002

Batch 7 was a 15-day summer batch study, and was conducted from June 11^{th}-26^{th}, 2002. The target initial NO_3^- - N concentration was doubled from Batch 6 to 60 mg/L. Actual average initial concentration was 58 ± 1 mg/L NO_3^- - N across all of the treatments. The bulrush stand was almost fully established at the time of this study. Average water temperature in the wetland mesocosms was 23.2 °C during the batch study. All of the wetland treatments performed well in treating this elevated level of NO_3^- - N.

Figures 18a and b show the SSWs NO_3^- - N treatment curves in terms of concentration and percent removal. NO_3^- - N levels were reduced below 10 mg/L in slightly over 13 days, in slightly under 9 days, and in slightly under 11 days in the SS, SSB11%, and the SSB16% wetland treatments, respectively. Analysis of the % NO_3^- - N removal curves reveal that the SSB11% wetlands outperformed all of the other SSWs and the control. The NO_3^- - N removed in the SSB16% wetland treatment exceeded that in the SS treatment and the control, while the SS wetland treatment exceeded the NO_3^- - N removal in the control. Table 8 shows the probability values generated during analysis of equality between the treatments.

Figures 19a and b show the plots of NO_3^- - N removal on the basis of concentration and percent removal for the DMWs. The DM treatment took 10.5 days to reduce NO_3^- - N levels below 10 mg/L. The DMB18% wetlands reached this level in nearly 12 days, while the DMB22% wetlands attained this level in only 6.5 days. Percent NO_3^- - N removal curves, when analyzed for equality, showed that all of the DMWs removed NO_3^- - N more quickly than in the control. The DMB22% wetlands reduced NO_3^- - N significantly faster than the other two DMW treatments. There was no difference in the NO_3^- - N treatment observed between the DM and the DMB18% wetlands. The P values for this analysis are listed in Table 8.

Batch 8 – July 2nd - 24th, 2002

This final batch study was conducted from July 2nd – 24th, 2002. The initial target NO_3^- - N concentration was once again doubled compared to the previous batch to 120 mg/L. The actual average initial NO_3^- - N concentrations in all treatments was 117 ± 3 mg/L

(neglecting one outlier of 110 mg/L in replicate A of the SSB11% treatment). The average water temperature in this batch was the warmest observed in the entire study at 24.3 °C.

Figures 20a and b give the NO_3^- - N removal curves based on concentration and percent removal. Treatment was good in all of the SSWs during this batch. NO_3^- - N concentrations were reduced to 10 mg/L in 19.5 days, 15 days, and in slightly over 17 days in the SS, SSB11%, and SSB16% wetland treatments, respectively. Analysis of the percent removal curves indicated significant increases in NO_3^- - N reduction in the SSWs over the control. The SSB11% wetlands outperformed the SS wetlands in NO_3^- - N removal, but no difference in treatment efficiency was found when compared to the SSB16% wetlands. The SSB16% wetlands showed treatment that was slightly higher than the SS wetlands (P=0.0341). All P values for this analysis can be found in Table 9.

The NO_3^- - N removal curves as concentration and as percent removal for the DMWs are shown in Figures 21a and b. Treatment observed in the DMWs was also good, especially in the DMB22% wetlands. NO_3^- - N was reduced to 10 mg/L in only 11.5 days in the DMB22% wetland treatment, while it took the DM and the DMB18% wetland treatments about 18.5 days. Clearly, the DMB22% wetlands outperformed the rest of the DMW treatments, and this was verified during analysis of the % NO_3^- - N removal curves. The DMWs as a whole reduced NO_3^- - N faster than the control, but there was no difference in efficiency between the DM and the DMB18% wetlands. Table 9 lists the P values generated during analysis.

Discussion of NO_3^- - N Removal Studies

With the exception of Batch 1, Batch 4 and Batch 5, representing the initial, the Fall and the Winter batches respectively, the constructed wetlands performed well in NO_3^- - N removal. Statistical analysis of the % NO_3^- - N removal revealed many differences in treatment efficiency between the wetland treatments.

Summary of treatment differences observed in Batches 1-8

Table 10 summarizes the differences in NO_3^- - N treatment observed at the P=0.05 level between the SSWs with OM addition (SSB11% and SSB16%) and the wetland treatment with no OM addition (SS). At least one of the wetland treatments with OM addition outperformed the SS treatment in Batches 1-4 and 6-8. There was no advantage observed in OM addition to wetland substrate in Batch 5, which was conducted during the winter months. Probability values between 0.01 and 0.05 were observed in Batches 1, 4, and 8 (for the SSB16% only), so for these batches, the differences appeared to have small significance. P values in Batches 2, 3, 6, 7, 8 (for the SSB11% only) indicated that the increased treatment observed when compared to the SS wetlands was strongly significant (P values <0.01). The differences in NO_3^- - N treatment between the DMWs with OM addition (DMB18% and DMB22%) and the wetland treatment with no OM addition (DM), are also summarized in Table 10. An advantage in OM addition in improving NO_3^- - N removal was observed in the DMWs in Batch 1-4 and 6-8, but only in the DMW22% wetlands. All of the P values indicated that these differences were strongly significant (P values < 0.01) except in Batch 4 (P = 0.0294). Therefore, no advantage in NO_3^- - N treatment was observed until OM levels reached 22% in the DMWs.

Table 11 summarizes the head-to-head differences at the P=0.05 level between the wetlands amended with OM. Treatment differences between the SSB11% and the SSB16% wetlands were observed only in Batch 7, so there appears to be no advantage in increasing OM contents in the wetland substrate to 16%. On the other hand, additions of OM to the DMWs had to reach 22% before an advantage in treatment was observed. The DMB22% wetland outperformed the DMB16% wetlands in Batches 2, 3, 5, 6, 7, and 8. P values indicated that these differences were strongly significant (P values < 0.01) in Batches 3, 6, 7 and 8, and less significant (0.01< P < 0.05) in Batches 2 and 5.

Days required for 90% NO_3^- - N removal

Calculating the average number of days required for each wetland treatment to remove 90% of the initial NO_3^- - N concentration is a simple way to visualize and assess the magnitude of the effect of OM addition to substrate on wetland NO_3^- - N removal. This is also helpful in reinforcing the idea that fewer days required for treatment may imply a reduction in the wetland area required. As the time required for treatment decreases, the size of the wetland may be reduced. Figures 22 and 23 show the average days (rounded up to the next 0.5 day) required to remove 90% of the NO_3^- - N in Batches 1-8 for the SSWs and the DMWs, respectively. Despite the problems in initial concentrations in Batches 2-4, the same trends are evident in Batches 6-8 when more reliable data was collected. In 6 of the 8 batches, the SSB11% wetlands achieved 90% removal in the fewest days of all the SSWs. By averaging the days required for 90% removal in all batches (except those where 90% removal was not reached -Batches 4 and 5), the SS, SSB11%, and the SSB16% wetlands averaged 13.9, 9.2, and 11.1 days, respectively. In the DMWs, 90% NO_3^- - N removal was

achieved in the fewest days by the DMB22% treatment in all of the batches that were long enough for 90% removal to be reached (7 out of 8). There was no difference in the overall average number of days require to achieve 90% reduction in the DM and the DMB18% wetlands (slightly over 11 days), but the DMB22% averaged only 7.4 days. Though it was not the goal to evaluate SSWs versus DMWs, these comparisons indicate that the wetlands with the dredged material based substrates removed the NO_3^- - N more efficiently than the wetlands with the site soil based substrates. Based on this analysis, the DMB22% wetland treatment appears to be the top overall performer, regardless of substrate type, in removing 90% NO_3^- - N most quickly.

Effect of Temperature, Season, pH, Dissolved Oxygen, and Redox on NO_3^- - N removal

Water temperature, season of the year, pH, DO, and substrate Eh potential are parameters affecting NO_3^- - N treatment within wetland systems. Changes in some of these parameters were also useful in describing processes occurring within the wetlands.

Temperature

Air/water temperature affects NO_3^- - N removal rates. Warmer water temperatures tend to increase denitrification rates (Knowles, 1982). Figures 24-31 show the water temperatures measured hourly during each batch study. The most rapid NO_3^- - N removal occurred in the Spring and the Summer, when warmer air temperatures increased wetland water temperatures. The effects of cold water temperatures were obvious in Batch 5, where the greatest NO_3^- - N removal was only about 50%. The colder water temperatures slowed activity of the denitrifying microbes within the substrate. In addition, colder water has a

greater capacity to hold DO. This effect, coupled with reductions in microbial activity that also reduced the effectiveness of aerobic microorganisms in the wetland system to deplete oxygen, resulted in higher DO concentrations which hindered denitrification.

Seasonal effects

During the batch studies, there appeared to be a seasonal effect on NO_3^- - N reduction within the wetlands, which was not necessarily strongly correlated with temperature. Water temperatures in Batch 4 (Fall) and Batch 6 (Spring) were about 18 °C, but NO_3^- - N removal observed in Batch 6 was much faster than in Batch 4. While only speculation, the growth stage of the bulrush may offer an explanation for the difference. The bulrush was rapidly growing during the Spring, but in the Fall the growth was reduced and even undergoing senescence. Nutrient uptake by wetland plants from the water column is generally considered small (10-20%). Nevertheless, this small amount of NO_3^- - N uptake by the plants may have been reduced during the end of the growing season.

Evapotranspiration in this study was extremely high in the wetland mesocosms. Values between 1 and 2 cm/d were measured from the late Spring to the early Fall. Appendix 3-A gives an example of these measurements. Reduced ET in the wetlands at the end of the growing season is also shown in Appendix 3-A. This reduction in transpiration by the bulrush in the Fall could have reduced the amount of NO_3^- - N that was translocated into the anaerobic zones within the substrate. This could limit the amount of NO_3^- - N that encounters zones where denitrification can occur, reducing wetland treatment effectiveness.

Dissolved Oxygen

Denitrification occurs only under anaerobic conditions, so maintaining low DO near the substrate/water interface is critical in achieving effective NO_3^- - N removal. Table 12 shows the average DO readings in the wetlands during the batch studies. Poorer than expected removal observed in Batch 1(12 mg/L) was most likely a result of high DO conditions at the onset of the study. This occurred because the wetlands had not been saturated sufficiently to create anoxic conditions near the substrate prior to loading. DO levels at the soil-water interface were between 4-7 mg/L at the onset of the study, and did not fall to or below 1 mg/L until at least 5 days into the study. This most likely limited denitrification in the wetland treatments. Average DO in the wetland treatments in Batch 1 was higher than in all of the batches except the winter Batch 5. As mentioned earlier, colder temperatures reduced microbial uptake of oxygen and increased DO saturation capacity in the water column. This combination reduced the potential for denitrification as evidenced by the low NO_3^- - N removal.

The control treatment was consistently supersaturated with dissolved oxygen down to the substrate-water interface during the hours when the measurements were made. The growth of algae in the controls was extensive, because there was no bulrush to provide shading. Virtually no algae were observed growing in the other wetland treatment mesocosms, due to shading by the wetland vegetation. Photosynthesis by the algae played a large role in increasing DO levels in the water column during the daylight hours. Reaeration also contributed to increased DO levels in the controls more than in the wetland treatments, because thick stands of tall wetland plants such as bulrush dampen wind action on the water column.

In 2001 (Batches 1-4), the bulrush in the SS wetlands was more sparse than the rest of the wetland treatments, and consistently possessed slightly higher DO levels than the other wetland treatments. This may also be attributed to an increase in reaeration when compared to the other wetland treatments with denser stands of bulrush. This slight increase in DO may have contributed to lower denitrification at the substrate-water interface by reducing the number of anaerobic microsites available, resulting in the decreased NO_3^- - N removal observed.

pH

Denitrification potential is maximized at pH values between 7-8 (Knowles, 1982; Kadlec and Knight, 1996). Microbial enzymes responsible for the reduction of NO_3^- completely to N_2 are inhibited at low pH (Sylvia et al., 1998). Average pH values near the substrate-water interface for the wetland treatments and the control are listed in Table 12. pH in all of the wetland treatments averaged between 6.0 and 6.5, just below the optimum level for denitrification. The pH of the drainage water used in the study ranged from 5.0 - 6.0. Therefore, pH in this study may have limited denitrification rates, but the magnitude of the effect is unclear.

The process of denitrification tends to increase pH in treatment systems because of the formation of OH^- (Metcalf and Eddy, Inc., 1991). Formation of OH^- results in increased alkalinity in the water column, but this was not measured. Increases in pH were observed in all of the wetland treatments during the batch studies. Increases were generally on the order of 0.5 units through each batch study. These increases were not helpful in evaluating the

magnitude of denitrification that was occurring, but this supports the idea that denitrification was occurring within the wetland treatments.

pH levels were higher in the control. The growth of algae in these mesocosms is most likely responsible for these observations. During photosynthesis, CO_2 is removed from the water as the carbon source for algal biomass production. This affects the carbonate equilibrium within the water column, causing a shift that reduces the H^+ within the water column, resulting in an increase in pH, but not in alkalinity (Wetzel, 1983; Sawyer et al., 1994). If alkalinity in the controls had been measured, changes in pH due to photosynthesis and not denitrification could have been verified if no change in alkalinity in the water column was observed.

Substrate Redox (Eh*)*

Average substrate redox for each treatment is shown in Table 13. Readings were taken at the 2 cm and 15 cm depth. It is generally accepted that denitrification may occur at Eh values less than 350 mV, with complete NO_3^- - N reduction expected at Eh values of 220 mV (Ponnamperuma, 1972; Engler and Patrick, 1974; Kadlec and Knight, 1996). Average Eh values during all of the studies in all of the treatments, including the control, were below these critical values. The average Eh at 2 cm was –32 mV, with a range of 141 to –161 mV. The average Eh at 15 cm was –117 mV, with a range of 22 to –238 mV. Eh values at 2 cm were slightly higher due to a higher potential for oxygen at that depth, as well as an increased density of bulrush roots in the wetland treatments that increase oxygen levels in that zone. Addition of OM to the wetland substrate did not appear to strongly influence the reduction of Eh values below the critical level for denitrification. However,

wetlands with increased OM had a larger pool of carbon critical for maximizing denitrification rates at these Eh values.

Wetland Biomass

Providing OM and nutrients to the substrate to support increased denitrification rates early in the life of a wetland may also be beneficial in enhancing wetland plant growth, the ultimate renewable carbon source. Besides providing carbon when the plants decay, increased biomass also may help nitrate diffuse into the subsurface by increasing permeability of the upper reaches of the wetland substrate, and by translocating water into the substrate during transpiration. Increased biomass can also translate into increased microbial attachment sites below the substrate surface and in the decaying litter produced through the years, which can increase microbial activity. Increased amounts of biomass within a treatment wetland will also inhibit algae growth through shading. This will decrease reaeration possibly resulting in an increase of anaerobic processes. By providing nutrients (from OM and BIONSOIL™) to the wetland substrate prior to planting, wetland plant growth may be accelerated to reach the production more commonly observed in older wetlands. If this is accomplished, the wetland will function more efficiently in removing NO_3^- - N at an earlier age.

Figures 32 and 33 shows the yearly mass of above ground *Scirpus validus* in the wetland treatments in 2000 (before nitrate addition), 2001, and in 2002. Average growth for bulrush is about 2000 g/m^2 in full-scale wetlands systems (Reed et al., 1995). This level was not reached in 2000, the year used to establish the bulrush, in any of the wetland treatments. However, the above-ground biomass produced in all of the wetlands were significantly

greater in 2001 and 2002, and all of the wetland treatments exceeded 2000 g/m^2 on average. The most striking observation is the increase in biomass from 2000 to 2001. In 2001, all of the site SSWs at least doubled the biomass produced in 2000, while each of the DMWs nearly doubled their biomass. There was no difference in biomass growth in 2002 when compared to 2001.

Figures 32 and 33 also show the differences in above ground biomass production between wetland treatments within each year. In 2000, there was no difference between the SSWs. In 2001 however, the growth in SSB11% and SSB16% significantly exceeded that of the SS wetlands. The vegetation in the SS treatment wetlands was much more sparse, and the shoots were thinner and shorter than the rest of the treatments. This supports the idea that the increased OM and nutrients can increase production of biomass early in the life of the wetland, in this case within the first two years. In 2002, there was no difference in biomass production between the SSWs. Essentially, (neglecting the first year of wetland establishment) the SS wetland treatment took an extra growing season to equal the yearly production of above-ground biomass of the SSB11% and SSB16% wetland systems with added nutrients. Differences within the DMWs were not observed in any of the years. Nutrients within the DM treatment were much less limiting than in the SS treatment at the beginning of the study (see Table 1), and it appears that nutrient enhancement had a greater affect on biomass production in the SSWs than in the DMWs.

Engineering a wetland substrate, in relation to wetland plants, could prove to be beneficial with respect to economics and downstream water quality. Looser wetland soils, like those we created by adding cellulose, encourage root and rhizome penetration (Allen et al. 1989), and may encourage faster and denser wetland plant colonization. This could be

cost effective because fewer plants may be required in the initial planting of a constructed wetland system. Care must be taken, however, in the amount of organic material added, because soils with high organic matter are not well suited to physically support macrophytes (Allen et al., 1989). The lower biomass production of the SSB16% wetland when compared to the SSB11% wetlands, even though the SSB16% blend was higher in nutrients, could be related to the low bulk density of the blend, which made it difficult for the plants to become established in 2000. This could be a serious engineering drawback when considering manufacturing substrate for full-scale wetland systems. The high nutrient content of the manufactured substrates reduces the amount of fertilizers required to maintain growth of wetland vegetation. This could help protect downstream water quality because fertilizing vegetation in flooded systems is difficult, and improper application can lead to larger export of nutrients from a constructed wetland (Allen et al., 1989).

Denitrification or Plant Uptake?

Discussion regarding NO_3^- - N reduction in the wetlands thus far has centered around denitrification, while in fact, the contribution of denitrification in the wetlands is unclear because it was not measured directly. Plant uptake is generally regarded as a minor factor in NO_3^- - N reduction in constructed wetlands, but can account for as much as 16-75% of total N uptake in a wetland (Reddy and DeBusk, 1987). To determine the contribution of plant uptake in this study, an estimate of plant uptake was conducted for 2002. Once an estimate of plant uptake was known, then the majority of the remaining NO_3^- - N loss could be more accurately attributed to denitrification.

Percent N was measured in the above-ground shoots of the bulrush in each mesocosm before the end of the growing season. With the mass of above-ground biomass in each mesocosm known, the mass of N in the above-ground biomass was calculated. These values can be found in Appendix 3-B.

To estimate the maximum amount of NO_3^- - N that was taken up by the bulrush, some assumptions had to be made. First of all, the below ground biomass was neglected in the calculation, because rhizomes formed in 2002 could not be distinguished from those established in previous years. The growing season for *Scirpus validus* was assumed to occur between March 15 and September 15 (180 days). Before Batch 6 was conducted (May 7), it was observed that approximately 50% of the total biomass had already emerged, so it was assumed that 50% N measured in the final plant biomass had already been assimilated by the bulrush prior to the batch studies. From May 7th - July 24th (72 days), Batches 6-8 were conducted. It was further assumed that an additional 35% of the total biomass growth occurred during this period. Nitrogen uptake rate for each mesocosm between May 7th and July 24th was calculated by

$$N_r = (TN_b \, x \, PG)/t$$

where:

N_r = Nitrogen uptake rate (g/d)

TN_b = Total nitrogen in the biomass in each mesocosm in 2002 (g)

PG = Percent growth (0.35 for the period May 7th - July 24th)

t = 72 days

The nitrogen uptake rate during the period of May 7th-July 24th was assumed to be constant.

The nitrogen uptake rates for each of the wetland mesocosms averaged 0.34 g N/d, with a range of 0.28 – 0.42 g N/d. The wetland biomass was exposed to the NO_3^- - N for a total of 52 days during Batches 6-8, so the mass of nitrogen assimilated by the plants during this period was estimated by multiplying N_r for each mesocosm by 52 days. Approximately 100 g of NO_3^- - N was introduced to each of the mesocosms during Batch 6-8. Any residual NO_3^- - N remaining after each study was subtracted from the initial mass of NO_3^- - N to obtain a total mass of NO_3^- - N removed during each study. Percentage of maximum plant uptake was then calculated by dividing the estimated total mass of plant NO_3^- - N uptake in Batches 6-8 by the total NO_3^- - N removal in Batches 6-8. Appendix 3-C shows these calculated results.

On average, a maximum of 18% of the NO_3^- - N removal observed in these batches was estimated to be due to plant removal. That leaves 82% of the NO_3^- - N unaccounted for; an amount that was most likely lost through denitrification. This estimate supports the original assumption, and the assumptions and observations of other researchers, that the majority of the losses of NO_3^- - N in these wetlands was due to denitrification – the mechanism of NO_3^- - N removal that was the goal in the design of these wetlands.

As mentioned earlier, the estimate of plant N uptake was conservative. Bachand and Horne (2000b) agree; they estimated N uptake by the plants to be somewhere around 10%. There are several reasons. The assumption that the bulrush did not utilize soil N during this time is not supported, because substantial N removal was observed in the wetland substrate during the course of the study (see Appendix 3-D). Wetland plants usually utilize ammonia as an N source, because NO_3^- - N is not available for uptake in highly reduced soils. As observed in Table 13, the soils in these wetlands possessed Eh values far less than 350 mV,

so it was likely the majority of the NO_3^- - N diffusing into the substrate would be denitrified before reaching the bulrush roots. This would make it more unlikely that large amounts of NO_3^- - N would be extracted from the water column, and would lend support to the possibility of denitrification playing a larger role in NO_3^- - N removal in these wetlands than estimated.

Implications of Research

Wetland sizing

By increasing wetland treatment with OM addition, the time required for treating NO_3^- - N to a particular level is reduced. Therefore, less area would be required for a wetland that performs more efficiently. Reduced wetland area results in reduced cost with regards to property acquisition and construction. This section attempts to compare the wetland area required to treat drainage water from a watershed, based on the results observed for each of the wetland treatments evaluated in this study.

Most researchers regard NO_3^- - N reduction in wetlands as a first order process (Reed et al., 1995; Kadlec and Knight, 1996) expressed mathematically as

$$\frac{C}{C_o} = e^{-kt}$$

where

C = Concentration at time t (mg/L)

C_o = Initial concentration (mg/L)

k = Removal rate constant (d^{-1})

t = time (d).

This model was used to estimate k for each mesocosm during each batch in 2002. Once this k was determined the wetland area required for NO_3^- - N treatment could be estimated by (Reed et al., 1995):

$$A_s = \frac{Q\,ln\left(\frac{C_e}{C_o}\right)}{k_{NO_3}\,yn}$$

where

A_s = Surface area of the wetland (m^2)

Q = Flow into the wetland (m^3/d)

C_e = Target effluent NO_3^- - N concentration (mg/L)

C_o = Initial NO_3^- - N concentration (mg/L)

k_{NO3} = NO_3^- - N removal rate constant (d^{-1})

y = Depth of water in the wetland (m)

n = porosity of the wetland (0.65 – 0.75).

The wetland was sized to treat water from a 50 ha subwatershed located at the NCDA – Tidewater Research Station near Plymouth, N.C. The site received swine waste applications, and was drained with ditches and tile lines. Unpublished data collected from 1996-2000, from the outlet canal of this subwatershed, was used to estimate flow and NO_3^- - N concentrations that would enter the wetland. Daily flow was estimated to be 3000 m^3/d (97% of the daily flow events were less than this value). The flow-weighted average NO_3^- - N concentration in the drainage water was 5 mg/L. To comply with the

Neuse River Rule, whose goal is to reduce non-point source pollution N by 30%, the target NO_3^- - N concentration for the wetland effluent was chosen to be 3 mg/L, a 40 % reduction.

Batch 5 and Batch 6 were chosen to calculate k_{NO3} for NO_3^- - N reduction in each of the wetland treatments in cold and warm temperatures, respectively. The initial NO_3^- - N concentration was about 30 mg/L in both of these batches. Ideally, concentrations would have been closer to 5 mg/L initially to calculate k_{NO3}. The value of k_{NO3} was estimated using the following equation, which represents the slope of ln (C_e/C_o) vs. t.

$$k_{NO_3} = -\left(\frac{ln \frac{C_e}{C_o}}{t} \right)$$

For Batch 6, values for C_o and C_e used day 1 and day 10 NO_3^- - N concentrations of each of the wetland treatments. For the Batch 5 calculations of $k_{NO3,}$ day 1 NO_3^- - N concentrations were used for C_o and day 15 NO_3^- - N concentrations were used for C_e. This was done to achieve a better fit to the first order model. To be first order, the ln (C_e/C_o) vs. t relationship should be linear. The data for Batch 5 and 6, as well as the other batches, did not perfectly fit this model, especially the data at the beginning and the end of each batch study. Excluding the NO_3^- - N concentrations values at the beginning and the end of each batch improved the fit, as was evidenced by increased r^2 values when a linear regression was applied to this reduced data set. Appendix 3-E shows the graphical relationships used in calculating k_{NO3} for both of these batch studies.

Table 14 shows the areas required for each of the wetland treatments studied to reduce NO_3^- - N from 5 mg/L to 3 mg/L. Water temperature averaged about 18 °C in Batch 6. The wetland area required for treatment was reduced by OM addition in both the SSWs and the DMWs. The area required for a wetland constructed like SSB11% was 48% smaller than a wetland constructed with site soil alone. Similarly, a wetland constructed like DMB22% would require 52% less area than one constructed with DM alone as the substrate. Batch 5 was used to determine k_{NO3} during the winter. The average temperature, for this batch was 7.5 °C. There was a huge increase in wetland area required for treatment at these temperatures, and there appeared to be no advantage gained in wetland area reduction by OM addition to the substrate during the winter.

The accuracy of these area estimates can be evaluated against a model used by Reed et al. (1995) for the calculation of k_{NO3}:

$$k_{NO_3} = 1.000(1.15)^{(t-20)}$$

for temperatures above 1°C. At a water temperature of 18°C, this equation yields a k_{NO3} value of 0.75 d^{-1}. Wetland area required to reduce NO_3^- - N from 5 mg/L to 3 mg/L, based on this value, would be 0.8 ha. Values for k_{NO3} from this study ranged from 0.19 – 0.55 d^{-1}, with the resulting wetland areas ranging from 1.1 – 2.1 ha. For winter conditions with water temperature of 7.5 °C, k_{NO3} calculated from the Reed et al. (1995) equation would equal 0.17 d^{-1}. The wetland area required for treatment under these cold conditions would be 2.3 ha using the calculated value for k_{NO3}. Winter values for k_{NO3} in this study were much lower than the calculated value, ranging from 0.011 to 0.02, resulting in wetland areas over 20 ha.

Values for k_{NO3} generated from this study to treat low levels of NO_3^- - N may have been more accurate had a batch been run with initial NO_3^- - N concentrations <10 mg/L in the summer and the winter. However, wetland areas estimated using the Batch 6 data appeared to be reasonable, and would be a safer design than the Reed et al. (1995) estimate, which may tend to underestimate area requirements. Estimates using the Batch 5 data for winter conditions resulted in extremely large wetland areas, which would not be practical to construct from a cost standpoint. Like the warm weather estimate, the Reed et al. (1995) estimate for area required during the winter months may have also been underestimated. Nevertheless, much more wetland area is required for treatment during the winter months. Area could be minimized with control structures upstream from the wetland, which could reduce the flow of water entering the wetland, and by raising the water level within the wetland to 1 m, which would double the hydraulic retention time of the water within the wetland.

Dredged material in treatment wetlands

The use of dredged material to construct wetlands is not a new idea, and has been implemented on many sites. The use of dredged material in *treatment* wetlands is an idea that is just now receiving attention. Results of this research indicate that dredged material, with and without OM addition, is very efficient in the treatment of NO_3^- - N. The U.S. Army Corps of Engineers spend millions of dollars each year maintaining and building confined disposal facilities (CDFs) to store material dredged from waterways in the U.S. Alternative uses for this material could save the Corps a substantial amount of money each year. Dredged material has been used as an ingredient in topsoil, landfill covers, and in

construction materials to name a few, but treatment wetlands appear in this research to be feasible as another alternative. Locations near dredging operations would be ideal for the use of dredged material as a substrate in constructed wetlands. Incorporation of *Phragmites* as an OM source not only would help the wetlands improve treatment efficiency, but removing *Phragmites* from the CDF opens space for more storage of dredged material. In addition to agricultural drainage, wetlands of this sort could be used for tertiary treatment of municipal wastewater, as well as in the treatment of stormwater, wastewater from small, isolated developments, landfill leachates, and golf course runoff.

CONCLUSIONS

Manufacturing substrate for constructed wetlands, for treatment of NO_3^- - N-laden waters, is a promising method of improving the substrate at sites with less than ideal soils. All wetland treatments showed significantly improved treatment of NO_3^- - N when compared to the control. Addition of organic matter to the site soil (Cape Fear Loam, with 5% OM initially) and the dredged material (with 12% OM initially) increased NO_3^- - N removal efficiency in 7 out of 8 batch studies conducted. The added OM appears to have created an environment at the substrate-water interface that increased the potential for denitrification. Nitrate-nitrogen removal slowed considerably in the winter, and the additional OM in the substrate did not significantly improve removal. OM addition to the SSWs from 11% to 16% did not improve treatment efficiency of the wetlands. However, improvement in treatment efficiency in the DMWs was observed by increasing OM from 18% to 22% in 7 of the 8 batch studies.

Above-ground biomass, the wetlands ultimate renewable carbon source critical in maximizing denitrification rates, was evaluated for enhancement by substrate OM and nutrient additions. After establishment in 2000, growth of *Scirpus validus* in all of the mesocosms exceeded 2000 g/m^2. Increased OM addition and nutrients to the SSWs significantly increased biomass growth in 2001, but not in 2002. This supports the hypothesis that enhancement of nutrient-poor soils used for wetland substrate may reduce the time required for wetlands to reach production levels common in more mature wetlands. OM and nutrient addition to the DMWs had no effect on biomass production, but the DM soils were initially richer in nutrients than was the site soil.

The use of dredged material as a wetland substrate in treatment wetlands appeared to be feasible. Though it was not a goal to compare the efficiency of the SSWs and the DMWs, the DMWs appeared to outperform the SSWs in most of the batch studies, and the DMB22% treatment was the overall top performer in NO_3^- - N removal. Using dredged material in constructed wetlands may be an alternative to costly disposal, and may prove to be a better alternative for wetland substrate than soils located near the site where the wetland is to be constructed.

Overall, it appeared that the wetland substrates containing over 11 % or more OM may have increased NO_3^- - N treatment efficiency. Increased OM content of the wetland substrate may help to jump-start nitrate removal efficiencies in the early years of establishment, providing carbon and reduced conditions critical for denitrification. Improving NO_3^- - N removal efficiency reduced the time required for treatment, and can reduce area requirements for wetlands, making their use more economically feasible. Denitrification was most likely the major contributor of NO_3^- - N removal, based on conditions measured in the wetland substrate and the substrate/water interface, and on an estimate of plant N uptake during the batch studies. The combination of substrate organic matter and increased biomass production, which will serve as a renewable carbon source to the wetland, will help maintain ideal conditions for denitrification and subsequently high nitrate removal in these constructed wetlands during the life of the system.

Table 1. Description of the wetland substrate conditions tested (± indicate 1 standard deviation)

Substrate	Substrate Type	ID	Plants ?	Bulk[1] Density g/cm^3	Organic Matter %	Carbon %	Total N mg/Kg	Total P mg/Kg
Cape Fear Loam	Soil	Control	No	1.01 ± 0.09	5.49 ± 0.23	2.38 ± 0.34	1526 ± 213	262 ± 14
Cape Fear Loam	Soil	SS	Yes	0.93 ± 0.08	5.10 ± 0.56	2.21 ± 0.28	1463 ± 165	262 ± 14
Cape Fear Loam + Straw + BION™	Blend	SSB11%	Yes	0.63 ± 0.10	10.57 ± 1.50	4.40 ± 0.70	3867 ± 618	2551 ± 174
Cape Fear Loam + Straw + BION™	Blend	SSB16%	Yes	0.34 ± 0.04	15.89 ± 1.30	5.98 ± 0.60	4621 ± 320[2]	2996 ± 294
Dredged Material	Soil	DM	Yes	0.42 ± 0.003	12.40 ± 0.22	5.42 ± 0.09	3848 ± 111	1249 ± 65
Dredged Material + Phragmites Compost + BION™	Blend	DMB18%	Yes	0.44 ± 0.03	17.75 ± 0.74	7.97 ± 0.28	7755 ± 345	4310 ± 383
Dredged Material + Phragmites Compost + BION™	Blend	DMB22%	Yes	0.41 ± 0.02	22.26 ± 1.76	9.84 ± 0.28	9394 ± 845	4502 ± 435

1 - Bulk density as loaded into wetland mesocosms
2 - Only two replicates used in determination of the mean of the SSB16% wetlands

Table 2. Batch 1 P values generated through univariant and multivariate ANOVA procedures to test for equality between the NO_3^- - N percent removal regression equations. No adjustments for multiplicity were made. Numbers in bold indicate significant differences at the $\alpha = 0.05$ experimentwise error rate.

		Probability		
Treatment (Site Soil Wetlands)	**Control**	**SS**	**SSB11%**	**SSB16%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
SS	**<0.0001**		**0.0116**	0.0850
SSB11%	**<0.0001**	**0.0116**		0.6951
SSB16%	**<0.0001**	0.0850	0.6951	
		Probability		
Treatment (Dredged Material Wetlands)	**Control**	**DM**	**DMB18%**	**DMB22%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
DM	**<0.0001**		0.5979	**0.0252**
DMB18%	**<0.0001**	0.5979		0.2033
DMB22%	**<0.0001**	**0.0252**	0.2033	

Table 3. Batch 2 P values generated through univariant and multivariate ANOVA procedures to test for equality between the NO_3^- - N percent removal regression equations. No adjustments for multiplicity were made. Numbers in bold indicate significant differences at the $\alpha = 0.05$ experimentwise error rate.

		Probability		
Treatment (Site Soil Wetlands)	**Control**	**SS**	**SSB11%**	**SSB16%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
SS	**<0.0001**		**<0.0001**	**<0.0001**
SSB11%	**<0.0001**	**<0.0001**		0.1622
SSB16%	**<0.0001**	**<0.0001**	0.1622	
		Probability		
Treatment (Dredged Material Wetlands)	**Control**	**DM**	**DMB18%**	**DMB22%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
DM	**<0.0001**		0.8053	**0.0027**
DMB18%	**<0.0001**	0.8053		**0.0161**
DMB22%	**<0.0001**	**0.0027**	**0.0161**	

Table 4. Batch 3 P values generated through univariant and multivariate ANOVA procedures to test for equality between the NO_3^- - N percent removal regression equations. No adjustments for multiplicity were made. Numbers in bold indicate significant differences at the $\alpha = 0.05$ experimentwise error rate.

		Probability		
Treatment (Site Soil Wetlands)	**Control**	**SS**	**SSB11%**	**SSB16%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
SS	**<0.0001**		**<0.0001**	**<0.0001**
SSB11%	**<0.0001**	**<0.0001**		0.6452
SSB16%	**<0.0001**	**<0.0001**	0.6452	
		Probability		
Treatment (Dredged Material Wetlands)	**Control**	**DM**	**DMB18%**	**DMB22%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
DM	**<0.0001**		0.7286	**0.0017**
DMB18%	**<0.0001**	0.7286		**0.0002**
DMB22%	**<0.0001**	**0.0017**	**0.0002**	

Table 5. Batch 4 P values generated through univariant and multivariate ANOVA procedures to test for equality between the NO_3^- - N percent removal regression equations. No adjustments for multiplicity were made. Numbers in bold indicate significant differences at the $\alpha = 0.05$ experimentwise error rate.

		Probability		
Treatment (Site Soil Wetlands)	**Control**	**SS**	**SSB11%**	**SSB16%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
SS	**<0.0001**		**0.0474**	0.2312
SSB11%	**<0.0001**	**0.0474**		0.7229
SSB16%	**<0.0001**	0.2312	0.7229	
		Probability		
Treatment (Dredged Material Wetlands)	**Control**	**DM**	**DMB18%**	**DMB22%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
DM	**<0.0001**		0.5779	**0.0294**
DMB18%	**<0.0001**	0.5779		0.1130
DMB22%	**<0.0001**	**0.0294**	0.1130	

Table 6. Batch 5 P values generated through univariant and multivariate ANOVA procedures to test for equality between the NO_3^- - N percent removal regression equations. No adjustments for multiplicity were made. Numbers in bold indicate significant differences at the $\alpha = 0.05$ experimentwise error rate.

		Probability		
Treatment (Site Soil Wetlands)	**Control**	**SS**	**SSB11%**	**SSB16%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
SS	**<0.0001**		0.2067	0.3758
SSB11%	**<0.0001**	0.2067		0.7186
SSB16%	**<0.0001**	0.3758	0.7186	
		Probability		
Treatment (Dredged Material Wetlands)	**Control**	**DM**	**DMB18%**	**DMB22%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
DM	**<0.0001**		0.1784	0.2735
DMB18%	**<0.0001**	0.1784		**0.0181**
DMB22%	**<0.0001**	0.2735	**0.0181**	

Table 7. Batch 6 P values generated through univariant and multivariate ANOVA procedures to test for equality between the NO_3^- - N percent removal regression equations. No adjustments for multiplicity were made. Numbers in bold indicate significant differences at the $\alpha = 0.05$ experimentwise error rate.

		Probability		
Treatment (Site Soil Wetlands)	**Control**	**SS**	**SSB11%**	**SSB16%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
SS	**<0.0001**		**<0.0001**	**0.0005**
SSB11%	**<0.0001**	**<0.0001**		0.6630
SSB16%	**<0.0001**	**0.0005**	0.6630	
		Probability		
Treatment (Dredged Material Wetlands)	**Control**	**DM**	**DMB18%**	**DMB22%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
DM	**<0.0001**		0.1210	**<0.0001**
DMB18%	**<0.0001**	0.1210		**<0.0001**
DMB22%	**<0.0001**	**<0.0001**	**<0.0001**	

Table 8. Batch 7 P values generated through univariant and multivariate ANOVA procedures to test for equality between the NO_3^- - N percent removal regression equations. No adjustments for multiplicity were made. Numbers in bold indicate significant differences at the $\alpha = 0.05$ experimentwise error rate.

		Probability		
Treatment (Site Soil Wetlands)	**Control**	**SS**	**SSB11%**	**SSB16%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
SS	**<0.0001**		**<0.0001**	**0.0097**
SSB11%	**<0.0001**	**<0.0001**		**0.0078**
SSB16%	**<0.0001**	**0.0097**	**0.0078**	
		Probability		
Treatment (Dredged Material Wetlands)	**Control**	**DM**	**DMB18%**	**DMB22%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
DM	**<0.0001**		0.2510	**<0.0001**
DMB18%	**<0.0001**	0.2510		**<0.0001**
DMB22%	**<0.0001**	**<0.0001**	**0.0181**	

Table 9. Batch 8 P values generated through univariant and multivariate ANOVA procedures to test for equality between the NO_3^- - N percent removal regression equations. No adjustments for multiplicity were made. Numbers in bold indicate significant differences at the $\alpha = 0.05$ experimentwise error rate.

		Probability		
Treatment (Site Soil Wetlands)	**Control**	**SS**	**SSB11%**	**SSB16%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
SS	**<0.0001**		**0.0004**	**0.0341**
SSB11%	**<0.0001**	**0.0004**		0.3262
SSB16%	**<0.0001**	**0.0341**	0.3262	
		Probability		
Treatment (Dredged Material Wetlands)	**Control**	**DM**	**DMB18%**	**DMB22%**
Control		**<0.0001**	**<0.0001**	**<0.0001**
DM	**<0.0001**		0.9880	**<0.0001**
DMB18%	**<0.0001**	0.9880		**<0.0001**
DMB22%	**<0.0001**	**<0.0001**	**<0.0001**	

Table 10. Summary of when additions of OM to the the site soil (SSB11% *and* SSB16%) and the dredged material (DMB18% *and* DMB22%) resulted in increased NO_3^- - N removal by the wetlands, when compared to no OM addition.

Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Batch 7	Batch 8
Site Soil OM Amended Wetland Treatment(s) Exhibiting Significantly Greater NO_3^- - N Removal Over SS Wetland With No OM Additions							
SSB11%	SSB11%	SSB11%	SSB11%	No Difference	SSB11%	SSB11%	SSB11%
	SSB16%	SSB16%			SSB16%	SSB16%	SSB16%
Dredged Material OM Amended Wetland Treatment(s) Exhibiting Significantly Greater NO_3^- - N Removal Over DM Wetland With No OM Additions							
DMB22%	DMB22%	DMB22%	DMB22%	No Difference	DMB22%	DMB22%	DMB22%

Table 11. Evaluation of which blend outperformed the other in NO_3^- - N removal within the site soil (SSB11% vs. SSB16%) and dredged material (DMB18% vs. DMB22%) wetland treatments

Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Batch 7	Batch 8
Site Soil OM Amended Wetland Treatment Exhibiting Significantly Greater NO_3^- - N Removal							
No Difference	No Difference	No Difference	No Difference	No Difference	No Difference	SSB11%	No Difference
Dredged Material Amended OM Wetland Treatment Exhibiting Improved NO_3^- - N Removal							
No Difference	DMB22%	DMB22%	DMB22%	DMB22%	DMB22%	DMB22%	DMB22%

Table 12. Average DO and pH readings observed 2 cm above the wetland substrate/water interface during **a)** Batch 1 – **h)** Batch 8

a) Batch 1

Treatment	DO(mg/L)	pH
Control	12.59	7.01
SS	3.07	6.11
SSB11%	2.18	6.25
SSB16%	2.30	6.28
DM	2.21	6.18
DMB18%	2.05	6.13
DMB22%	2.09	6.33

b) Batch 2

Treatment	DO(mg/L)	pH
Control	13.61	8.05
SS	1.31	6.19
SSB11%	0.78	6.35
SSB16%	0.78	6.30
DM	0.94	6.51
DMB18%	0.62	6.31
DMB22%	0.58	6.39

c) Batch 3

Treatment	DO(mg/L)	pH
Control	13.74	7.61
SS	0.82	6.24
SSB11%	0.54	6.39
SSB16%	0.53	6.34
DM	0.67	6.41
DMB18%	0.52	6.32
DMB22%	0.41	6.42

d) Batch 4

Treatment	DO(mg/L)	pH
Control	12.22	7.35
SS	2.44	6.39
SSB11%	1.21	6.42
SSB16%	1.23	6.48
DM	1.35	6.44
DMB18%	1.13	6.42
DMB22%	1.06	6.43

e) Batch 5

Treatment	DO(mg/L)	pH
Control	11.24	6.71
SS	6.06	6.47
SSB11%	4.85	6.45
SSB16%	4.87	6.54
DM	5.53	6.51
DMB18%	5.14	6.50
DMB22%	2.99	6.42

f) Batch 6

Treatment	DO(mg/L)	pH
Control	14.80	8.24
SS	2.13	6.14
SSB11%	1.57	6.09
SSB16%	1.59	6.14
DM	1.67	6.13
DMB18%	1.69	6.11
DMB22%	1.15	6.14

g) Batch 7

Treatment	DO(mg/L)	pH
Control	15.68	8.51
SS	1.64	6.43
SSB11%	1.28	6.28
SSB16%	1.33	6.45
DM	1.33	6.29
DMB18%	1.41	6.34
DMB22%	1.08	6.30

h) Batch 8

Treatment	DO(mg/L)	pH
Control	9.96	7.70
SS	1.14	6.50
SSB11%	0.93	6.49
SSB16%	0.89	6.61
DM	1.03	6.47
DMB18%	0.93	6.56
DMB22%	0.89	6.50

Table 13. Average Eh readings (mV) observed 2 cm and 15 cm below the wetland substrate surface **a)** Batch 1 – **h)** Batch 8.

a) Batch 1

Treatment	2 cm	15 cm
Control	-145	-238
SS	-22	-24
SSB11%	67	-15
SSB16%	-40	-127
DM	91	17
DMB18%	-36	22
DMB22%	-40	-115

b) Batch 2

Treatment	2 cm	15 cm
Control	-128	-136
SS	40	-62
SSB11%	-91	-200
SSB16%	-72	-230
DM	-42	-146
DMB18%	-127	-94
DMB22%	-44	-141

c) Batch 3

Treatment	2 cm	15 cm
Control	-118	-120
SS	67	-59
SSB11%	-9	-174
SSB16%	-161	-225
DM	-48	-181
DMB18%	-117	-182
DMB22%	-130	-199

d) Batch 4

Treatment	2 cm	15 cm
Control	-132	-164
SS	110	-22
SSB11%	61	-151
SSB16%	-49	-217
DM	-16	-142
DMB18%	-50	-173
DMB22%	-65	-195

e) Batch 5

Treatment	2 cm	15 cm
Control	16	-169
SS	53	18
SSB11%	32	-21
SSB16%	-67	-148
DM	77	-28
DMB18%	-51	-47
DMB22%	57	-20

f) Batch 6

Treatment	2 cm	15 cm
Control	139	-87
SS	72	-36
SSB11%	-82	-193
SSB16%	-127	-221
DM	51	-56
DMB18%	32	-138
DMB22%	-44	-44

g) Batch 7

Treatment	2 cm	15 cm
Control	-34	-71
SS	19	-34
SSB11%	-114	-167
SSB16%	-62	-203
DM	3	-72
DMB18%	-10	-155
DMB22%	-111	-64

h) Batch 8

Treatment	2 cm	15 cm
Control	141	-105
SS	-36	-56
SSB11%	-126	-195
SSB16%	-111	-195
DM	5	-104
DMB18%	-130	-184
DMB22%	-133	-50

Table 14. Estimated wetland area required to reduce drainage water NO_3^- - N concentrations from a 50 ha watershed in Plymouth, NC from 5 mg/L to 3 mg/L

	Area (ha)	
Treatment	**Spring**	**Winter**
SS	2.1	27.2
SSB11%	1.1	28.7
SSB16%	1.4	34.5
DM	4.4	23.7
DMB18%	5.6	29.3
DMB22%	2.1	20.8

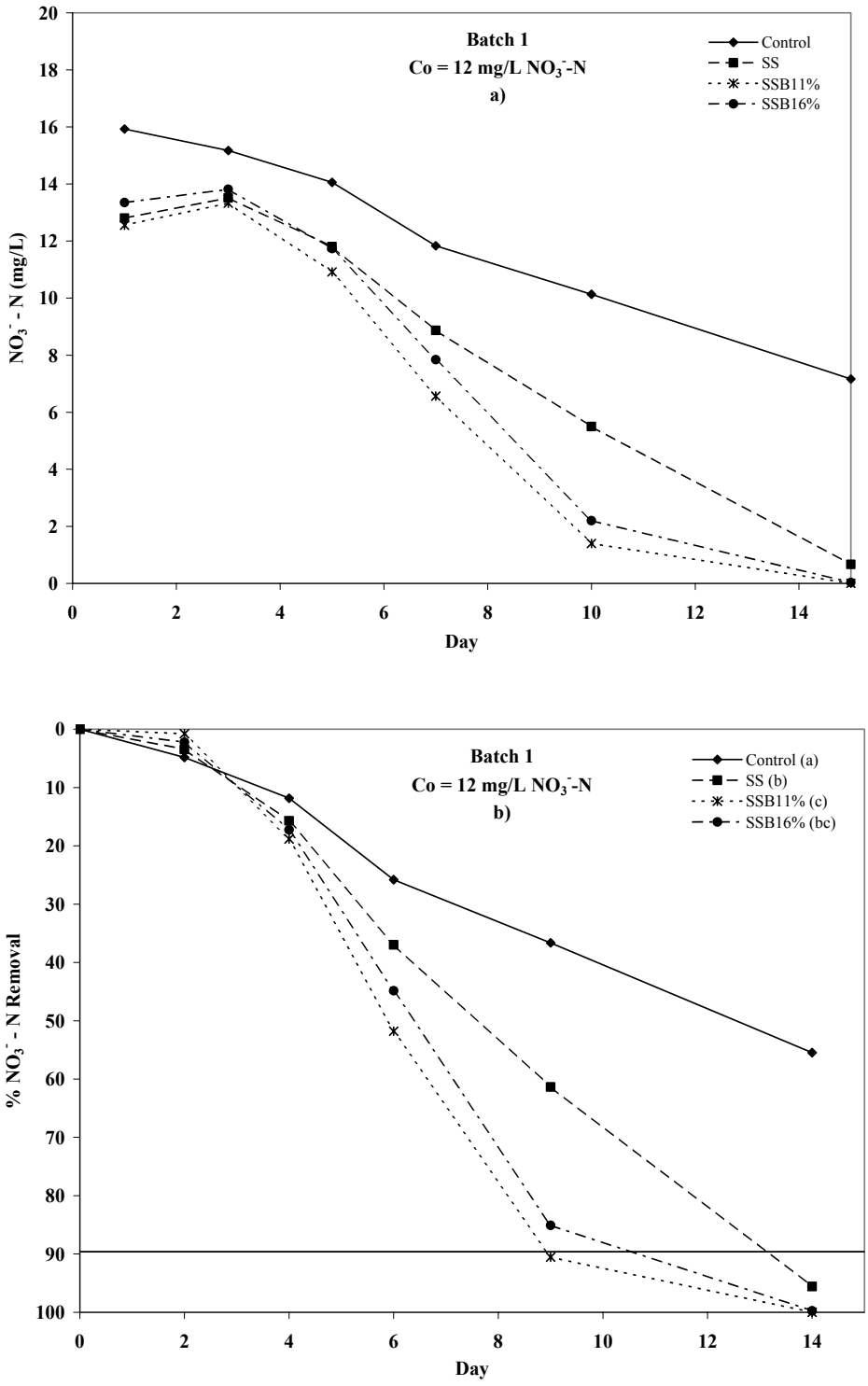


Figure 6. Batch 1 site soil based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

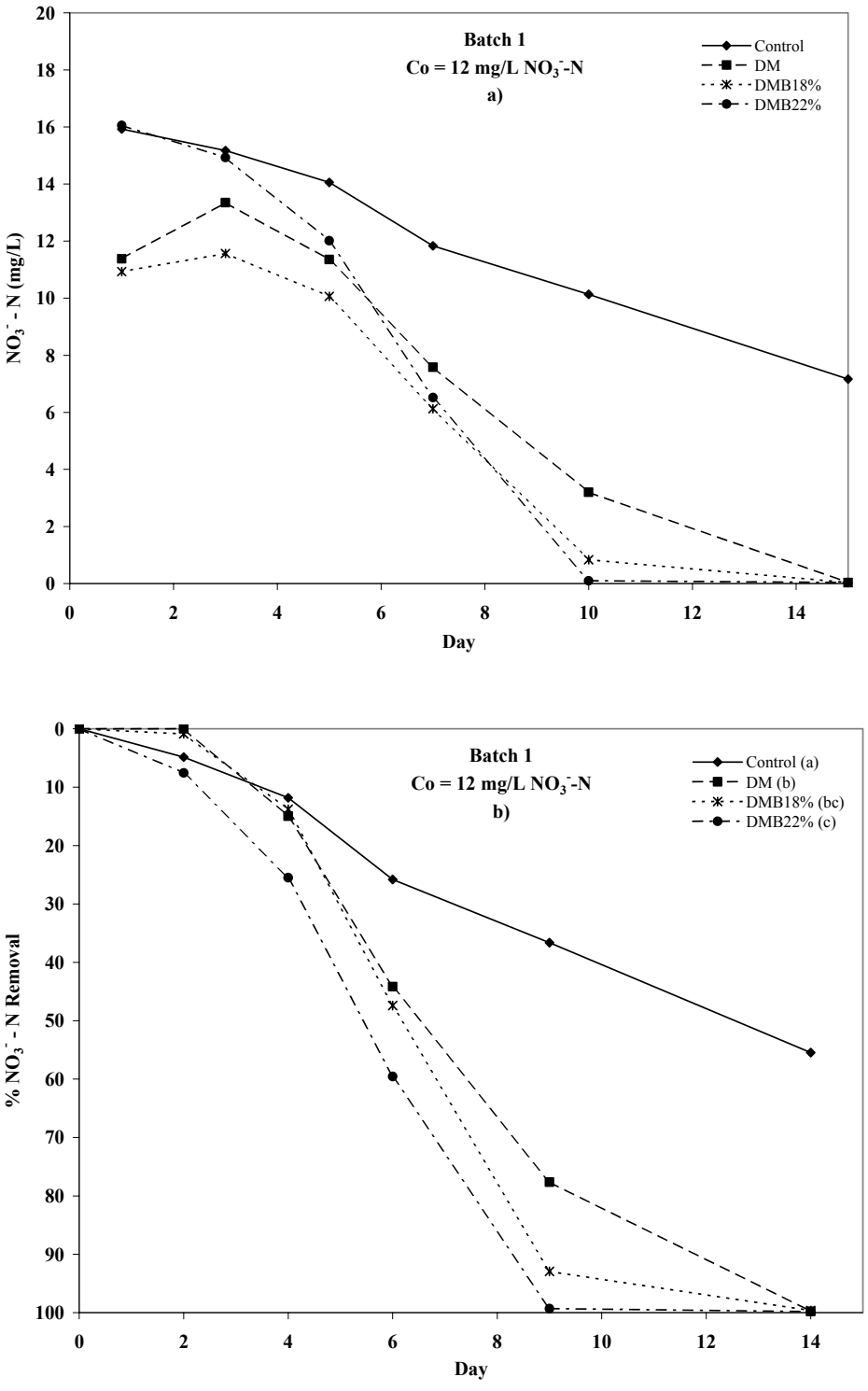


Figure 7. Batch 1 dredged material based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

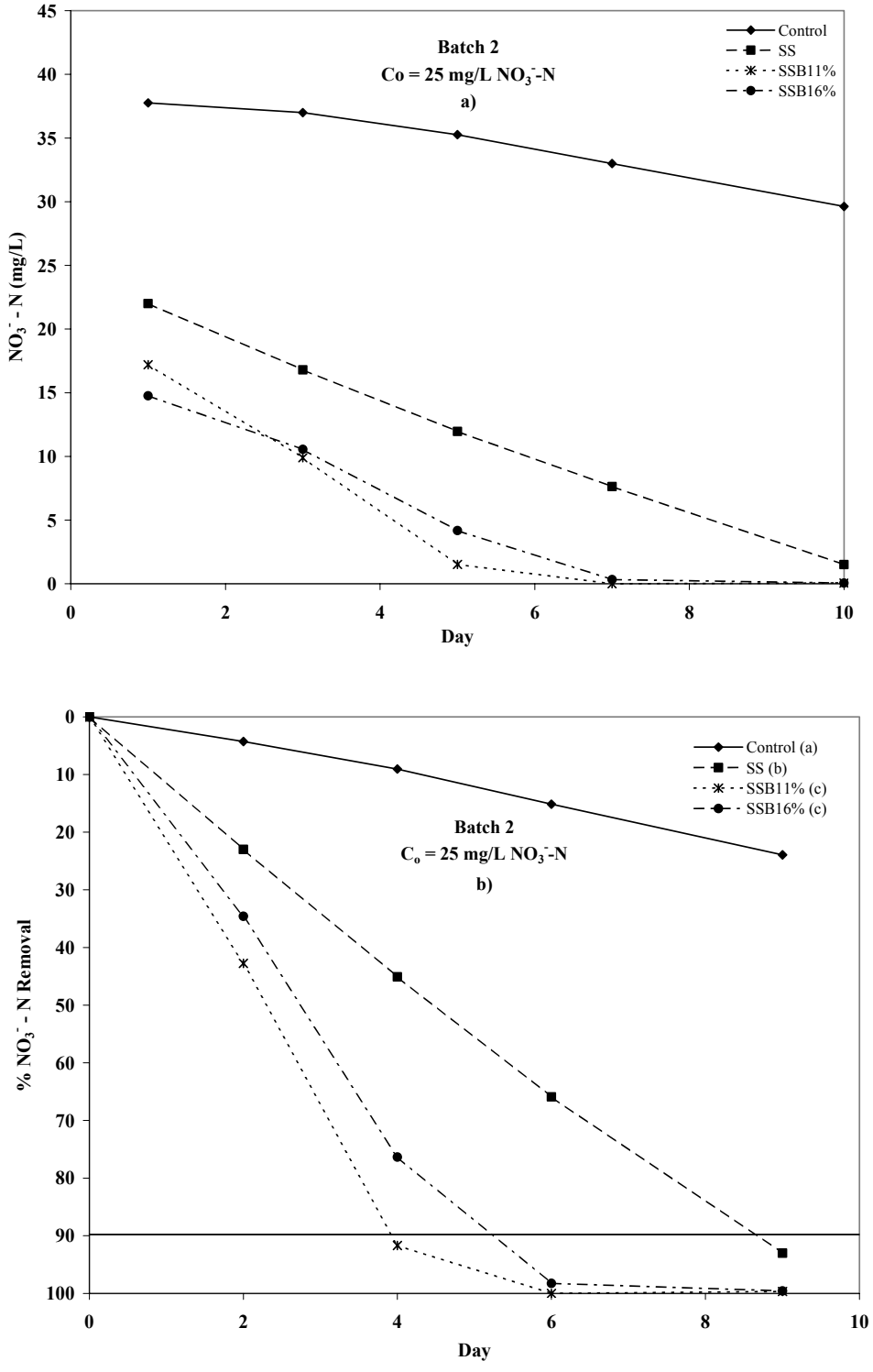


Figure 8. Batch 2 site soil based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

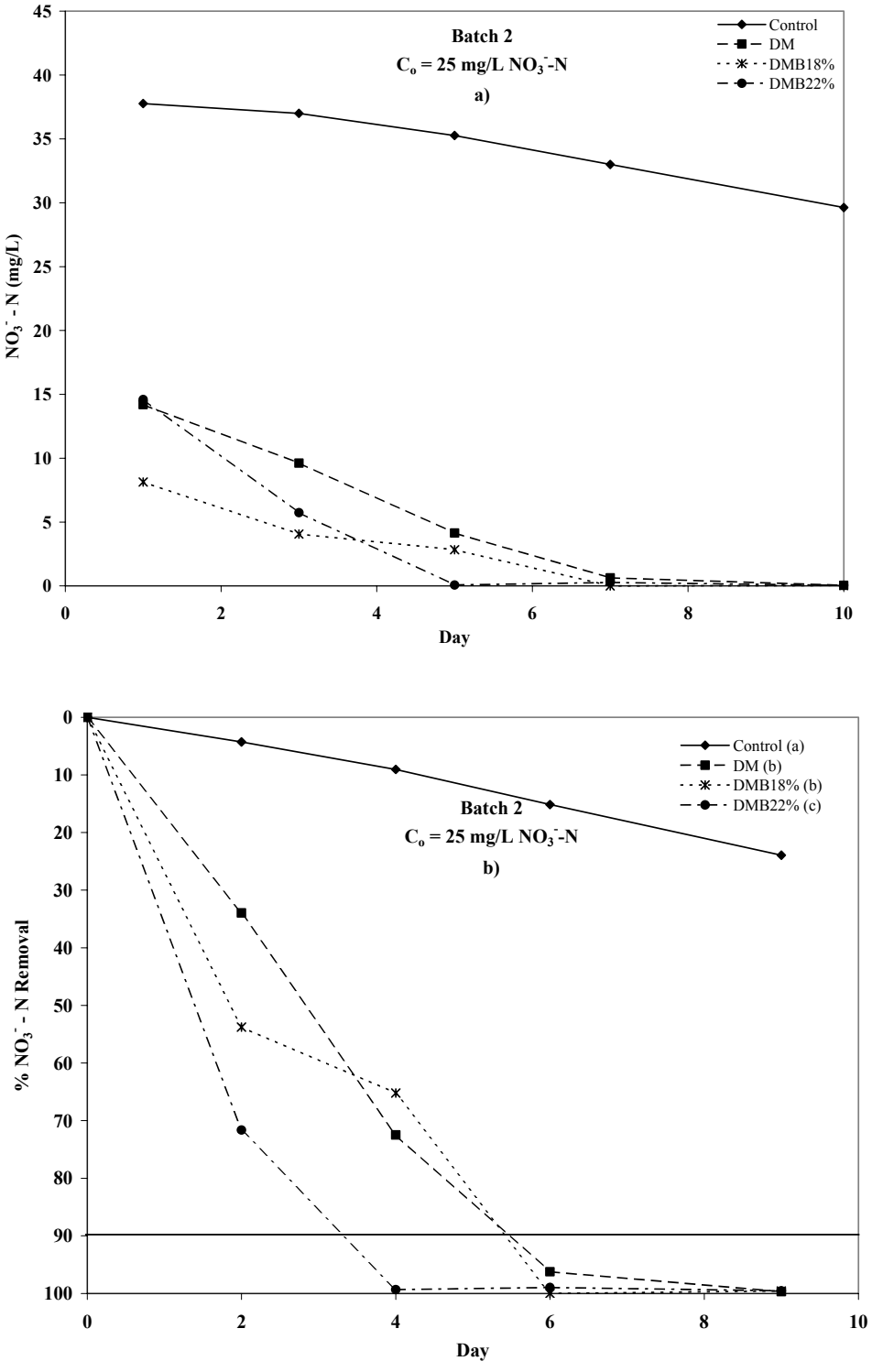


Figure 9. Batch 2 dredged material based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

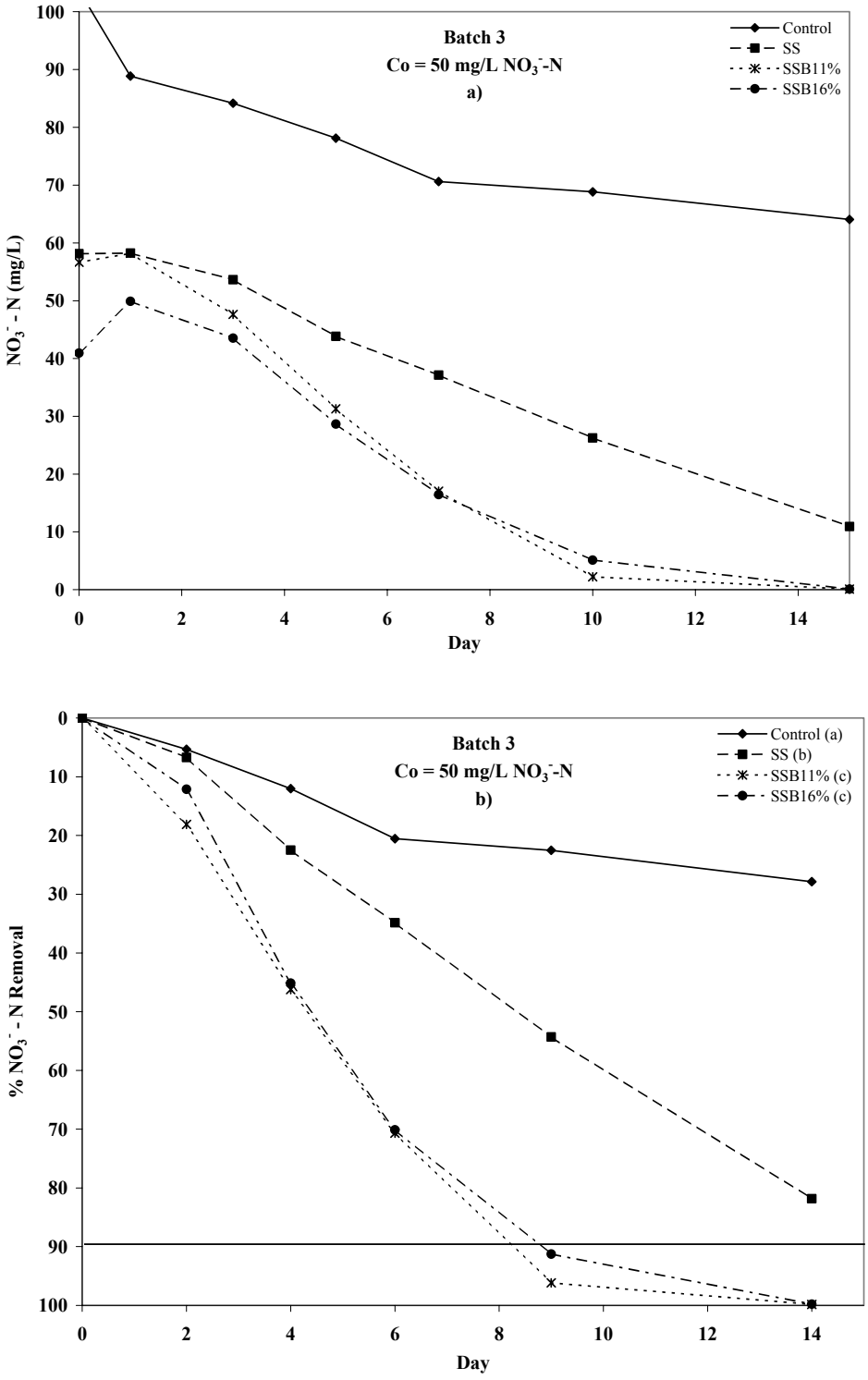


Figure 10. Batch 3 site soil based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

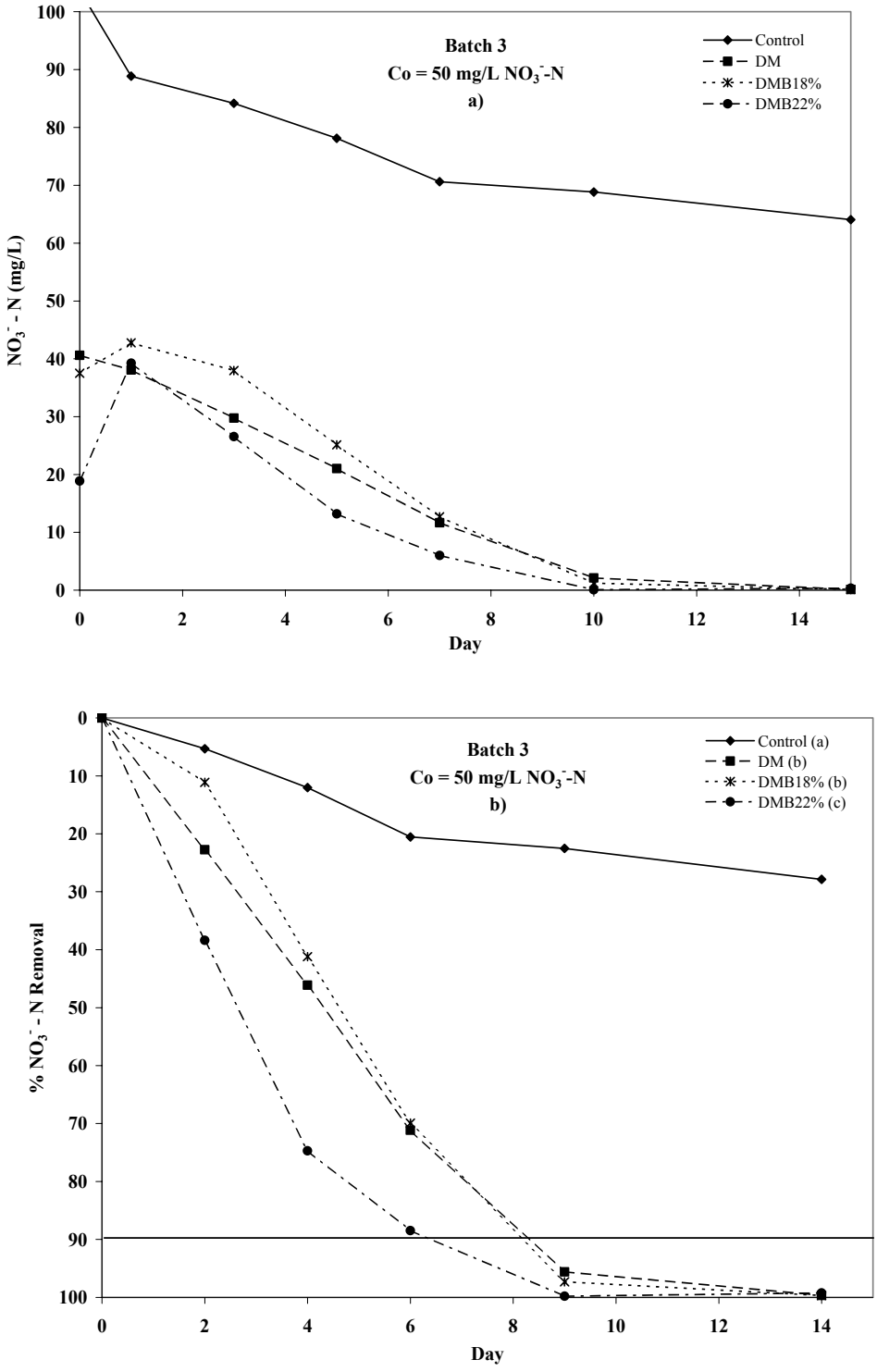


Figure 11. Batch 3 dredged material based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

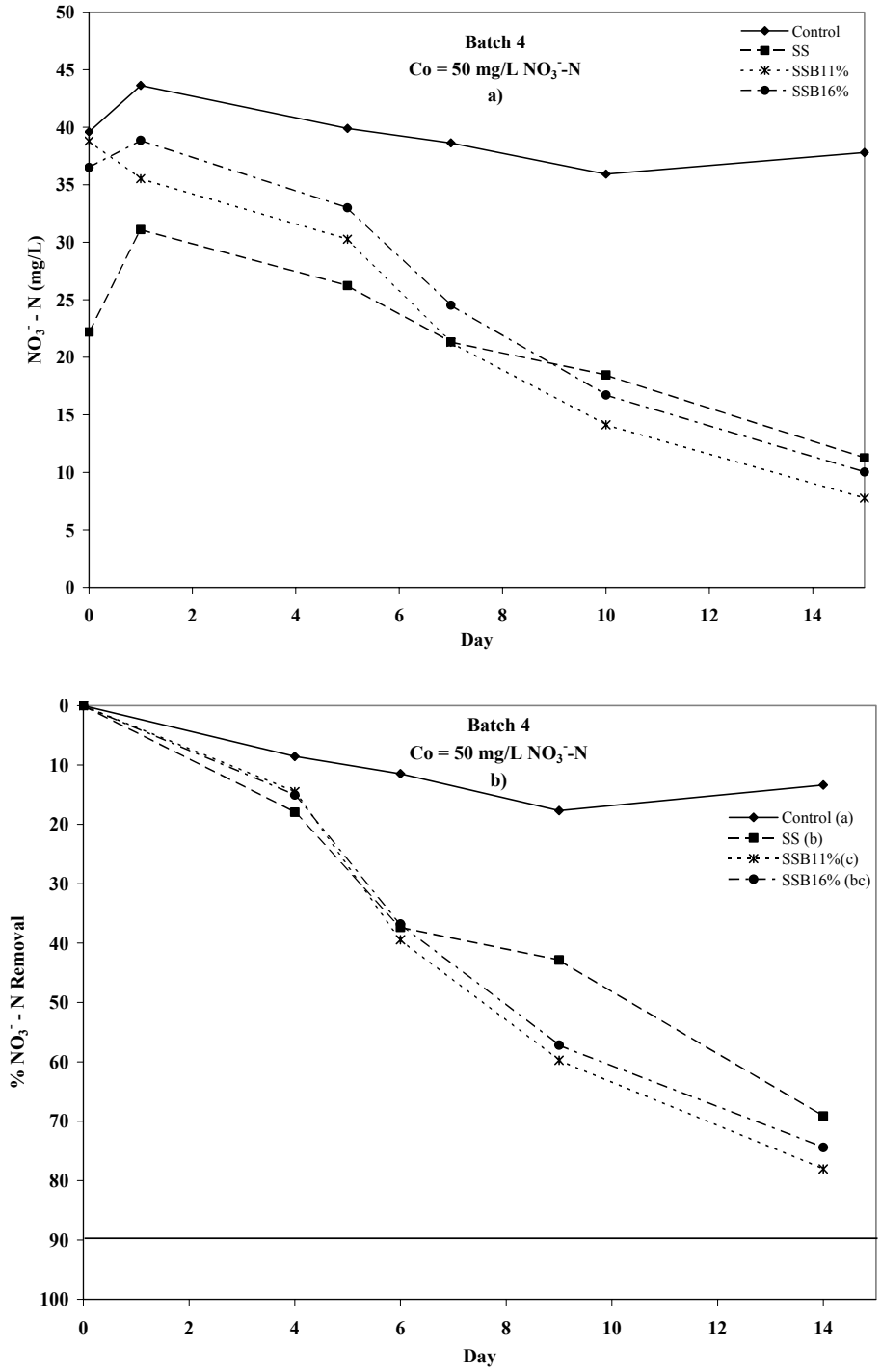


Figure 12. Batch 4 site soil based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

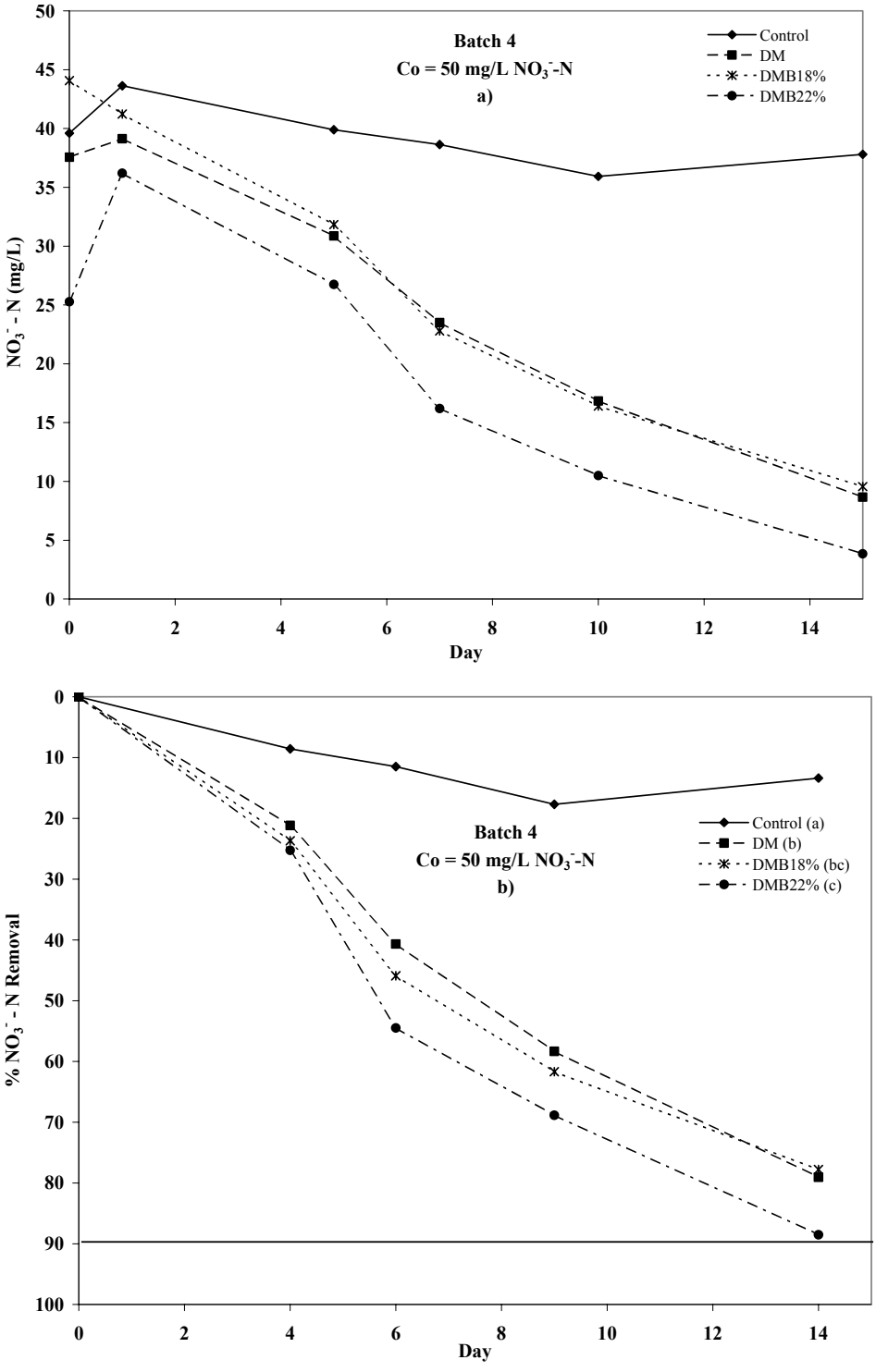


Figure 13. Batch 4 dredged material based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

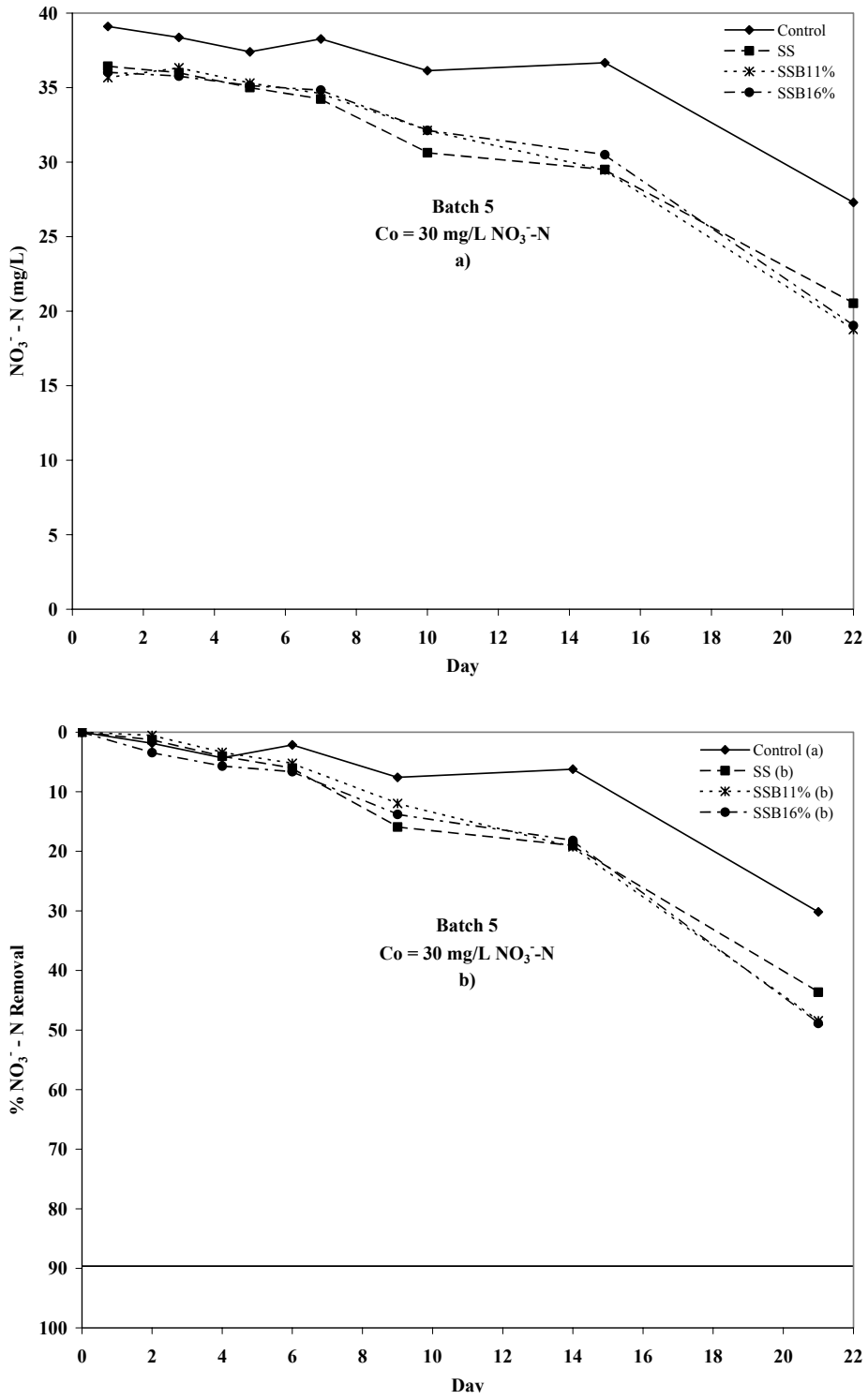


Figure 14. Batch 5 site soil based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

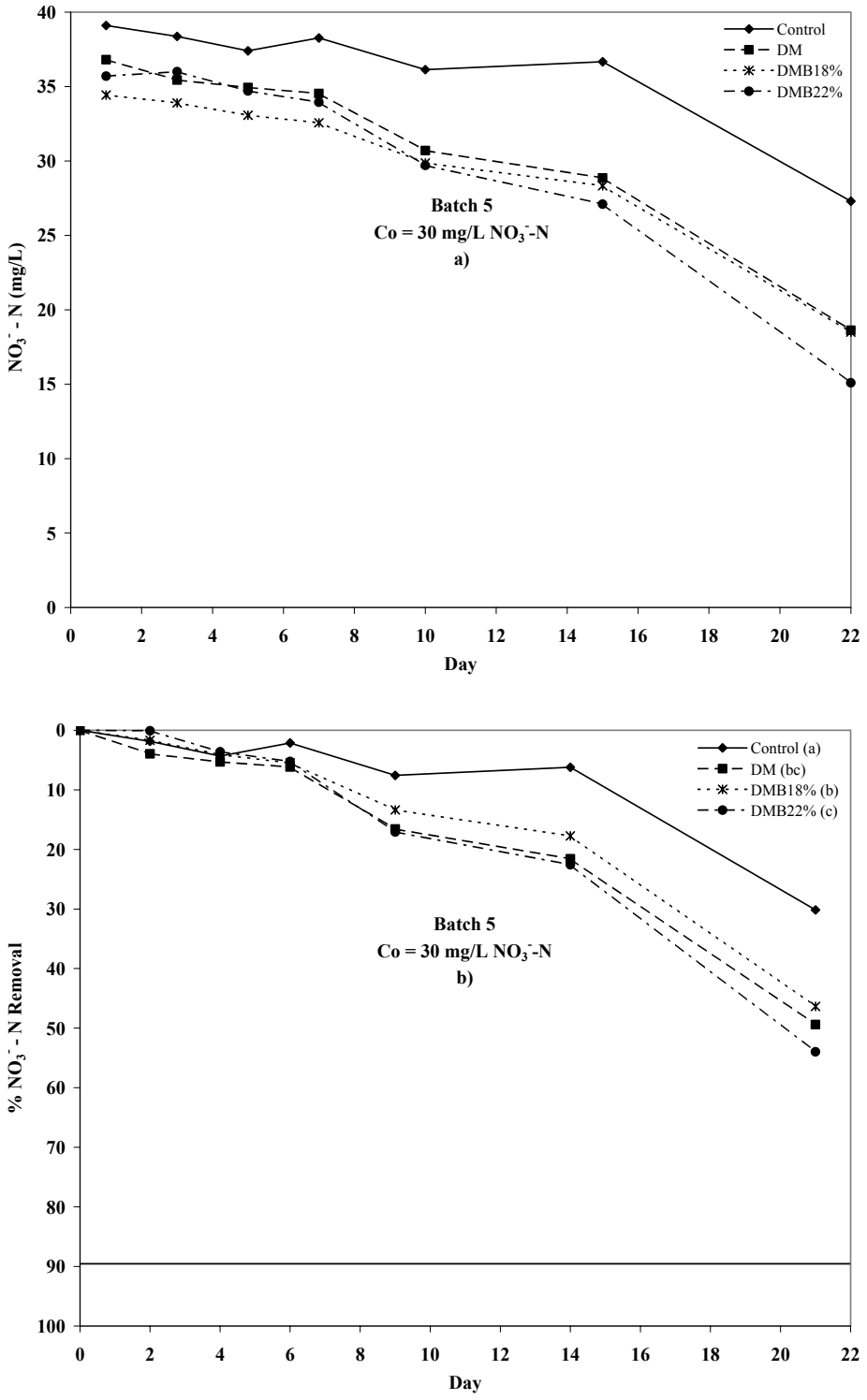


Figure 15. Batch 5 dredged material based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

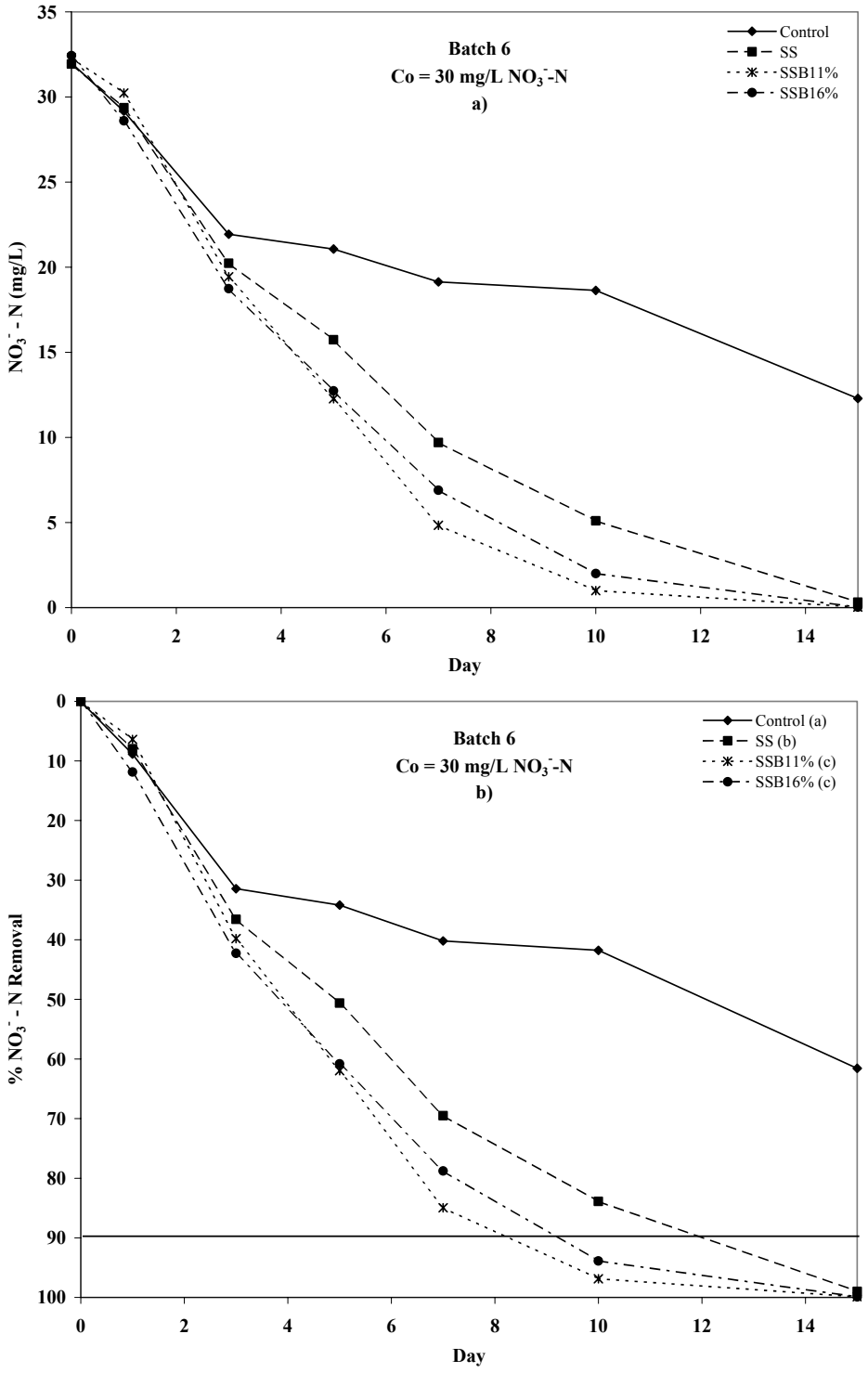


Figure 16. Batch 6 site soil based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

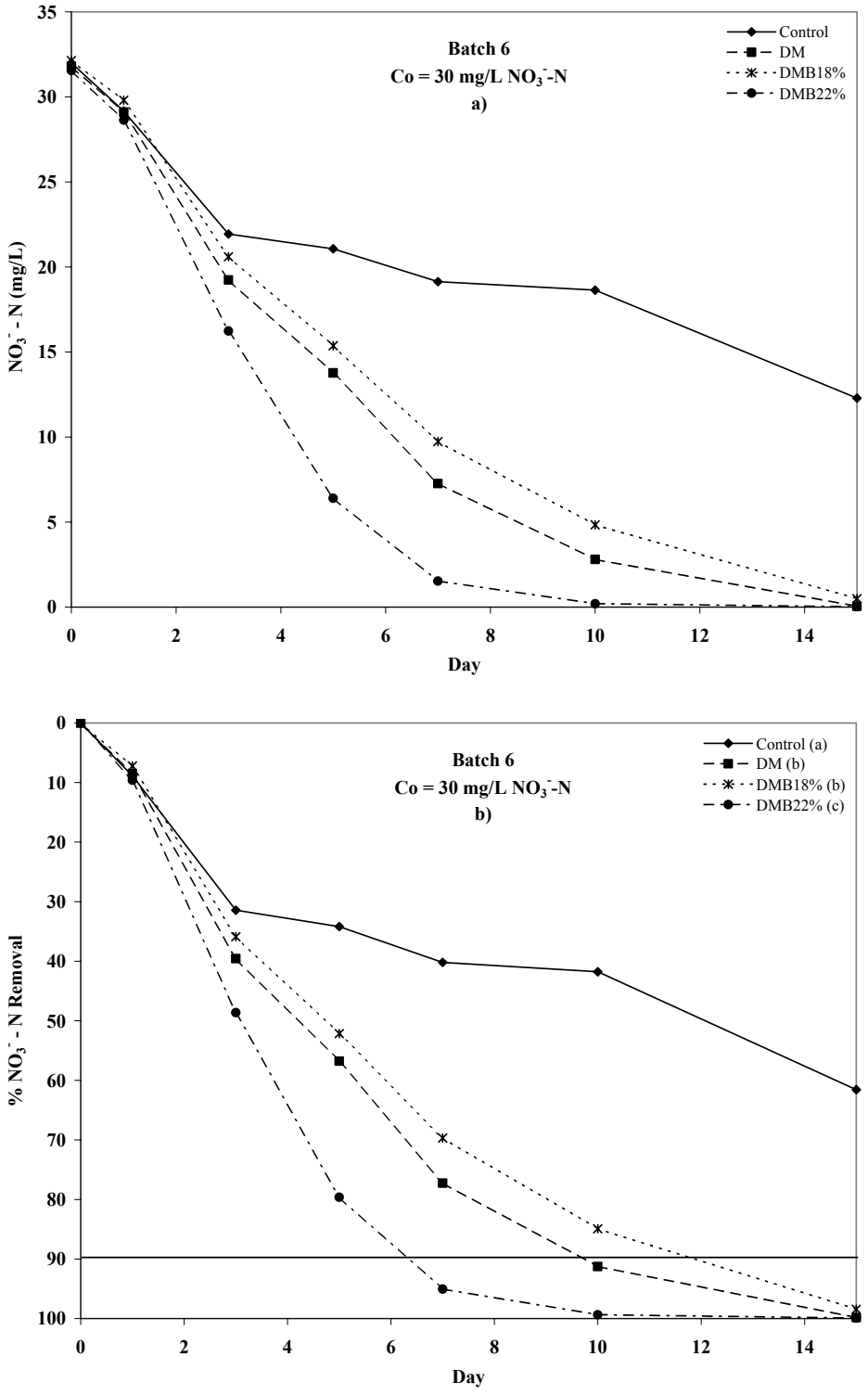


Figure 17. Batch 6 dredged material based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

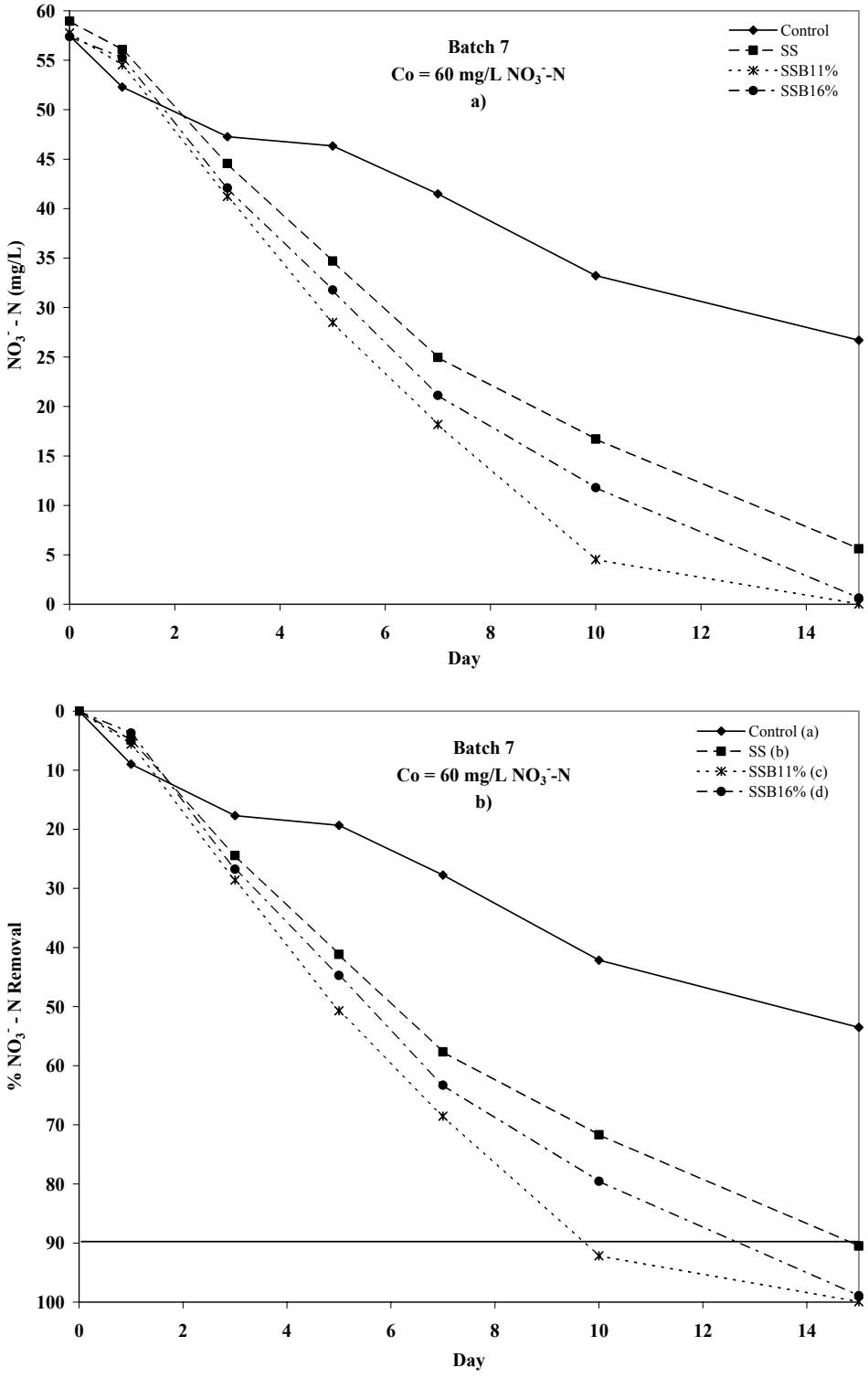
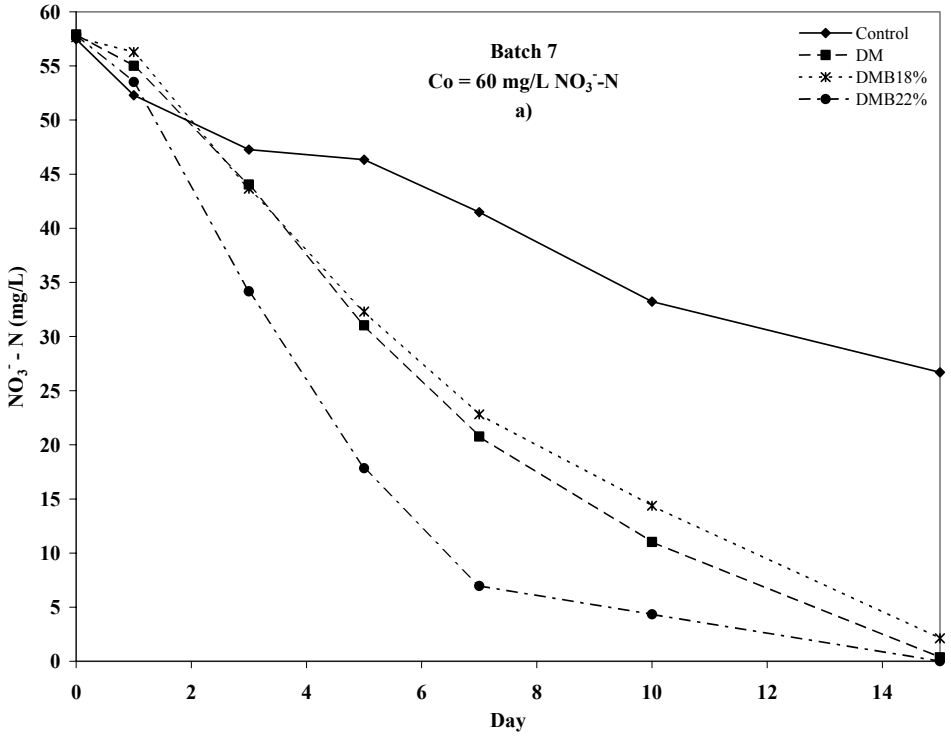


Figure 18. Batch 7 site soil based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)



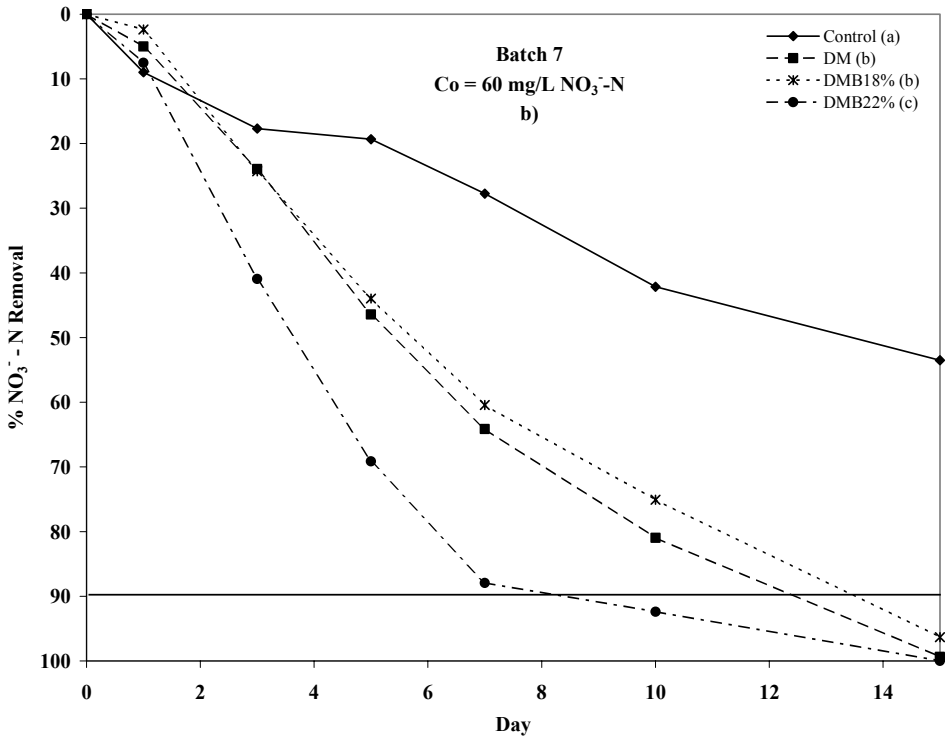


Figure 19. Batch 7 dredged material based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

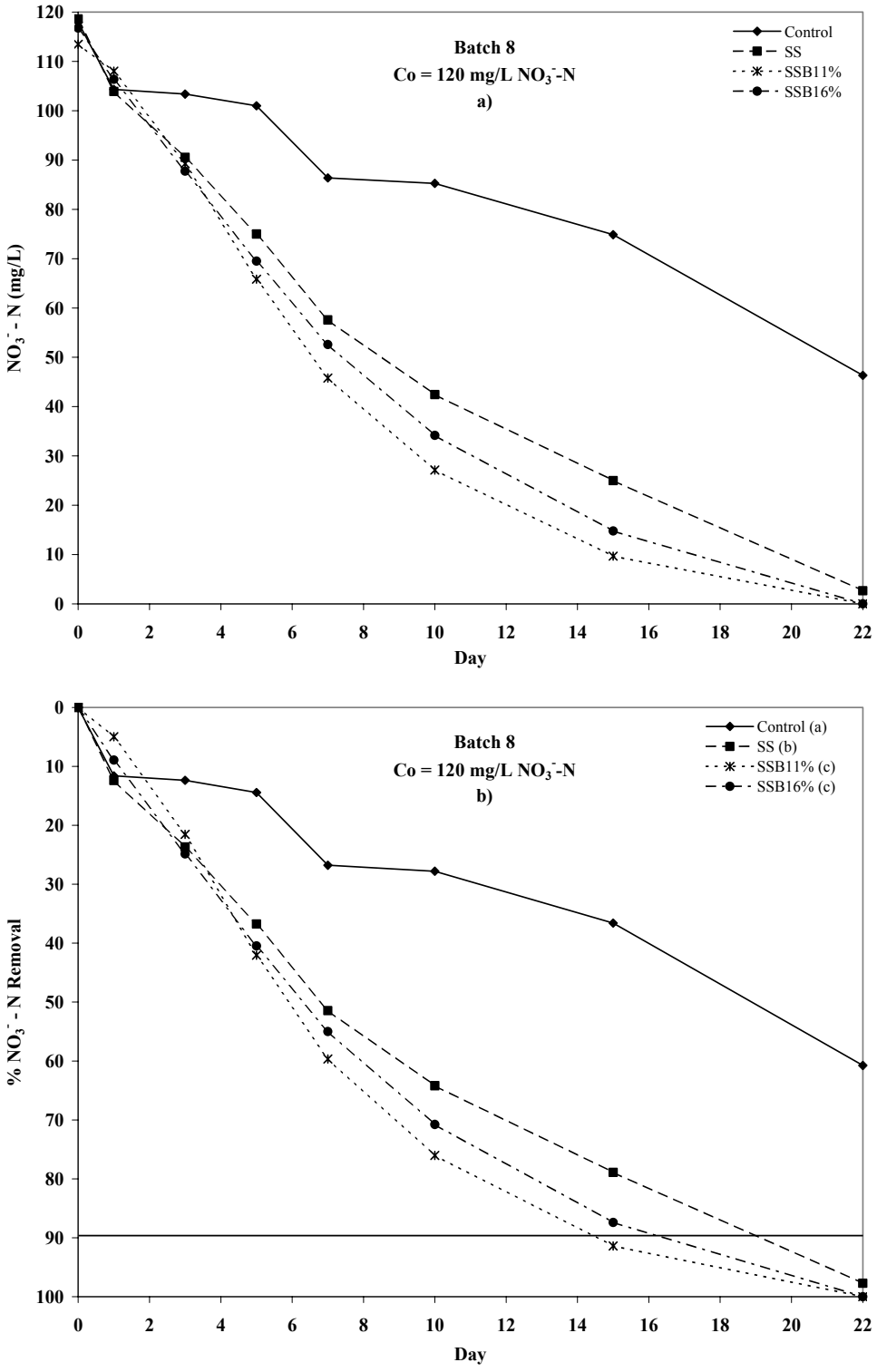


Figure 20. Batch 8 site soil based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

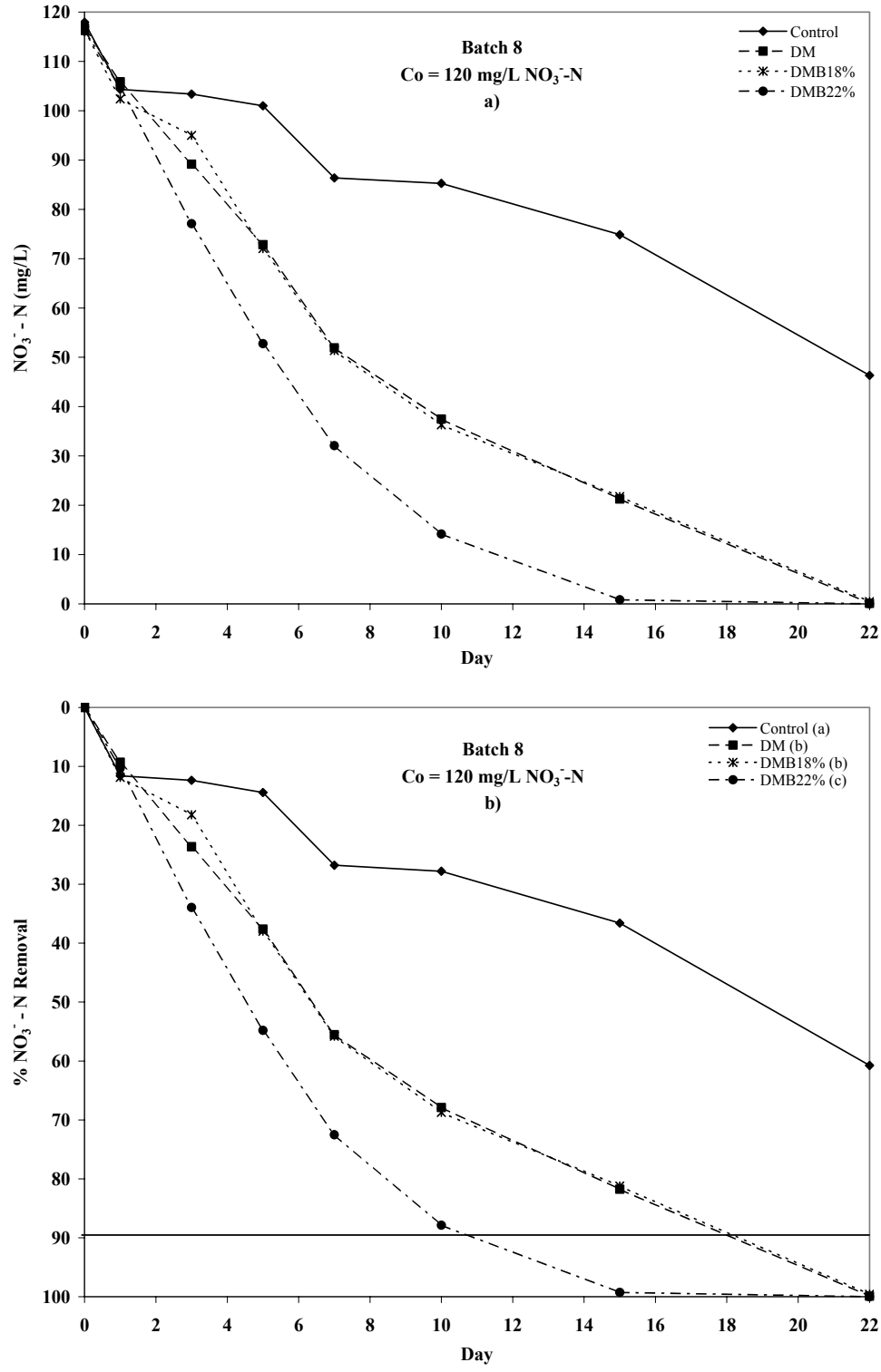


Figure 21. Batch 8 dredged material based wetland **a)** NO_3^--N concentrations and **b)** normalized % NO_3^--N removal curves (treatments with different letters represent treatment difference at p=0.05 level)

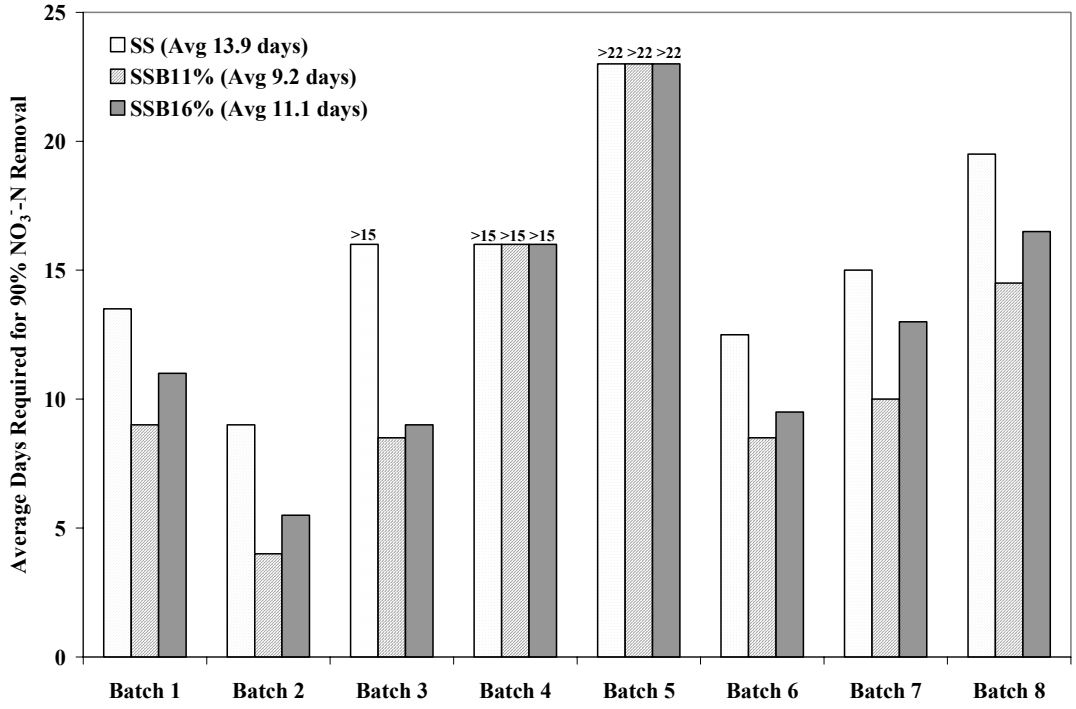


Figure 22. Average days required for the site soil based wetlands to remove 90% of the initial NO_3^--N in Batches 1-8

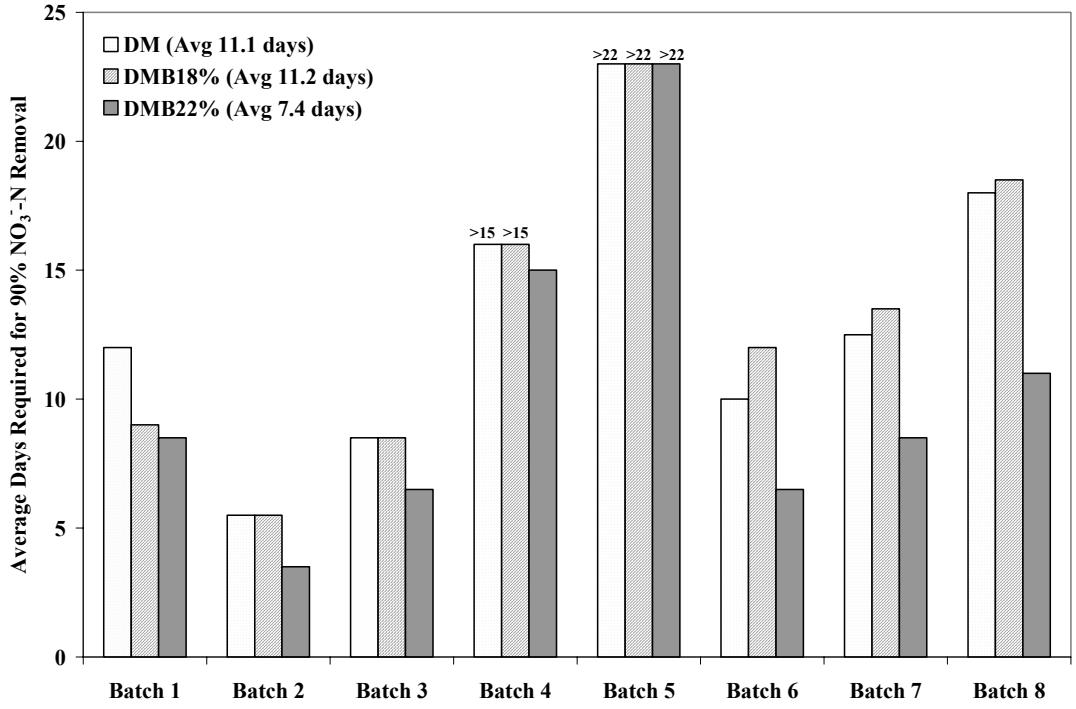


Figure 23. Average days required for the dredged material based wetlands to remove 90% of the initial NO_3^--N in Batches 1-8

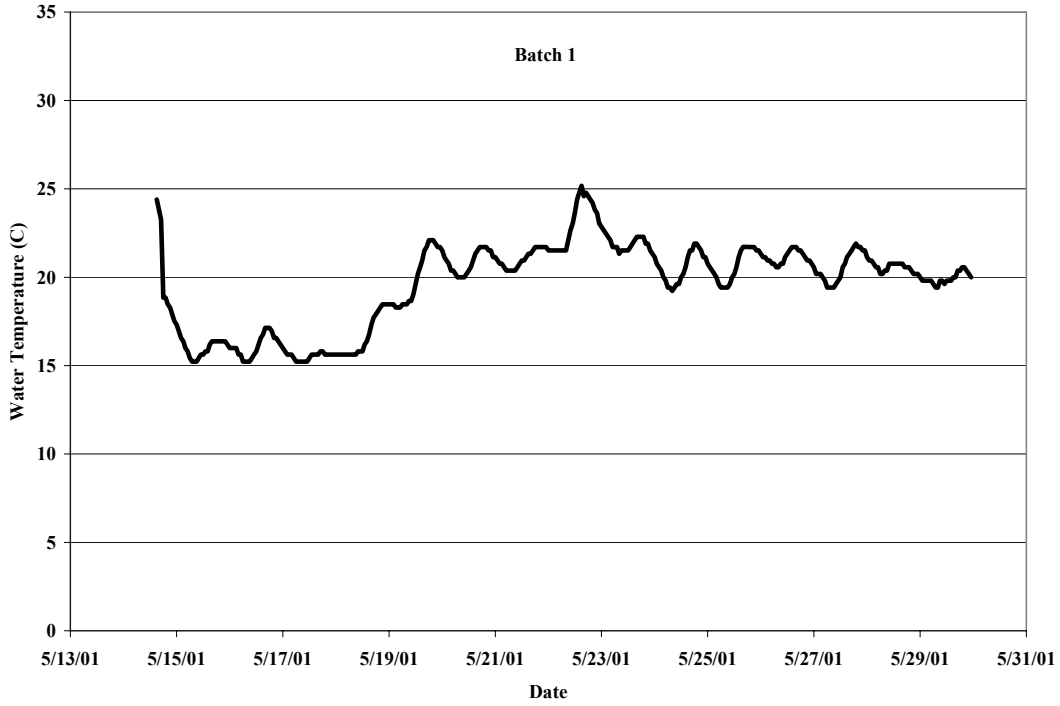


Figure 24. Average water temperature in wetland mesocosms in Batch 1

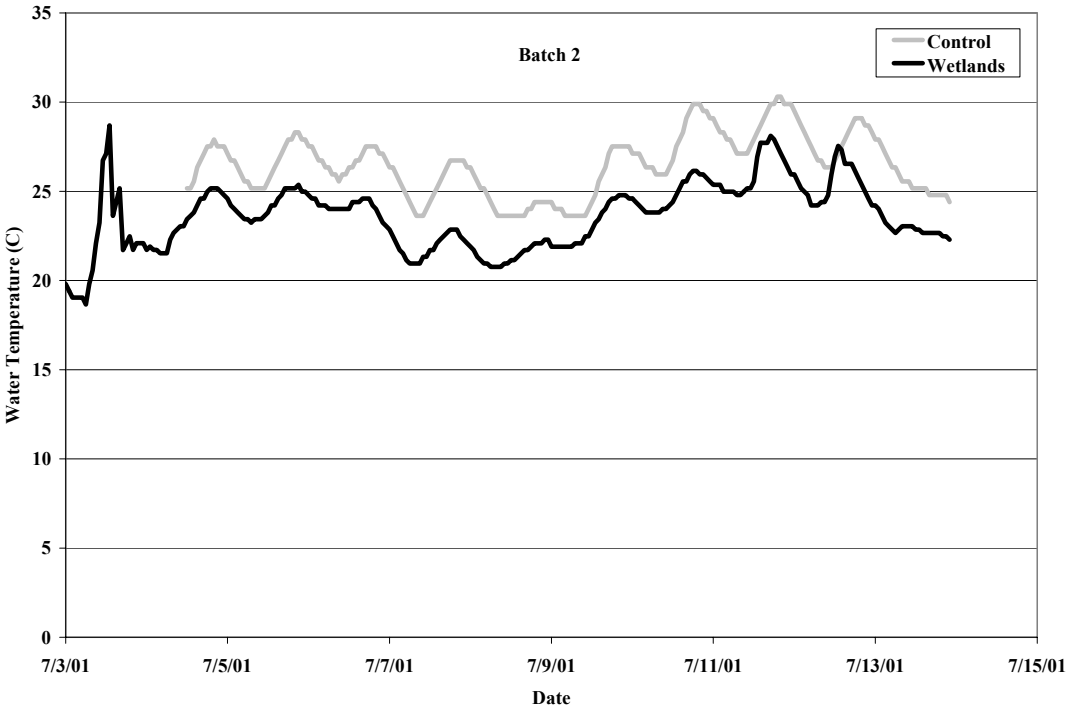


Figure 25. Average water temperature in wetland mesocosms in Batch 2 (including Control)

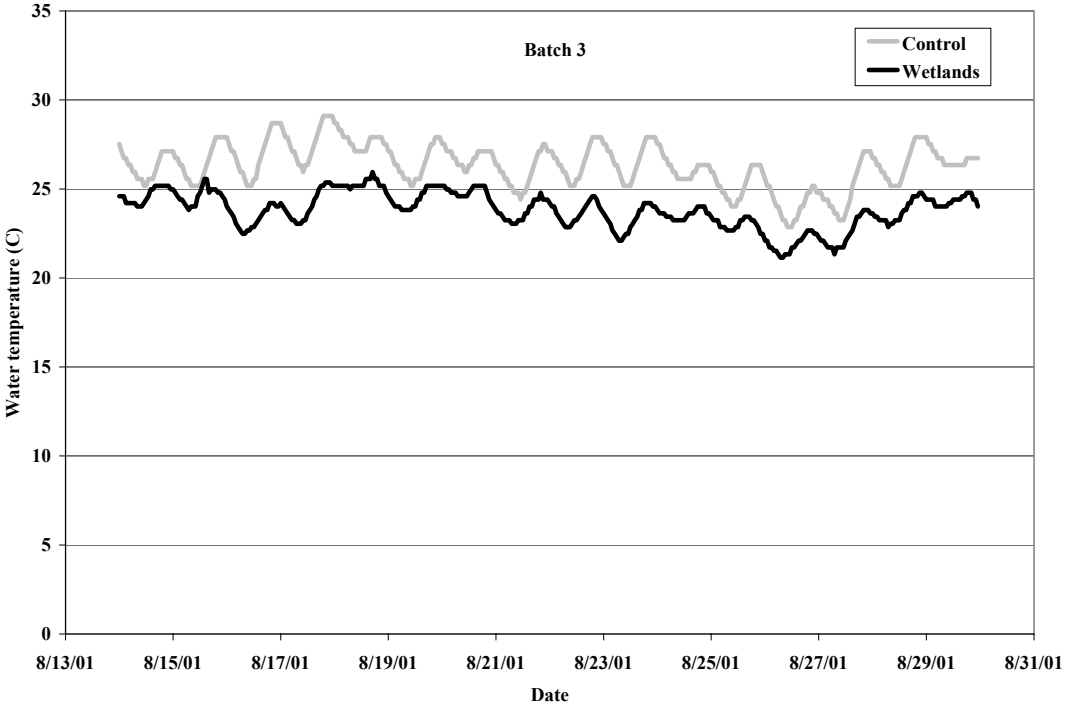


Figure 26. Average water temperature in wetland mesocosms in Batch 3 (including Control)

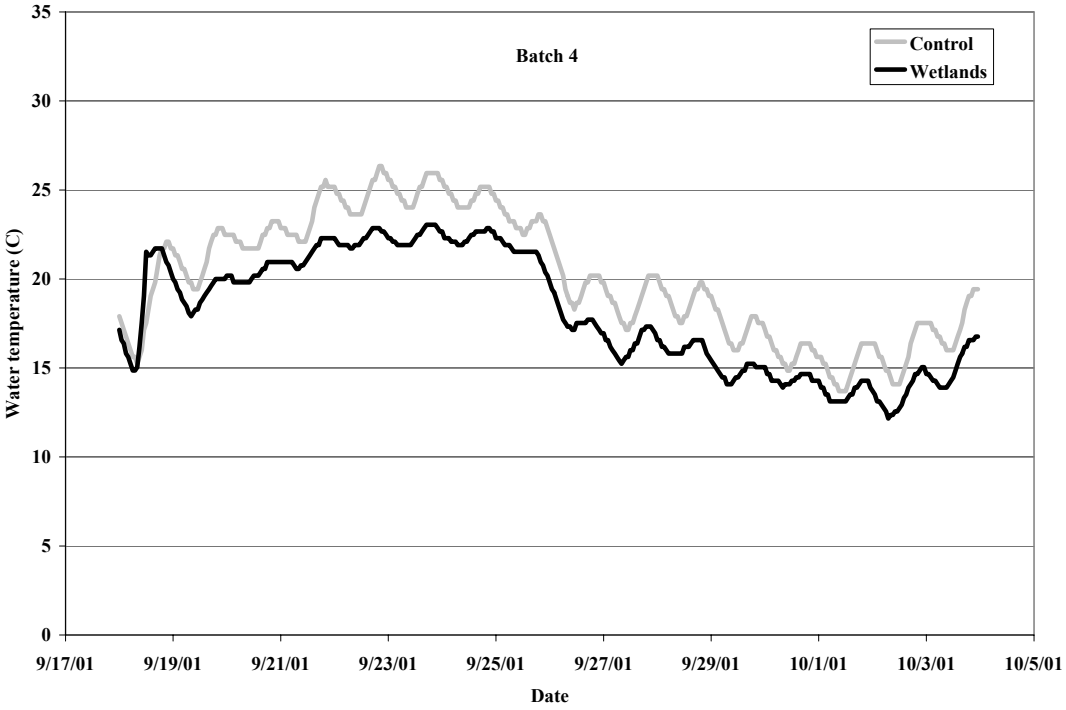


Figure 27. Average water temperature in wetland mesocosms in Batch 4 (including Control)

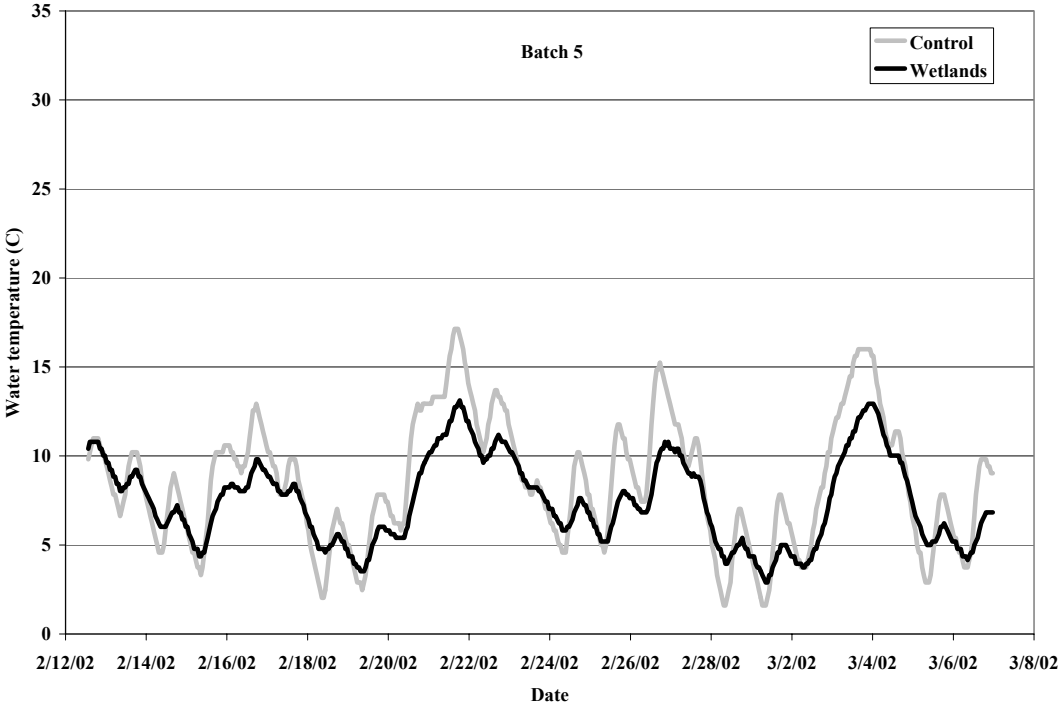


Figure 28. Average water temperature in wetland mesocosms in Batch 5 (including Control)

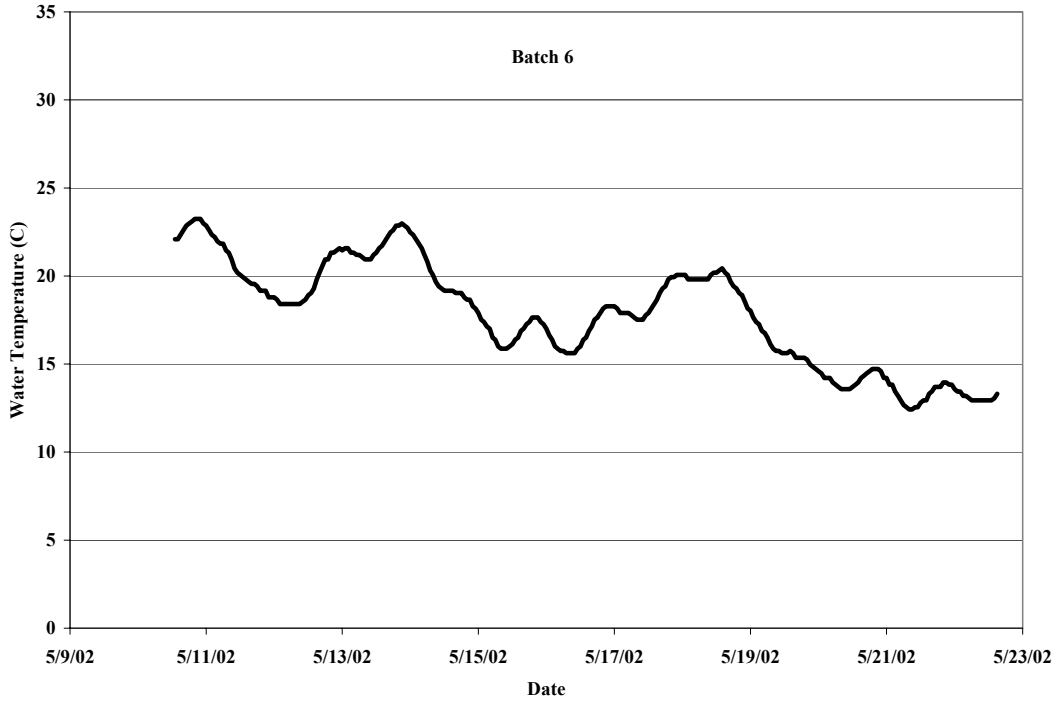


Figure 29. Average water temperature in wetland mesocosms in Batch 6

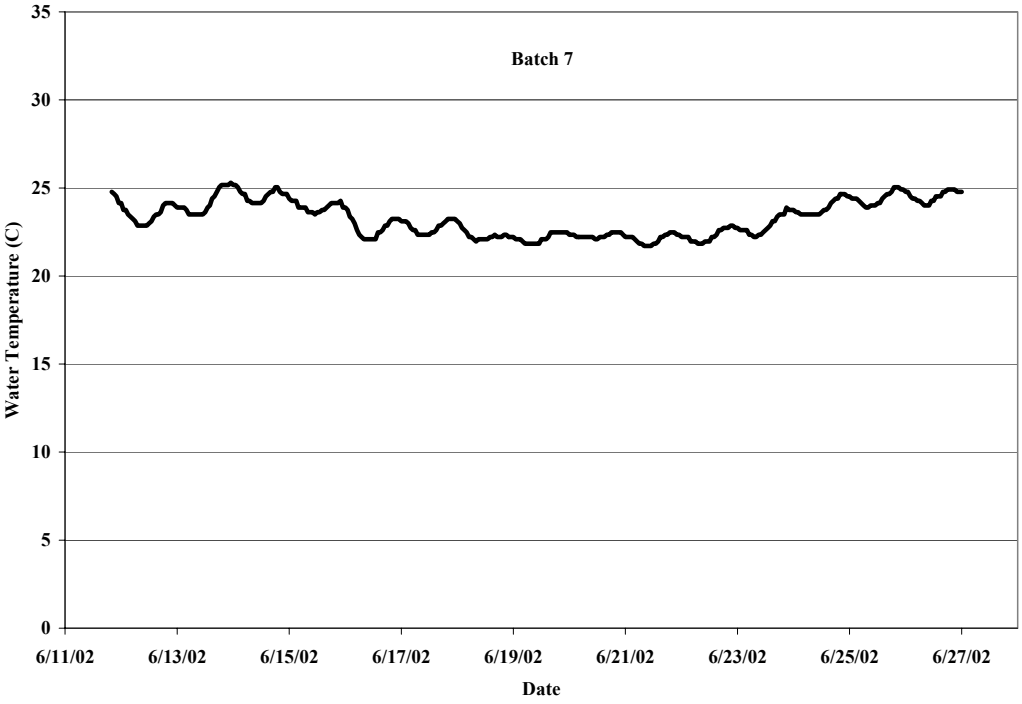


Figure 30. Average water temperature in wetland mesocosms in Batch 7

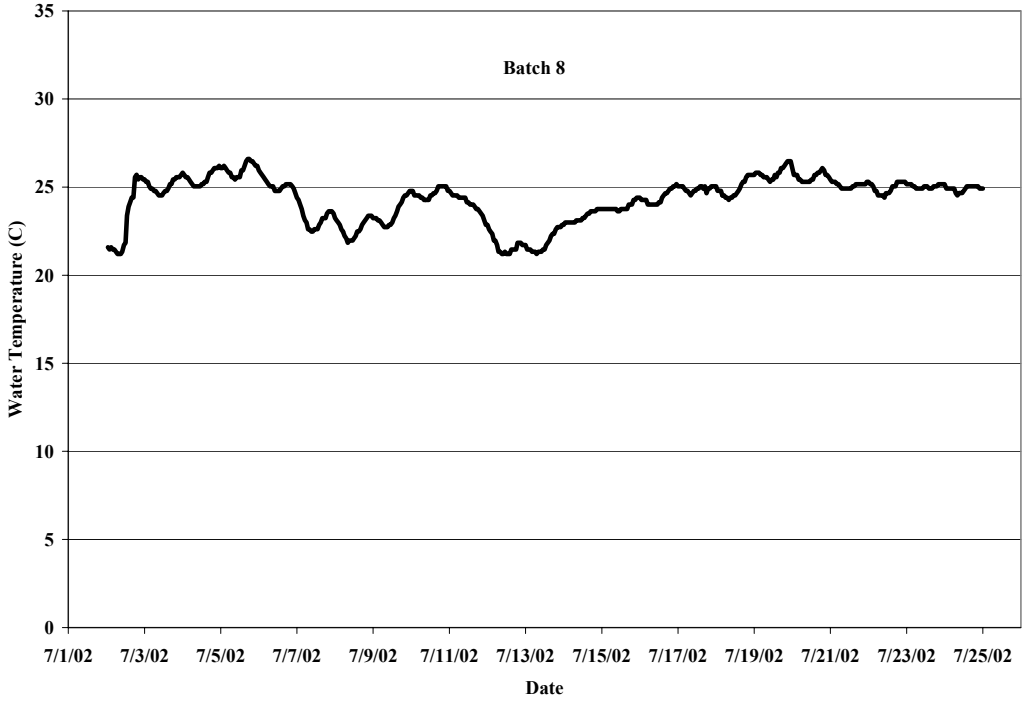


Figure 31. Average water temperature in wetland mesocosms in Batch 8

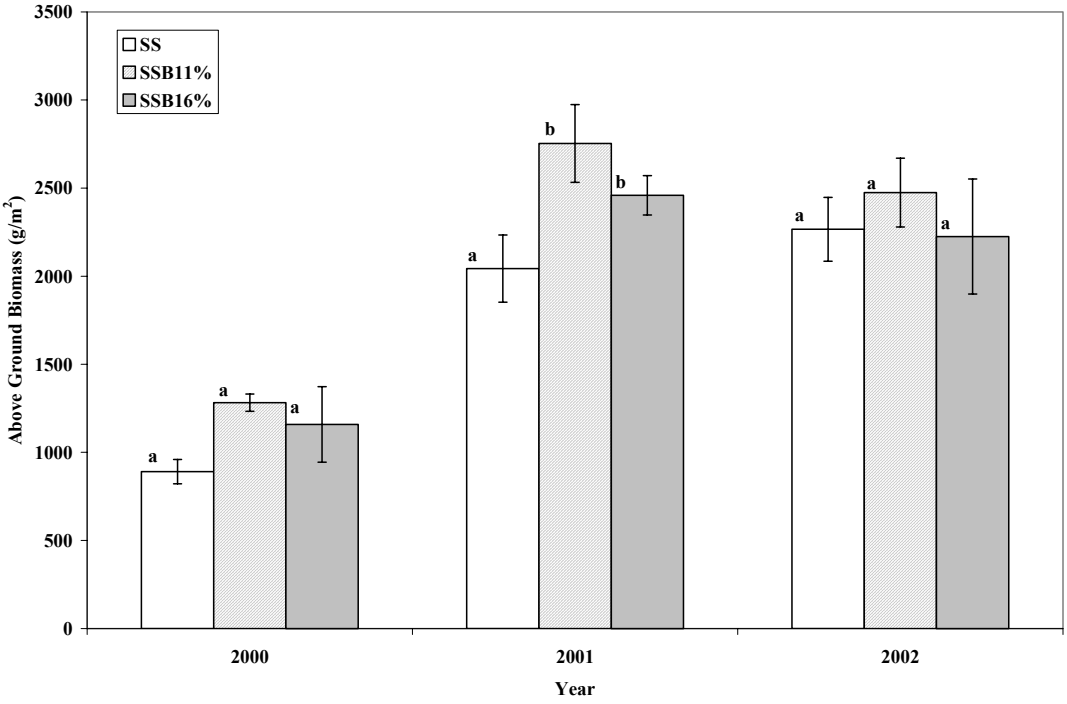


Figure 32. Above ground *Scirpus validus* biomass harvested from the site soil based wetland treatments. *Note:* Different letters indicate significant differences in production within that year at the P=0.05 level.

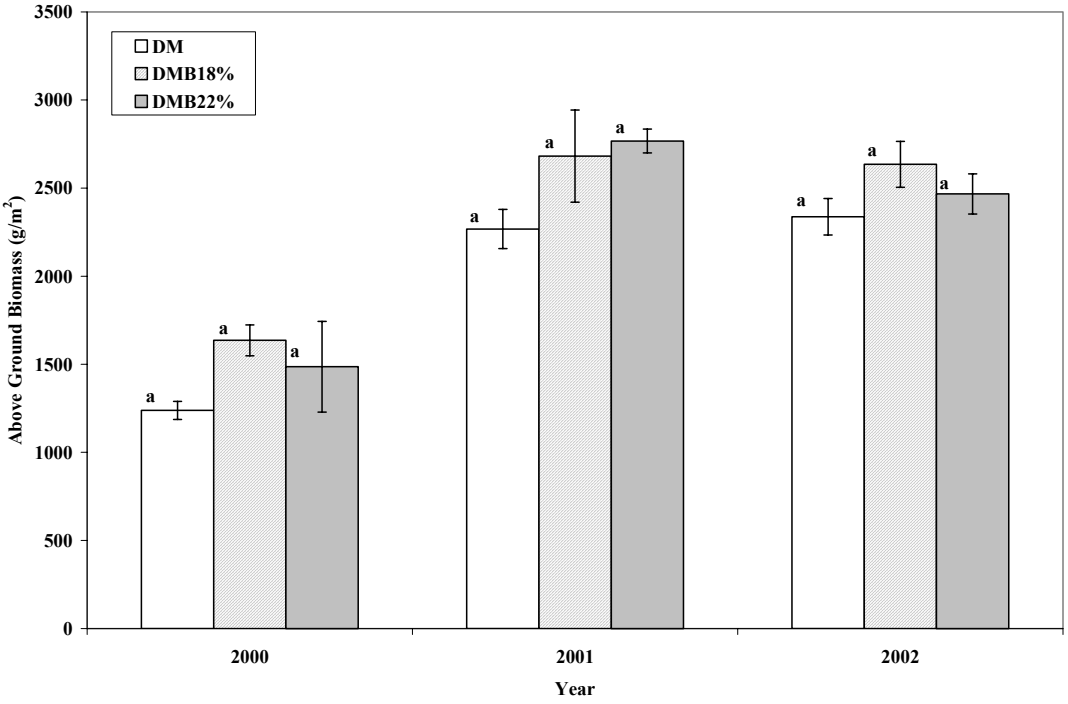


Figure 33. Above ground *Scirpus validus* biomass harvested from the dredged material based wetland treatments. *Note:* Different letters indicate significant differences in production within that year at the P=0.05 level.

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APPENDICES

APPENDIX 1

APPENDIX 1-A

Tipping Bucket Calibration Data Used in Drainage Flow Measurements

Table A.1. Calibration factors for each of the drains

Date	P1A m3/tip	P1B m3/tip	P1C m3/tip	P2A m3/tip	P2B m3/tip	P2C m3/tip
1 Jan 2001 - 29 Mar 2001	0.00276	0.00255	0.00238	0.00234	0.00230	0.00258
30 Mar 2001 - 31 Mar 2002	0.00269	0.00275	0.00239	0.00250	0.00238	0.00262
1 April 2002 - 30 Sept 2002	0.00281	0.00280	0.00263	0.00245	0.00250	0.00275

APPENDIX 1-B

Drainage Flow Data for Plot 1

Table B.1. Plot 1 daily drainage flow in 2001

2001 Flow - Plot 1 (deep drains)
Drain Depth = 1.44 m Drain Spacing = 25 m
Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
1	0.037	0.037	0.028	0.028	0.045	0.045	0.037	0.037
2	0.034	0.071	0.025	0.053	0.043	0.088	0.034	0.071
3	0.034	0.104	0.026	0.079	0.043	0.131	0.034	0.105
4	0.034	0.138	0.025	0.104	0.044	0.175	0.034	0.139
5	0.035	0.172	0.026	0.131	0.045	0.220	0.035	0.175
6	0.033	0.205	0.020	0.151	0.038	0.258	0.030	0.205
7	0.031	0.236	0.019	0.170	0.036	0.294	0.029	0.234
8	0.031	0.268	0.020	0.189	0.034	0.328	0.028	0.262
9	0.028	0.296	0.016	0.206	0.032	0.361	0.026	0.288
10	0.027	0.323	0.013	0.218	0.030	0.391	0.023	0.311
11	0.028	0.351	0.014	0.232	0.032	0.423	0.025	0.336
12	0.027	0.378	0.013	0.246	0.031	0.454	0.024	0.360
13	0.025	0.403	0.011	0.257	0.028	0.482	0.021	0.381
14	0.026	0.429	0.012	0.269	0.029	0.511	0.023	0.403
15	0.027	0.456	0.013	0.282	0.031	0.542	0.024	0.427
16	0.025	0.482	0.011	0.293	0.028	0.570	0.021	0.449
17	0.025	0.507	0.011	0.304	0.027	0.597	0.021	0.470
18	0.026	0.533	0.012	0.316	0.029	0.626	0.022	0.492
19	0.028	0.561	0.014	0.330	0.031	0.658	0.024	0.516
20	0.091	0.652	0.070	0.400	0.103	0.760	0.088	0.604
21	0.115	0.766	0.092	0.493	0.132	0.893	0.113	0.717
22	0.049	0.815	0.029	0.521	0.061	0.954	0.046	0.764
23	0.097	0.911	0.076	0.597	0.112	1.066	0.095	0.859
24	0.056	0.967	0.044	0.641	0.032	1.098	0.044	0.903
25	0.067	1.034	0.048	0.689	0.038	1.136	0.051	0.953
26	0.028	1.062	0.042	0.731	0.034	1.170	0.035	0.988
27	0.056	1.118	0.039	0.770	0.031	1.201	0.042	1.030
28	0.048	1.166	0.031	0.802	0.026	1.227	0.035	1.065
29	0.047	1.213	0.030	0.832	0.026	1.253	0.034	1.100
30	0.048	1.260	0.032	0.864	0.028	1.281	0.036	1.136
31	0.042	1.302	0.027	0.891	0.024	1.305	0.031	1.166
32	0.037	1.339	0.021	0.912	0.020	1.325	0.026	1.193

Table B.1 (continued)

2001 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
33	0.038	1.378	0.023	0.935	0.021	1.346	0.028	1.220
34	0.034	1.412	0.018	0.954	0.018	1.364	0.023	1.243
35	0.035	1.447	0.020	0.973	0.022	1.386	0.026	1.269
36	0.041	1.488	0.024	0.997	0.022	1.408	0.029	1.298
37	0.036	1.523	0.019	1.016	0.019	1.426	0.024	1.322
38	0.034	1.557	0.016	1.032	0.017	1.443	0.022	1.344
39	0.033	1.590	0.016	1.048	0.017	1.460	0.022	1.366
40	0.034	1.624	0.017	1.065	0.019	1.479	0.023	1.390
41	0.033	1.657	0.016	1.081	0.017	1.496	0.022	1.412
42	0.028	1.685	0.011	1.092	0.016	1.512	0.018	1.430
43	0.030	1.715	0.014	1.106	0.015	1.528	0.020	1.450
44	0.030	1.745	0.015	1.121	0.016	1.544	0.020	1.470
45	0.031	1.776	0.015	1.136	0.017	1.561	0.021	1.491
46	0.029	1.806	0.014	1.150	0.016	1.576	0.020	1.511
47	0.028	1.833	0.012	1.162	0.014	1.590	0.018	1.529
48	0.081	1.915	0.053	1.215	0.042	1.633	0.059	1.588
49	0.075	1.990	0.054	1.269	0.040	1.673	0.057	1.644
50	0.064	2.053	0.044	1.312	0.034	1.707	0.047	1.691
51	0.056	2.110	0.038	1.350	0.030	1.737	0.041	1.733
52	0.049	2.159	0.031	1.381	0.026	1.763	0.035	1.768
53	0.138	2.297	0.095	1.476	0.074	1.837	0.102	1.870
54	0.218	2.516	0.187	1.663	0.116	1.953	0.174	2.044
55	0.157	2.673	0.136	1.799	0.087	2.040	0.127	2.171
56	0.129	2.802	0.110	1.909	0.073	2.113	0.104	2.275
57	0.108	2.910	0.089	1.998	0.060	2.173	0.086	2.361
58	0.092	3.003	0.074	2.071	0.051	2.224	0.072	2.433
59	0.082	3.085	0.065	2.136	0.046	2.270	0.064	2.497
60	0.072	3.157	0.056	2.192	0.041	2.311	0.056	2.554
61	0.066	3.223	0.049	2.241	0.040	2.351	0.052	2.605
62	0.057	3.280	0.041	2.283	0.036	2.387	0.045	2.650
63	0.157	3.437	0.118	2.400	0.082	2.469	0.119	2.769
64	0.160	3.597	0.138	2.539	0.088	2.558	0.129	2.898
65	0.130	3.727	0.114	2.653	0.075	2.633	0.106	3.004
66	0.103	3.830	0.087	2.740	0.059	2.692	0.083	3.087
67	0.087	3.916	0.070	2.810	0.050	2.741	0.069	3.156
68	0.075	3.991	0.059	2.869	0.044	2.785	0.059	3.215
69	0.064	4.055	0.047	2.916	0.036	2.821	0.049	3.264
70	0.057	4.112	0.041	2.957	0.032	2.854	0.044	3.308
71	0.053	4.165	0.037	2.994	0.031	2.885	0.040	3.348

Table B.1 (continued)

2001 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
72	0.052	4.217	0.038	3.032	0.030	2.915	0.040	3.388
73	0.051	4.268	0.030	3.062	0.033	2.947	0.038	3.426
74	0.078	4.346	0.048	3.110	0.035	2.982	0.054	3.480
75	0.068	4.414	0.049	3.159	0.048	3.031	0.055	3.535
76	0.054	4.468	0.039	3.198	0.056	3.087	0.050	3.585
77	0.045	4.513	0.029	3.227	0.047	3.134	0.040	3.625
78	0.040	4.553	0.024	3.251	0.042	3.176	0.036	3.660
79	0.040	4.593	0.025	3.277	0.046	3.223	0.037	3.698
80	0.092	4.685	0.066	3.342	0.097	3.320	0.085	3.783
81	0.075	4.760	0.057	3.399	0.080	3.400	0.071	3.853
82	0.057	4.817	0.042	3.441	0.159	3.559	0.086	3.939
83	0.050	4.867	0.035	3.475	0.068	3.627	0.051	3.990
84	0.044	4.911	0.029	3.504	0.058	3.686	0.044	4.034
85	0.042	4.953	0.027	3.531	0.047	3.733	0.039	4.073
86	0.038	4.992	0.022	3.553	0.040	3.773	0.033	4.106
87	0.038	5.030	0.021	3.574	0.040	3.813	0.033	4.139
88	0.047	5.077	0.030	3.604	0.050	3.864	0.042	4.182
89	0.049	5.126	0.037	3.640	0.055	3.918	0.047	4.229
90	0.042	5.168	0.030	3.670	0.047	3.966	0.040	4.268
91	0.043	5.210	0.029	3.699	0.047	4.012	0.039	4.307
92	0.038	5.249	0.024	3.723	0.040	4.052	0.034	4.342
93	0.039	5.288	0.026	3.748	0.043	4.095	0.036	4.377
94	0.037	5.324	0.023	3.771	0.039	4.134	0.033	4.410
95	0.036	5.360	0.022	3.793	0.038	4.172	0.032	4.442
96	0.036	5.396	0.024	3.817	0.041	4.213	0.033	4.476
97	0.033	5.429	0.020	3.837	0.036	4.249	0.029	4.505
98	0.032	5.461	0.019	3.855	0.035	4.284	0.029	4.534
99	0.030	5.492	0.019	3.874	0.034	4.317	0.028	4.561
100	0.027	5.518	0.013	3.887	0.028	4.345	0.022	4.584
101	0.018	5.536	0.010	3.897	0.024	4.370	0.018	4.601
102	0.011	5.547	0.008	3.905	0.022	4.392	0.014	4.615
103	0.007	5.554	0.006	3.912	0.021	4.413	0.011	4.627
104	0.007	5.561	0.003	3.915	0.016	4.429	0.009	4.635
105	0.007	5.568	0.002	3.916	0.016	4.444	0.008	4.643
106	0.005	5.572	0.001	3.917	0.011	4.455	0.005	4.649
107	0.000	5.573	0.000	3.917	0.012	4.467	0.004	4.653
108	0.003	5.576	0.001	3.918	0.011	4.478	0.005	4.658
109	0.022	5.599	0.012	3.930	0.025	4.504	0.020	4.678
110	0.017	5.616	0.008	3.938	0.020	4.524	0.015	4.693

Table B.1 (continued)

2001 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
111	0.010	5.627	0.001	3.939	0.011	4.535	0.008	4.700
112	0.008	5.635	0.000	3.939	0.006	4.541	0.005	4.705
113	0.006	5.641	0.000	3.939	0.004	4.545	0.003	4.708
114	0.004	5.645	0.000	3.939	0.002	4.546	0.002	4.710
115	0.020	5.664	0.005	3.944	0.022	4.569	0.016	4.726
116	0.017	5.682	0.008	3.952	0.021	4.590	0.015	4.741
117	0.010	5.692	0.001	3.952	0.009	4.598	0.007	4.748
118	0.004	5.696	0.000	3.952	0.002	4.600	0.002	4.750
119	0.000	5.696	0.000	3.952	0.000	4.600	0.000	4.750
120	0.000	5.696	0.000	3.952	0.000	4.600	0.000	4.750
121	0.000	5.696	0.000	3.952	0.000	4.600	0.000	4.750
122	0.000	5.696	0.000	3.952	0.000	4.600	0.000	4.750
123	0.000	5.696	0.000	3.952	0.000	4.600	0.000	4.750
124	0.000	5.696	0.000	3.952	0.000	4.600	0.000	4.750
125	0.000	5.696	0.000	3.952	0.000	4.600	0.000	4.750
126	0.000	5.696	0.000	3.952	0.000	4.600	0.000	4.750
127	0.000	5.696	0.000	3.952	0.000	4.600	0.000	4.750
128	0.000	5.696	0.000	3.952	0.000	4.600	0.000	4.750
129	0.000	5.696	0.000	3.952	0.000	4.600	0.000	4.750
130	0.000	5.696	0.000	3.952	0.000	4.600	0.000	4.750
131	0.000	5.696	0.000	3.952	0.000	4.600	0.000	4.750
132	0.314	6.010	0.308	4.260	0.358	4.958	0.327	5.076
133	0.925	6.935	0.918	5.178	1.054	6.012	0.966	6.042
134	0.141	7.076	0.135	5.314	0.160	6.172	0.146	6.188
135	0.095	7.171	0.097	5.410	0.108	6.280	0.100	6.288
136	0.067	7.238	0.065	5.475	0.076	6.356	0.069	6.357
137	0.049	7.287	0.045	5.520	0.070	6.426	0.055	6.411
138	0.040	7.327	0.034	5.554	0.055	6.481	0.043	6.454
139	0.029	7.356	0.021	5.575	0.037	6.518	0.029	6.483
140	0.019	7.375	0.010	5.584	0.022	6.541	0.017	6.500
141	0.019	7.393	0.009	5.593	0.021	6.562	0.016	6.516
142	0.014	7.407	0.004	5.597	0.014	6.575	0.010	6.527
143	0.153	7.561	0.125	5.722	0.175	6.750	0.151	6.678
144	0.095	7.655	0.078	5.800	0.105	6.855	0.092	6.770
145	0.056	7.711	0.043	5.843	0.064	6.918	0.054	6.824
146	0.078	7.789	0.063	5.906	0.089	7.007	0.076	6.901
147	0.077	7.866	0.066	5.972	0.088	7.095	0.077	6.978
148	0.049	7.915	0.037	6.009	0.055	7.150	0.047	7.025
149	0.040	7.955	0.029	6.038	0.046	7.196	0.038	7.063

Table B.1 (continued)

2001 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
150	0.030	7.985	0.018	6.056	0.034	7.231	0.028	7.091
151	0.022	8.008	0.010	6.067	0.023	7.254	0.019	7.110
152	0.065	8.073	0.045	6.112	0.073	7.327	0.061	7.171
153	0.249	8.322	0.243	6.355	0.283	7.610	0.258	7.429
154	0.114	8.436	0.109	6.463	0.130	7.740	0.118	7.547
155	0.075	8.510	0.067	6.531	0.085	7.825	0.076	7.622
156	0.052	8.562	0.043	6.574	0.059	7.884	0.051	7.674
157	0.675	9.237	0.669	7.243	0.769	8.653	0.704	8.378
158	0.183	9.420	0.187	7.429	0.231	8.884	0.200	8.578
159	0.120	9.540	0.118	7.547	0.153	9.037	0.130	8.708
160	0.086	9.626	0.082	7.629	0.110	9.147	0.093	8.801
161	0.062	9.688	0.056	7.684	0.078	9.226	0.065	8.866
162	0.046	9.734	0.038	7.722	0.056	9.282	0.047	8.913
163	0.035	9.769	0.025	7.746	0.040	9.322	0.033	8.946
164	0.027	9.796	0.016	7.762	0.028	9.350	0.024	8.970
165	0.121	9.918	0.103	7.865	0.135	9.485	0.120	9.090
166	0.122	10.039	0.113	7.978	0.143	9.627	0.126	9.215
167	0.228	10.267	0.235	8.212	0.259	9.886	0.240	9.455
168	0.208	10.475	0.219	8.431	0.241	10.127	0.222	9.678
169	0.131	10.605	0.132	8.563	0.155	10.282	0.139	9.817
170	0.097	10.702	0.092	8.655	0.115	10.397	0.101	9.918
171	0.075	10.777	0.067	8.722	0.091	10.487	0.078	9.996
172	0.062	10.839	0.050	8.772	0.070	10.557	0.061	10.057
173	0.050	10.889	0.038	8.810	0.056	10.613	0.048	10.104
174	0.081	10.970	0.069	8.879	0.093	10.706	0.081	10.185
175	0.068	11.038	0.056	8.934	0.079	10.786	0.068	10.253
176	0.050	11.087	0.044	8.978	0.055	10.841	0.050	10.302
177	0.038	11.125	0.033	9.011	0.041	10.882	0.037	10.340
178	0.032	11.157	0.026	9.037	0.032	10.913	0.030	10.370
179	0.037	11.194	0.032	9.070	0.038	10.951	0.036	10.405
180	0.033	11.227	0.025	9.094	0.034	10.985	0.031	10.436
181	0.024	11.250	0.013	9.107	0.021	11.006	0.019	10.455
182	0.019	11.269	0.006	9.113	0.012	11.018	0.012	10.467
183	0.014	11.283	0.002	9.115	0.006	11.024	0.007	10.474
184	0.011	11.293	0.000	9.115	0.002	11.026	0.004	10.478
185	0.010	11.303	0.000	9.115	0.000	11.026	0.003	10.481
186	0.021	11.323	0.001	9.115	0.008	11.034	0.010	10.491
187	0.007	11.331	0.000	9.115	0.000	11.034	0.002	10.494
188	0.002	11.333	0.000	9.115	0.000	11.034	0.001	10.494

Table B.1 (continued)

2001 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
189	0.001	11.335	0.000	9.115	0.000	11.034	0.000	10.495
190	0.001	11.335	0.000	9.115	0.000	11.034	0.000	10.495
191	0.000	11.335	0.000	9.115	0.000	11.034	0.000	10.495
192	0.000	11.335	0.000	9.115	0.000	11.034	0.000	10.495
193	0.000	11.335	0.000	9.115	0.000	11.034	0.000	10.495
194	0.000	11.335	0.000	9.115	0.000	11.034	0.000	10.495
195	0.000	11.335	0.000	9.115	0.000	11.034	0.000	10.495
196	0.000	11.335	0.000	9.115	0.000	11.034	0.000	10.495
197	0.000	11.335	0.000	9.115	0.000	11.034	0.000	10.495
198	0.000	11.335	0.000	9.115	0.000	11.034	0.000	10.495
199	0.000	11.335	0.000	9.115	0.000	11.034	0.000	10.495
200	0.008	11.344	0.000	9.115	0.000	11.034	0.003	10.498
201	0.003	11.347	0.000	9.115	0.000	11.034	0.001	10.499
202	0.000	11.347	0.000	9.115	0.000	11.034	0.000	10.499
203	0.000	11.347	0.000	9.115	0.000	11.034	0.000	10.499
204	0.050	11.398	0.022	9.137	0.025	11.059	0.033	10.532
205	0.041	11.439	0.019	9.156	0.025	11.084	0.028	10.560
206	0.017	11.456	0.003	9.159	0.006	11.090	0.009	10.569
207	0.007	11.463	0.000	9.159	0.000	11.090	0.002	10.571
208	0.377	11.840	0.371	9.530	0.405	11.495	0.384	10.955
209	0.168	12.008	0.171	9.701	0.204	11.699	0.181	11.136
210	1.361	13.369	1.353	11.054	1.550	13.249	1.421	12.558
211	0.855	14.224	0.848	11.902	0.974	14.223	0.892	13.450
212	0.293	14.517	0.323	12.225	0.334	14.557	0.317	13.767
213	0.109	14.626	0.199	12.424	0.124	14.681	0.144	13.911
214	0.054	14.680	0.137	12.562	0.169	14.850	0.120	14.031
215	0.096	14.777	0.100	12.661	0.124	14.974	0.107	14.138
216	0.072	14.849	0.073	12.735	0.091	15.065	0.079	14.217
217	0.054	14.903	0.049	12.784	0.068	15.133	0.057	14.274
218	0.042	14.946	0.034	12.818	0.048	15.181	0.041	14.315
219	0.033	14.978	0.022	12.840	0.034	15.215	0.030	14.345
220	0.026	15.005	0.013	12.853	0.023	15.238	0.021	14.366
221	0.018	15.023	0.006	12.859	0.013	15.252	0.013	14.378
222	0.013	15.036	0.002	12.861	0.006	15.258	0.007	14.386
223	0.011	15.047	0.001	12.862	0.002	15.260	0.004	14.390
224	0.008	15.055	0.000	12.862	0.001	15.261	0.003	14.393
225	0.136	15.191	0.107	12.970	0.128	15.389	0.124	14.517
226	0.483	15.674	0.493	13.463	0.525	15.914	0.501	15.017
227	0.208	15.882	0.215	13.678	0.251	16.165	0.225	15.242

Table B.1 (continued)

2001 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
228	0.130	16.012	0.131	13.808	0.158	16.322	0.139	15.381
229	0.091	16.103	0.089	13.897	0.110	16.433	0.097	15.478
230	0.070	16.173	0.063	13.960	0.084	16.516	0.072	15.550
231	0.078	16.250	0.071	14.032	0.089	16.605	0.079	15.629
232	0.123	16.373	0.123	14.155	0.145	16.750	0.130	15.760
233	0.135	16.509	0.144	14.299	0.166	16.916	0.148	15.908
234	0.092	16.601	0.091	14.390	0.113	17.029	0.099	16.007
235	0.072	16.673	0.065	14.455	0.084	17.113	0.074	16.081
236	0.059	16.732	0.049	14.504	0.069	17.182	0.059	16.140
237	0.048	16.780	0.036	14.540	0.054	17.236	0.046	16.186
238	0.042	16.822	0.028	14.567	0.045	17.282	0.038	16.224
239	0.035	16.857	0.021	14.589	0.036	17.318	0.031	16.255
240	0.028	16.886	0.014	14.603	0.027	17.345	0.023	16.278
241	0.055	16.941	0.037	14.640	0.045	17.390	0.046	16.324
242	0.079	17.020	0.066	14.706	0.090	17.480	0.078	16.402
243	0.065	17.084	0.054	14.760	0.085	17.565	0.068	16.470
244	0.044	17.129	0.034	14.794	0.058	17.622	0.045	16.515
245	0.034	17.162	0.023	14.817	0.042	17.664	0.033	16.548
246	0.027	17.189	0.015	14.832	0.032	17.696	0.025	16.573
247	0.023	17.212	0.010	14.842	0.025	17.721	0.019	16.592
248	0.018	17.230	0.006	14.848	0.019	17.740	0.014	16.606
249	0.014	17.244	0.002	14.850	0.012	17.751	0.009	16.615
250	0.011	17.255	0.000	14.850	0.008	17.759	0.006	16.622
251	0.008	17.262	0.000	14.850	0.003	17.762	0.004	16.625
252	0.005	17.267	0.000	14.850	0.000	17.762	0.002	16.627
253	0.003	17.270	0.000	14.850	0.000	17.762	0.001	16.628
254	0.001	17.271	0.000	14.850	0.000	17.762	0.000	16.628
255	0.026	17.297	0.024	14.874	0.006	17.768	0.019	16.647
256	0.040	17.337	0.043	14.917	0.047	17.815	0.044	16.690
257	0.026	17.364	0.025	14.942	0.035	17.851	0.029	16.719
258	0.012	17.376	0.007	14.949	0.011	17.862	0.010	16.729
259	0.006	17.382	0.001	14.950	0.003	17.864	0.003	16.732
260	0.002	17.384	0.000	14.950	0.000	17.864	0.001	16.733
261	0.000	17.384	0.000	14.950	0.000	17.864	0.000	16.733
262	0.000	17.384	0.000	14.950	0.000	17.864	0.000	16.733
263	0.056	17.440	0.037	14.986	0.050	17.915	0.048	16.781
264	0.051	17.491	0.036	15.022	0.056	17.970	0.047	16.828
265	0.023	17.514	0.011	15.033	0.022	17.992	0.019	16.847
266	0.012	17.526	0.002	15.035	0.007	18.000	0.007	16.854

Table B.1 (continued)

2001 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
267	0.020	17.546	0.005	15.040	0.015	18.015	0.013	16.867
268	0.043	17.589	0.026	15.066	0.042	18.057	0.037	16.904
269	0.079	17.667	0.122	15.189	0.106	18.162	0.102	17.006
270	0.061	17.728	0.092	15.281	0.082	18.244	0.078	17.085
271	0.033	17.761	0.045	15.326	0.052	18.296	0.043	17.128
272	0.020	17.782	0.025	15.351	0.031	18.327	0.025	17.153
273	0.014	17.795	0.014	15.365	0.023	18.349	0.017	17.170
274	0.009	17.805	0.007	15.371	0.012	18.362	0.009	17.180
275	0.005	17.809	0.002	15.373	0.004	18.365	0.003	17.183
276	0.002	17.811	0.000	15.373	0.000	18.366	0.001	17.184
277	0.000	17.812	0.000	15.373	0.000	18.366	0.000	17.184
278	0.000	17.812	0.000	15.373	0.000	18.366	0.000	17.184
279	0.000	17.812	0.000	15.373	0.000	18.366	0.000	17.184
280	0.000	17.812	0.000	15.373	0.000	18.366	0.000	17.184
281	0.000	17.812	0.000	15.373	0.000	18.366	0.000	17.184
282	0.000	17.812	0.000	15.373	0.000	18.366	0.000	17.184
283	0.017	17.829	0.001	15.374	0.002	18.368	0.007	17.191
284	0.001	17.830	0.000	15.374	0.000	18.368	0.000	17.191
285	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
286	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
287	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
288	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
289	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
290	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
291	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
292	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
293	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
294	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
295	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
296	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
297	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
298	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
299	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
300	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
301	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
302	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
303	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
304	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
305	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191

Table B.1 (continued)

2001 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
306	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
307	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
308	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
309	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
310	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
311	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
312	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
313	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
314	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
315	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
316	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
317	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
318	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
319	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
320	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
321	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
322	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
323	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
324	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
325	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
326	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
327	0.000	17.830	0.000	15.374	0.000	18.368	0.000	17.191
328	0.004	17.834	0.000	15.374	0.000	18.368	0.001	17.193
329	0.003	17.837	0.000	15.374	0.000	18.368	0.001	17.194
330	0.000	17.837	0.000	15.374	0.000	18.368	0.000	17.194
331	0.000	17.837	0.000	15.374	0.000	18.368	0.000	17.194
332	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
333	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
334	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
335	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
336	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
337	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
338	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
339	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
340	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
341	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
342	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
343	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
344	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194

Table B.1 (continued)

2001 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
345	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
346	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
347	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
348	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
349	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
350	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
351	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
352	0.000	17.837	0.000	15.374	0.000	18.369	0.000	17.194
353	0.000	17.837	0.000	15.375	0.000	18.369	0.000	17.194
354	0.000	17.837	0.000	15.375	0.000	18.369	0.000	17.194
355	0.000	17.837	0.000	15.375	0.000	18.369	0.000	17.194
356	0.000	17.837	0.000	15.375	0.000	18.369	0.000	17.194
357	0.000	17.837	0.000	15.375	0.000	18.369	0.000	17.194
358	0.000	17.837	0.000	15.375	0.000	18.369	0.000	17.194
359	0.000	17.837	0.000	15.375	0.000	18.369	0.000	17.194
360	0.000	17.837	0.000	15.375	0.000	18.369	0.000	17.194
361	0.000	17.837	0.000	15.375	0.000	18.369	0.000	17.194
362	0.000	17.837	0.000	15.375	0.000	18.369	0.000	17.194
363	0.000	17.837	0.000	15.375	0.000	18.369	0.000	17.194
364	0.000	17.837	0.000	15.375	0.000	18.369	0.000	17.194
365	0.000	**17.837**	0.000	**15.375**	0.000	**18.369**	0.000	**17.194**

Table B.2. Plot 1 daily drainage flow in 2002

2002 Flow - Plot 1 (deep drains)
Drain Depth = 1.44 m Drain Spacing = 25 m
Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.302	0.302	0.270	0.270	0.344	0.344	0.305	0.305
7	0.283	0.585	0.272	0.542	0.322	0.666	0.292	0.598
8	0.143	0.727	0.138	0.680	0.162	0.829	0.148	0.745
9	0.106	0.833	0.102	0.782	0.121	0.949	0.109	0.855
10	0.084	0.917	0.081	0.863	0.107	1.057	0.091	0.946
11	0.070	0.987	0.065	0.928	0.088	1.145	0.074	1.020
12	0.061	1.048	0.055	0.983	0.078	1.223	0.065	1.085
13	0.531	1.580	0.565	1.548	0.592	1.816	0.563	1.648
14	0.219	1.799	0.232	1.780	0.268	2.083	0.240	1.887
15	0.328	2.126	0.345	2.125	0.368	2.451	0.347	2.234
16	0.197	2.324	0.237	2.362	0.238	2.689	0.224	2.458
17	0.153	2.477	0.201	2.563	0.185	2.875	0.180	2.638
18	0.125	2.602	0.136	2.699	0.151	3.026	0.138	2.776
19	0.217	2.819	0.218	2.917	0.218	3.243	0.217	2.993
20	0.626	3.445	0.684	3.601	0.682	3.926	0.664	3.657
21	0.306	3.751	0.328	3.929	0.352	4.278	0.329	3.986
22	0.257	4.008	0.271	4.200	0.296	4.574	0.275	4.261
23	0.420	4.428	0.430	4.629	0.434	5.008	0.428	4.688
24	0.401	4.829	0.421	5.051	0.441	5.449	0.421	5.109
25	0.251	5.080	0.263	5.314	0.288	5.736	0.267	5.377
26	0.202	5.282	0.211	5.525	0.232	5.968	0.215	5.592
27	0.169	5.451	0.172	5.697	0.192	6.160	0.178	5.769
28	0.145	5.596	0.145	5.842	0.163	6.322	0.151	5.920
29	0.125	5.721	0.123	5.965	0.140	6.463	0.129	6.049
30	0.109	5.830	0.106	6.070	0.121	6.584	0.112	6.162
31	0.097	5.927	0.092	6.162	0.108	6.692	0.099	6.260
32	0.090	6.017	0.084	6.245	0.099	6.790	0.091	6.351
33	0.078	6.095	0.069	6.315	0.083	6.874	0.077	6.428
34	0.074	6.168	0.066	6.381	0.080	6.954	0.073	6.501
35	0.067	6.235	0.058	6.439	0.074	7.027	0.066	6.567
36	0.058	6.293	0.048	6.487	0.061	7.088	0.055	6.623

Table B.2 (continued)

2002 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
37	0.054	6.348	0.044	6.531	0.057	7.145	0.052	6.675
38	0.181	6.528	0.192	6.723	0.196	7.341	0.190	6.864
39	0.150	6.679	0.152	6.875	0.167	7.508	0.156	7.021
40	0.118	6.797	0.114	6.989	0.130	7.638	0.121	7.141
41	0.103	6.899	0.096	7.085	0.111	7.749	0.103	7.245
42	0.106	7.006	0.101	7.186	0.112	7.861	0.107	7.351
43	0.093	7.099	0.084	7.270	0.096	7.957	0.091	7.442
44	0.080	7.178	0.069	7.338	0.081	8.039	0.077	7.519
45	0.069	7.248	0.058	7.396	0.070	8.109	0.066	7.584
46	0.066	7.313	0.054	7.450	0.063	8.172	0.061	7.645
47	0.061	7.374	0.049	7.499	0.061	8.233	0.057	7.702
48	0.054	7.429	0.041	7.540	0.053	8.286	0.050	7.752
49	0.047	7.476	0.034	7.574	0.044	8.331	0.042	7.793
50	0.045	7.521	0.032	7.606	0.043	8.374	0.040	7.834
51	0.044	7.565	0.031	7.637	0.043	8.417	0.039	7.873
52	0.047	7.612	0.033	7.670	0.046	8.463	0.042	7.915
53	0.042	7.654	0.028	7.698	0.039	8.502	0.036	7.951
54	0.039	7.693	0.024	7.722	0.035	8.536	0.032	7.984
55	0.036	7.729	0.021	7.742	0.031	8.567	0.029	8.013
56	0.035	7.764	0.019	7.762	0.030	8.597	0.028	8.041
57	0.035	7.799	0.020	7.782	0.032	8.629	0.029	8.070
58	0.030	7.829	0.014	7.796	0.024	8.653	0.023	8.093
59	0.024	7.853	0.008	7.805	0.018	8.670	0.017	8.109
60	0.022	7.874	0.006	7.810	0.015	8.685	0.014	8.123
61	0.032	7.907	0.015	7.825	0.090	8.775	0.046	8.169
62	0.975	8.882	1.005	8.831	0.986	9.761	0.989	9.158
63	0.384	9.266	0.392	9.223	0.396	10.157	0.391	9.549
64	0.261	9.527	0.265	9.487	0.273	10.430	0.266	9.815
65	0.196	9.723	0.201	9.688	0.213	10.643	0.203	10.018
66	0.159	9.882	0.159	9.847	0.177	10.819	0.165	10.183
67	0.129	10.011	0.126	9.973	0.170	10.989	0.142	10.325
68	0.109	10.120	0.104	10.078	0.120	11.109	0.111	10.436
69	0.091	10.211	0.086	10.163	0.100	11.210	0.092	10.528
70	0.077	10.288	0.067	10.231	0.081	11.291	0.075	10.603
71	0.070	10.358	0.060	10.291	0.075	11.366	0.069	10.672
72	0.102	10.459	0.098	10.389	0.106	11.472	0.102	10.773
73	0.122	10.581	0.112	10.501	0.126	11.597	0.120	10.893
74	0.102	10.683	0.087	10.587	0.113	11.710	0.100	10.994
75	0.084	10.767	0.069	10.656	0.095	11.805	0.083	11.076

Table B.2 (continued)

2002 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
76	0.072	10.839	0.057	10.713	0.083	11.888	0.071	11.147
77	0.070	10.909	0.054	10.767	0.081	11.969	0.068	11.215
78	0.063	10.972	0.046	10.813	0.074	12.044	0.061	11.276
79	0.068	11.040	0.054	10.866	0.071	12.115	0.064	11.340
80	0.089	11.128	0.077	10.943	0.080	12.196	0.082	11.422
81	0.102	11.230	0.085	11.028	0.095	12.291	0.094	11.516
82	0.086	11.316	0.066	11.095	0.078	12.369	0.077	11.593
83	0.073	11.389	0.054	11.149	0.066	12.434	0.064	11.657
84	0.061	11.450	0.042	11.191	0.054	12.488	0.053	11.710
85	0.069	11.519	0.056	11.247	0.063	12.552	0.063	11.773
86	0.380	11.900	0.382	11.630	0.368	12.920	0.377	12.150
87	0.278	12.178	0.276	11.906	0.288	13.208	0.281	12.431
88	0.194	12.372	0.188	12.094	0.201	13.409	0.194	12.625
89	0.163	12.535	0.156	12.250	0.165	13.574	0.161	12.786
90	0.266	12.801	0.238	12.488	0.250	13.824	0.251	13.038
91	0.873	13.674	0.832	13.321	0.888	14.712	0.865	13.902
92	0.362	14.037	0.367	13.688	0.406	15.118	0.378	14.281
93	0.256	14.292	0.266	13.954	0.291	15.409	0.271	14.552
94	0.297	14.589	0.294	14.247	0.317	15.727	0.303	14.854
95	0.216	14.805	0.213	14.460	0.241	15.968	0.223	15.078
96	0.173	14.978	0.169	14.629	0.196	16.163	0.179	15.257
97	0.143	15.121	0.138	14.767	0.163	16.327	0.148	15.405
98	0.122	15.243	0.117	14.883	0.141	16.468	0.127	15.531
99	0.105	15.349	0.100	14.983	0.122	16.589	0.109	15.640
100	0.094	15.443	0.088	15.071	0.109	16.698	0.097	15.737
101	0.087	15.530	0.078	15.150	0.099	16.797	0.088	15.825
102	0.079	15.608	0.071	15.220	0.090	16.886	0.080	15.905
103	0.072	15.681	0.063	15.284	0.082	16.969	0.073	15.978
104	0.068	15.748	0.058	15.342	0.077	17.046	0.067	16.045
105	0.061	15.810	0.051	15.392	0.070	17.115	0.061	16.106
106	0.056	15.866	0.043	15.436	0.062	17.177	0.054	16.160
107	0.052	15.918	0.038	15.474	0.057	17.234	0.049	16.209
108	0.047	15.965	0.033	15.507	0.052	17.287	0.044	16.253
109	0.043	16.008	0.029	15.536	0.048	17.335	0.040	16.293
110	0.041	16.049	0.027	15.563	0.045	17.380	0.038	16.331
111	0.036	16.085	0.022	15.584	0.040	17.420	0.033	16.363
112	0.038	16.123	0.020	15.605	0.038	17.458	0.032	16.395
113	0.029	16.152	0.013	15.618	0.030	17.488	0.024	16.419
114	0.037	16.188	0.021	15.639	0.035	17.523	0.031	16.450

Table B.2 (continued)

2002 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
115	0.074	16.263	0.057	15.696	0.079	17.602	0.070	16.520
116	0.055	16.318	0.042	15.738	0.063	17.665	0.053	16.574
117	0.041	16.359	0.027	15.765	0.047	17.712	0.038	16.612
118	0.038	16.397	0.025	15.791	0.045	17.757	0.036	16.648
119	0.030	16.426	0.017	15.808	0.034	17.791	0.027	16.675
120	0.023	16.450	0.010	15.817	0.025	17.817	0.020	16.695
121	0.029	16.479	0.013	15.831	0.029	17.846	0.024	16.718
122	0.025	16.503	0.010	15.841	0.025	17.871	0.020	16.738
123	0.019	16.522	0.005	15.846	0.018	17.889	0.014	16.752
124	0.024	16.546	0.009	15.855	0.023	17.912	0.019	16.771
125	0.030	16.576	0.017	15.872	0.030	17.942	0.026	16.797
126	0.024	16.600	0.010	15.882	0.024	17.966	0.019	16.816
127	0.022	16.622	0.008	15.891	0.022	17.988	0.017	16.834
128	0.018	16.640	0.005	15.896	0.017	18.005	0.013	16.847
129	0.016	16.656	0.004	15.900	0.015	18.021	0.012	16.859
130	0.013	16.669	0.001	15.901	0.011	18.032	0.008	16.867
131	0.011	16.679	0.000	15.901	0.007	18.039	0.006	16.873
132	0.012	16.691	0.000	15.901	0.010	18.049	0.007	16.880
133	0.021	16.712	0.004	15.905	0.020	18.069	0.015	16.895
134	0.075	16.787	0.052	15.957	0.079	18.148	0.069	16.964
135	0.038	16.825	0.021	15.977	0.039	18.187	0.032	16.996
136	0.027	16.852	0.012	15.989	0.027	18.214	0.022	17.018
137	0.021	16.873	0.008	15.997	0.020	18.234	0.016	17.035
138	0.055	16.928	0.034	16.031	0.053	18.288	0.047	17.082
139	0.053	16.981	0.034	16.065	0.055	18.343	0.047	17.129
140	0.036	17.016	0.019	16.084	0.036	18.378	0.030	17.160
141	0.025	17.042	0.011	16.095	0.024	18.402	0.020	17.180
142	0.083	17.125	0.063	16.158	0.073	18.475	0.073	17.253
143	0.068	17.193	0.057	16.215	0.068	18.543	0.064	17.317
144	0.041	17.234	0.034	16.249	0.045	18.587	0.040	17.357
145	0.025	17.259	0.018	16.268	0.028	18.616	0.024	17.381
146	0.017	17.276	0.010	16.277	0.018	18.634	0.015	17.396
147	0.011	17.287	0.004	16.281	0.011	18.645	0.009	17.404
148	0.008	17.295	0.001	16.282	0.006	18.651	0.005	17.410
149	0.006	17.301	0.000	16.282	0.004	18.655	0.003	17.413
150	0.006	17.307	0.000	16.282	0.003	18.658	0.003	17.416
151	0.003	17.310	0.000	16.282	0.001	18.659	0.001	17.417
152	0.002	17.312	0.000	16.282	0.000	18.659	0.001	17.418
153	0.000	17.312	0.000	16.282	0.000	18.659	0.000	17.418

Table B.2 (continued)

2002 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
154	0.000	17.312	0.000	16.282	0.000	18.659	0.000	17.418
155	0.000	17.312	0.000	16.282	0.000	18.659	0.000	17.418
156	0.000	17.312	0.000	16.282	0.000	18.659	0.000	17.418
157	0.000	17.312	0.000	16.282	0.000	18.659	0.000	17.418
158	0.150	17.462	0.134	16.416	0.153	18.812	0.146	17.563
159	0.058	17.520	0.052	16.469	0.067	18.879	0.059	17.622
160	0.034	17.554	0.029	16.498	0.040	18.919	0.034	17.657
161	0.018	17.572	0.014	16.511	0.022	18.940	0.018	17.675
162	0.009	17.581	0.004	16.515	0.009	18.950	0.007	17.682
163	0.004	17.585	0.000	16.515	0.003	18.953	0.002	17.684
164	0.001	17.586	0.000	16.515	0.000	18.953	0.000	17.685
165	0.000	17.586	0.000	16.515	0.000	18.953	0.000	17.685
166	0.000	17.586	0.000	16.515	0.000	18.953	0.000	17.685
167	0.000	17.586	0.000	16.515	0.000	18.953	0.000	17.685
168	0.000	17.586	0.000	16.515	0.000	18.953	0.000	17.685
169	0.000	17.586	0.000	16.515	0.000	18.953	0.000	17.685
170	0.028	17.614	0.021	16.536	0.030	18.983	0.026	17.711
171	0.027	17.642	0.020	16.556	0.035	19.018	0.027	17.738
172	0.005	17.647	0.002	16.558	0.007	19.025	0.005	17.743
173	0.000	17.647	0.000	16.558	0.000	19.025	0.000	17.743
174	0.000	17.647	0.000	16.558	0.000	19.025	0.000	17.743
175	0.000	17.647	0.000	16.558	0.000	19.025	0.000	17.743
176	0.000	17.647	0.000	16.558	0.000	19.025	0.000	17.743
177	0.000	17.647	0.000	16.558	0.000	19.025	0.000	17.743
178	0.038	17.685	0.045	16.603	0.046	19.071	0.043	17.786
179	0.067	17.752	0.075	16.678	0.088	19.159	0.077	17.863
180	0.041	17.793	0.045	16.722	0.054	19.213	0.047	17.909
181	0.012	17.805	0.011	16.733	0.016	19.230	0.013	17.922
182	0.002	17.806	0.000	16.733	0.002	19.232	0.001	17.924
183	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
184	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
185	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
186	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
187	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
188	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
189	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
190	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
191	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
192	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924

Table B.2 (continued)

2002 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
193	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
194	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
195	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
196	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
197	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
198	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
199	0.000	17.806	0.000	16.733	0.000	19.232	0.000	17.924
200	0.216	18.022	0.109	16.842	0.228	19.460	0.184	18.108
201	0.678	18.699	0.723	17.564	0.727	20.187	0.709	18.817
202	0.320	19.019	0.342	17.907	0.349	20.536	0.337	19.154
203	0.151	19.171	0.160	18.067	0.172	20.708	0.161	19.315
204	0.142	19.313	0.148	18.215	0.162	20.870	0.150	19.466
205	0.282	19.595	0.293	18.507	0.325	21.195	0.300	19.766
206	0.275	19.870	0.282	18.789	0.329	21.523	0.295	20.061
207	0.426	20.296	0.418	19.207	0.455	21.978	0.433	20.494
208	0.324	20.620	0.326	19.533	0.371	22.349	0.340	20.834
209	0.185	20.805	0.189	19.722	0.225	22.573	0.200	21.034
210	0.126	20.931	0.126	19.848	0.158	22.732	0.137	21.171
211	0.089	21.021	0.087	19.935	0.115	22.847	0.097	21.268
212	0.104	21.124	0.116	20.051	0.129	22.976	0.116	21.384
213	0.096	21.221	0.095	20.147	0.107	23.083	0.100	21.484
214	0.062	21.283	0.061	20.207	0.076	23.159	0.066	21.550
215	0.044	21.327	0.042	20.249	0.056	23.215	0.047	21.597
216	0.031	21.358	0.028	20.277	0.040	23.255	0.033	21.630
217	0.023	21.380	0.018	20.296	0.028	23.283	0.023	21.653
218	0.017	21.397	0.012	20.308	0.020	23.303	0.016	21.669
219	0.009	21.407	0.004	20.312	0.008	23.312	0.007	21.677
220	0.004	21.410	0.000	20.312	0.002	23.314	0.002	21.678
221	0.001	21.411	0.000	20.312	0.000	23.314	0.000	21.679
222	0.000	21.411	0.000	20.312	0.000	23.314	0.000	21.679
223	0.000	21.411	0.000	20.312	0.000	23.314	0.000	21.679
224	0.000	21.411	0.000	20.312	0.000	23.314	0.000	21.679
225	0.000	21.411	0.000	20.312	0.000	23.314	0.000	21.679
226	0.000	21.411	0.000	20.312	0.000	23.314	0.000	21.679
227	0.044	21.456	0.051	20.363	0.069	23.383	0.055	21.734
228	0.038	21.494	0.035	20.398	0.056	23.439	0.043	21.777
229	0.014	21.507	0.007	20.405	0.017	23.456	0.013	21.790
230	0.004	21.511	0.000	20.405	0.003	23.459	0.002	21.792
231	0.000	21.511	0.000	20.405	0.000	23.459	0.000	21.792

Table B.2 (continued)

2002 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
232	0.000	21.511	0.000	20.405	0.000	23.459	0.000	21.792
233	0.000	21.511	0.000	20.405	0.000	23.459	0.000	21.792
234	0.000	21.511	0.000	20.405	0.000	23.459	0.000	21.792
235	0.000	21.511	0.000	20.405	0.000	23.459	0.000	21.792
236	0.004	21.515	0.004	20.409	0.000	23.459	0.003	21.794
237	0.002	21.518	0.002	20.411	0.006	23.465	0.004	21.798
238	0.633	22.150	0.612	21.023	0.005	23.470	0.417	22.215
239	0.522	22.672	0.564	21.588	0.320	23.790	0.469	22.683
240	0.293	22.965	0.313	21.901	0.369	24.158	0.325	23.008
241	0.192	23.157	0.202	22.103	0.239	24.397	0.211	23.219
242	1.727	24.884	1.735	23.837	1.841	26.238	1.767	24.987
243	1.256	26.140	0.594	24.432	1.337	27.575	1.063	26.049
244	0.506	26.647	0.592	25.024	0.546	28.121	0.548	26.597
245	0.307	26.954	0.592	25.616	0.342	28.463	0.414	27.011
246	0.212	27.166	0.219	25.835	0.246	28.709	0.226	27.237
247	0.158	27.324	0.160	25.995	0.186	28.895	0.168	27.405
248	0.109	27.433	0.117	26.112	0.143	29.038	0.123	27.527
249	0.094	27.527	0.090	26.202	0.114	29.152	0.100	27.627
250	0.075	27.601	0.070	26.272	0.092	29.244	0.079	27.706
251	0.061	27.662	0.055	26.327	0.075	29.319	0.064	27.770
252	0.053	27.716	0.047	26.374	0.066	29.386	0.055	27.825
253	0.062	27.778	0.063	26.437	0.076	29.461	0.067	27.892
254	0.060	27.838	0.056	26.493	0.068	29.529	0.061	27.953
255	0.049	27.887	0.039	26.533	0.054	29.582	0.047	28.001
256	0.042	27.929	0.032	26.564	0.046	29.628	0.040	28.040
257	0.037	27.966	0.026	26.590	0.040	29.668	0.034	28.075
258	0.034	28.001	0.022	26.612	0.036	29.704	0.031	28.106
259	0.207	28.208	0.202	26.814	0.213	29.917	0.207	28.313
260	0.322	28.530	0.321	27.135	0.328	30.245	0.323	28.636
261	0.215	28.745	0.214	27.349	0.231	30.476	0.220	28.857
262	0.212	28.957	0.219	27.568	0.228	30.704	0.220	29.076
263	0.172	29.128	0.164	27.732	0.191	30.895	0.175	29.252
264	0.127	29.255	0.123	27.855	0.149	31.044	0.133	29.384
265	0.100	29.355	0.097	27.952	0.120	31.164	0.106	29.490
266	0.082	29.437	0.077	28.029	0.099	31.263	0.086	29.576
267	0.068	29.505	0.061	28.089	0.083	31.346	0.070	29.647
268	0.095	29.600	0.090	28.180	0.098	31.444	0.094	29.741
269	0.123	29.723	0.123	28.303	0.119	31.562	0.122	29.863
270	0.100	29.823	0.099	28.402	0.105	31.668	0.101	29.964

Table B.2 (continued)

2002 Flow - Plot 1 (deep drains)

Drain Depth = 1.44 m Drain Spacing = 25 m

Estimated flow

	P1A		P1B		P1C		Average Plot 1	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
271	0.079	29.902	0.077	28.479	0.088	31.756	0.082	30.046
272	0.066	29.968	0.062	28.541	0.076	31.832	0.068	30.114
273	0.058	**30.026**	0.059	**28.600**	0.073	**31.905**	0.063	**30.177**

APPENDIX 1-C

Drainage Flow Data for Plot 2

Table C.1. Plot 2 daily drainage flow in 2001

2001 Flow - Plot 2 (shallow drains)
Drain Depth = 0.70 m Drain Spacing = 12.5 m
Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	0.001	0.001	0.037	0.037	0.068	0.068	0.035	0.035
21	0.001	0.003	0.037	0.074	0.116	0.183	0.051	0.087
22	0.001	0.004	0.024	0.098	0.079	0.262	0.035	0.122
23	0.001	0.006	0.023	0.121	0.063	0.325	0.029	0.151
24	0.000	0.006	0.008	0.129	0.046	0.370	0.018	0.168
25	0.000	0.006	0.001	0.130	0.036	0.406	0.012	0.181
26	0.000	0.006	0.001	0.131	0.023	0.429	0.008	0.189
27	0.000	0.006	0.000	0.131	0.017	0.446	0.006	0.194
28	0.000	0.006	0.000	0.131	0.003	0.449	0.001	0.195
29	0.000	0.006	0.000	0.131	0.000	0.449	0.000	0.195
30	0.000	0.006	0.000	0.131	0.002	0.451	0.001	0.196
31	0.000	0.006	0.000	0.131	0.000	0.451	0.000	0.196
32	0.000	0.006	0.000	0.131	0.000	0.451	0.000	0.196

Table C.1 (continued)

2001 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
33	0.000	0.006	0.000	0.131	0.000	0.451	0.000	0.196
34	0.000	0.006	0.000	0.131	0.000	0.451	0.000	0.196
35	0.000	0.006	0.000	0.131	0.000	0.451	0.000	0.196
36	0.000	0.006	0.000	0.131	0.000	0.451	0.000	0.196
37	0.000	0.006	0.000	0.131	0.000	0.452	0.000	0.196
38	0.000	0.006	0.000	0.131	0.000	0.452	0.000	0.196
39	0.000	0.006	0.000	0.131	0.000	0.452	0.000	0.196
40	0.000	0.006	0.000	0.131	0.000	0.452	0.000	0.196
41	0.000	0.006	0.000	0.131	0.000	0.452	0.000	0.196
42	0.000	0.006	0.000	0.131	0.000	0.452	0.000	0.196
43	0.000	0.006	0.000	0.131	0.000	0.452	0.000	0.196
44	0.000	0.006	0.000	0.131	0.000	0.452	0.000	0.196
45	0.000	0.006	0.000	0.131	0.000	0.452	0.000	0.196
46	0.000	0.006	0.000	0.131	0.000	0.452	0.000	0.196
47	0.000	0.006	0.000	0.131	0.000	0.452	0.000	0.196
48	0.006	0.012	0.020	0.151	0.078	0.529	0.035	0.231
49	0.000	0.012	0.007	0.158	0.091	0.621	0.033	0.264
50	0.000	0.012	0.000	0.158	0.055	0.676	0.018	0.282
51	0.000	0.012	0.000	0.158	0.036	0.712	0.012	0.294
52	0.000	0.012	0.000	0.158	0.023	0.735	0.008	0.302
53	0.083	0.095	0.117	0.276	0.184	0.919	0.128	0.430
54	0.063	0.158	0.198	0.473	0.342	1.261	0.201	0.631
55	0.016	0.174	0.102	0.576	0.196	1.458	0.105	0.736
56	0.001	0.175	0.062	0.637	0.127	1.585	0.063	0.799
57	0.000	0.175	0.048	0.685	0.101	1.685	0.049	0.848
58	0.000	0.175	0.028	0.713	0.073	1.759	0.034	0.882
59	0.000	0.175	0.018	0.731	0.058	1.817	0.025	0.908
60	0.000	0.175	0.010	0.740	0.044	1.861	0.018	0.925
61	0.000	0.175	0.004	0.745	0.034	1.894	0.013	0.938
62	0.000	0.176	0.000	0.745	0.026	1.920	0.009	0.947
63	0.075	0.251	0.149	0.894	0.213	2.133	0.146	1.092
64	0.030	0.281	0.149	1.042	0.231	2.364	0.137	1.229
65	0.015	0.296	0.089	1.132	0.152	2.516	0.085	1.314
66	0.002	0.297	0.049	1.180	0.099	2.615	0.050	1.364
67	0.000	0.297	0.029	1.210	0.071	2.686	0.033	1.398
68	0.000	0.297	0.018	1.228	0.050	2.736	0.023	1.420
69	0.000	0.297	0.008	1.235	0.034	2.769	0.014	1.434
70	0.000	0.297	0.002	1.237	0.024	2.794	0.009	1.443
71	0.000	0.297	0.000	1.237	0.018	2.812	0.006	1.449

Table C.1 (continued)

2001 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
72	0.003	0.300	0.000	1.237	0.017	2.829	0.007	1.456
73	0.000	0.300	0.002	1.239	0.010	2.840	0.004	1.460
74	0.047	0.347	0.097	1.336	0.136	2.976	0.093	1.553
75	0.016	0.364	0.045	1.381	0.063	3.039	0.042	1.595
76	0.000	0.364	0.015	1.396	0.028	3.067	0.014	1.609
77	0.000	0.364	0.004	1.400	0.007	3.074	0.004	1.613
78	0.000	0.364	0.000	1.400	0.000	3.074	0.000	1.613
79	0.000	0.364	0.000	1.400	0.000	3.074	0.000	1.613
80	0.024	0.388	0.042	1.442	0.038	3.112	0.035	1.647
81	0.000	0.388	0.022	1.463	0.022	3.134	0.015	1.662
82	0.000	0.388	0.005	1.469	0.004	3.138	0.003	1.665
83	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
84	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
85	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
86	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
87	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
88	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
89	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
90	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
91	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
92	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
93	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
94	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
95	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
96	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
97	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
98	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
99	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
100	0.000	0.388	0.000	1.469	0.000	3.138	0.000	1.665
101	0.000	0.388	0.000	1.469	0.001	3.139	0.000	1.666
102	0.000	0.388	0.000	1.469	0.000	3.139	0.000	1.666
103	0.000	0.388	0.000	1.469	0.000	3.139	0.000	1.666
104	0.000	0.388	0.000	1.469	0.000	3.139	0.000	1.666
105	0.000	0.388	0.000	1.469	0.000	3.139	0.000	1.666
106	0.000	0.388	0.000	1.469	0.000	3.139	0.000	1.666
107	0.000	0.388	0.000	1.469	0.000	3.139	0.000	1.666
108	0.000	0.388	0.000	1.469	0.000	3.139	0.000	1.666
109	0.000	0.388	0.000	1.470	0.000	3.139	0.000	1.666
110	0.000	0.388	0.000	1.470	0.000	3.139	0.000	1.666

Table C.1 (continued)

2001 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
111	0.000	0.388	0.000	1.470	0.000	3.139	0.000	1.666
112	0.000	0.388	0.000	1.470	0.000	3.139	0.000	1.666
113	0.000	0.388	0.000	1.470	0.000	3.139	0.000	1.666
114	0.000	0.388	0.000	1.470	0.000	3.139	0.000	1.666
115	0.001	0.389	0.002	1.472	0.000	3.140	0.001	1.667
116	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
117	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
118	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
119	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
120	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
121	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
122	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
123	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
124	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
125	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
126	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
127	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
128	0.000	0.389	0.000	1.472	0.001	3.140	0.000	1.667
129	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
130	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
131	0.000	0.389	0.000	1.472	0.000	3.140	0.000	1.667
132	0.013	0.402	0.112	1.584	0.135	3.276	0.087	1.754
133	0.000	0.402	0.072	1.656	0.120	3.396	0.064	1.818
134	0.000	0.402	0.000	1.656	0.001	3.397	0.000	1.818
135	0.000	0.402	0.000	1.656	0.000	3.397	0.000	1.818
136	0.000	0.402	0.000	1.656	0.000	3.397	0.000	1.818
137	0.000	0.402	0.000	1.656	0.000	3.397	0.000	1.818
138	0.000	0.402	0.000	1.656	0.000	3.397	0.000	1.818
139	0.000	0.402	0.000	1.656	0.000	3.397	0.000	1.818
140	0.000	0.402	0.000	1.656	0.000	3.397	0.000	1.818
141	0.000	0.402	0.000	1.656	0.000	3.397	0.000	1.818
142	0.000	0.402	0.000	1.656	0.000	3.397	0.000	1.818
143	0.000	0.402	0.015	1.671	0.020	3.417	0.012	1.830
144	0.000	0.402	0.001	1.672	0.000	3.417	0.000	1.830
145	0.000	0.402	0.000	1.672	0.000	3.417	0.000	1.830
146	0.001	0.403	0.010	1.682	0.011	3.428	0.007	1.838
147	0.000	0.403	0.000	1.682	0.000	3.428	0.000	1.838
148	0.000	0.403	0.000	1.682	0.000	3.428	0.000	1.838
149	0.000	0.403	0.000	1.682	0.000	3.428	0.000	1.838

Table C.1 (continued)

2001 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
150	0.000	0.403	0.000	1.682	0.000	3.428	0.000	1.838
151	0.000	0.403	0.000	1.682	0.000	3.428	0.000	1.838
152	0.004	0.407	0.026	1.708	0.029	3.457	0.019	1.857
153	0.065	0.473	0.197	1.905	0.258	3.715	0.174	2.031
154	0.000	0.473	0.004	1.909	0.017	3.732	0.007	2.038
155	0.000	0.473	0.000	1.909	0.000	3.732	0.000	2.038
156	0.000	0.473	0.000	1.909	0.000	3.732	0.000	2.038
157	0.407	0.879	0.529	2.438	0.578	4.310	0.505	2.542
158	0.009	0.888	0.073	2.511	0.106	4.415	0.062	2.605
159	0.000	0.888	0.007	2.518	0.028	4.443	0.012	2.616
160	0.000	0.888	0.000	2.518	0.003	4.447	0.001	2.617
161	0.000	0.888	0.000	2.518	0.000	4.447	0.000	2.617
162	0.000	0.888	0.000	2.518	0.000	4.447	0.000	2.617
163	0.000	0.888	0.000	2.518	0.000	4.447	0.000	2.617
164	0.000	0.888	0.000	2.518	0.000	4.447	0.000	2.618
165	0.001	0.889	0.037	2.555	0.085	4.532	0.041	2.658
166	0.000	0.889	0.032	2.587	0.087	4.618	0.040	2.698
167	0.239	1.128	0.405	2.992	0.528	5.146	0.391	3.089
168	0.149	1.277	0.267	3.259	0.369	5.515	0.262	3.350
169	0.002	1.280	0.056	3.315	0.140	5.655	0.066	3.417
170	0.000	1.280	0.006	3.321	0.083	5.738	0.030	3.446
171	0.000	1.280	0.004	3.325	0.052	5.790	0.019	3.465
172	0.000	1.280	0.000	3.325	0.029	5.819	0.010	3.475
173	0.000	1.280	0.000	3.325	0.011	5.830	0.004	3.478
174	0.000	1.280	0.006	3.331	0.089	5.918	0.032	3.510
175	0.000	1.280	0.000	3.331	0.067	5.985	0.022	3.532
176	0.000	1.280	0.000	3.331	0.023	6.009	0.008	3.540
177	0.000	1.280	0.000	3.331	0.002	6.010	0.001	3.540
178	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
179	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
180	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
181	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
182	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
183	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
184	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
185	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
186	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
187	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
188	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541

Table C.1 (continued)

2001 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
189	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
190	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
191	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
192	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
193	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
194	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
195	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
196	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
197	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
198	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
199	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
200	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
201	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
202	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
203	0.000	1.280	0.000	3.332	0.000	6.010	0.000	3.541
204	0.000	1.281	0.000	3.332	0.000	6.010	0.000	3.541
205	0.000	1.281	0.000	3.332	0.000	6.010	0.000	3.541
206	0.000	1.281	0.000	3.332	0.000	6.010	0.000	3.541
207	0.000	1.281	0.000	3.332	0.000	6.010	0.000	3.541
208	0.130	1.411	0.257	3.589	0.391	6.401	0.259	3.800
209	0.000	1.411	0.020	3.609	0.066	6.467	0.029	3.829
210	1.045	2.456	1.080	4.689	1.218	7.685	1.114	4.943
211	0.660	3.115	0.796	5.485	1.013	8.698	0.823	5.766
212	0.074	3.189	0.176	5.661	0.339	9.037	0.197	5.962
213	0.001	3.190	0.043	5.705	0.174	9.211	0.073	6.035
214	0.000	3.191	0.006	5.711	0.091	9.302	0.033	6.068
215	0.000	3.191	0.000	5.711	0.043	9.345	0.014	6.082
216	0.000	3.191	0.000	5.711	0.012	9.357	0.004	6.086
217	0.000	3.191	0.000	5.711	0.000	9.357	0.000	6.086
218	0.000	3.191	0.000	5.711	0.000	9.357	0.000	6.086
219	0.000	3.191	0.000	5.711	0.000	9.357	0.000	6.086
220	0.000	3.191	0.000	5.711	0.000	9.357	0.000	6.086
221	0.000	3.191	0.000	5.711	0.000	9.357	0.000	6.086
222	0.000	3.191	0.000	5.711	0.000	9.357	0.000	6.086
223	0.000	3.191	0.000	5.711	0.000	9.357	0.000	6.086
224	0.000	3.191	0.000	5.711	0.000	9.357	0.000	6.086
225	0.001	3.192	0.026	5.738	0.064	9.421	0.030	6.117
226	0.347	3.539	0.531	6.269	0.832	10.253	0.570	6.687
227	0.010	3.549	0.091	6.359	0.206	10.459	0.102	6.789

Table C.1 (continued)

2001 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
228	0.000	3.549	0.004	6.363	0.070	10.529	0.025	6.814
229	0.000	3.549	0.000	6.363	0.020	10.549	0.007	6.820
230	0.000	3.549	0.000	6.363	0.002	10.551	0.001	6.821
231	0.000	3.549	0.000	6.363	0.029	10.580	0.010	6.831
232	0.001	3.550	0.064	6.426	0.176	10.756	0.080	6.911
233	0.000	3.550	0.090	6.516	0.253	11.009	0.114	7.025
234	0.000	3.550	0.014	6.530	0.121	11.130	0.045	7.070
235	0.000	3.550	0.000	6.530	0.066	11.196	0.022	7.092
236	0.000	3.550	0.000	6.530	0.036	11.232	0.012	7.104
237	0.000	3.550	0.000	6.530	0.014	11.246	0.005	7.109
238	0.000	3.550	0.000	6.530	0.001	11.246	0.000	7.109
239	0.000	3.550	0.000	6.530	0.000	11.246	0.000	7.109
240	0.000	3.550	0.000	6.530	0.000	11.246	0.000	7.109
241	0.000	3.550	0.000	6.530	0.000	11.246	0.000	7.109
242	0.000	3.550	0.000	6.530	0.000	11.246	0.000	7.109
243	0.000	3.550	0.000	6.530	0.001	11.247	0.000	7.109
244	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
245	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
246	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
247	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
248	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
249	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
250	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
251	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
252	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
253	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
254	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
255	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
256	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
257	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
258	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
259	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
260	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
261	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
262	0.000	3.550	0.000	6.530	0.000	11.247	0.000	7.109
263	0.000	3.551	0.000	6.530	0.000	11.247	0.000	7.109
264	0.000	3.551	0.000	6.530	0.000	11.247	0.000	7.109
265	0.000	3.551	0.000	6.530	0.000	11.247	0.000	7.109
266	0.000	3.551	0.000	6.530	0.000	11.247	0.000	7.109

Table C.1 (continued)

2001 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
267	0.000	3.551	0.000	6.530	0.000	11.247	0.000	7.109
268	0.000	3.551	0.000	6.530	0.000	11.247	0.000	7.109
269	0.001	3.552	0.002	6.531	0.000	11.247	0.001	7.110
270	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
271	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
272	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
273	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
274	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
275	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
276	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
277	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
278	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
279	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
280	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
281	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
282	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
283	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
284	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
285	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
286	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
287	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
288	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
289	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
290	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
291	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
292	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
293	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
294	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
295	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
296	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
297	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
298	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
299	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
300	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
301	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
302	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
303	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
304	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
305	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110

Table C.1 (continued)

2001 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
306	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
307	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
308	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
309	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
310	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
311	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
312	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
313	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
314	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
315	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
316	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
317	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
318	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
319	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
320	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
321	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
322	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
323	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
324	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
325	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
326	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
327	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
328	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
329	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
330	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
331	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
332	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
333	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
334	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
335	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
336	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
337	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
338	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
339	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
340	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
341	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
342	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
343	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
344	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110

Table C.1 (continued)

2001 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
345	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
346	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
347	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
348	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
349	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
350	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
351	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
352	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
353	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
354	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
355	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
356	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
357	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
358	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
359	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
360	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
361	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
362	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
363	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
364	0.000	3.552	0.000	6.531	0.000	11.247	0.000	7.110
365	0.000	**3.552**	0.000	**6.531**	0.000	**11.247**	0.000	**7.110**

Table C.2. Plot 2 daily drainage flow in 2002

2002 Flow - Plot 2 (shallow drains)
Drain Depth = 0.70 m Drain Spacing = 12.5 m
Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.217	0.217	0.306	0.306	0.000	0.000	0.174	0.174
7	0.121	0.338	0.235	0.541	0.386	0.386	0.247	0.421
8	0.000	0.338	0.028	0.569	0.250	0.635	0.093	0.514
9	0.000	0.338	0.001	0.570	0.025	0.660	0.009	0.523
10	0.000	0.338	0.000	0.570	0.000	0.660	0.000	0.523
11	0.000	0.338	0.000	0.570	0.000	0.660	0.000	0.523
12	0.000	0.338	0.000	0.570	0.000	0.660	0.000	0.523
13	0.700	1.038	0.861	1.431	0.891	1.551	0.817	1.340
14	0.067	1.105	0.167	1.598	0.169	1.720	0.134	1.474
15	0.408	1.513	0.460	2.057	0.486	2.206	0.451	1.926
16	0.062	1.575	0.146	2.203	0.155	2.361	0.121	2.047
17	0.014	1.589	0.077	2.280	0.090	2.451	0.060	2.107
18	0.000	1.589	0.040	2.320	0.059	2.509	0.033	2.140
19	0.160	1.749	0.180	2.500	0.212	2.721	0.184	2.324
20	0.863	2.612	0.953	3.453	0.996	3.717	0.937	3.261
21	0.281	2.893	0.344	3.797	0.383	4.101	0.336	3.597
22	0.184	3.077	0.258	4.055	0.298	4.399	0.247	3.844
23	0.593	3.670	0.607	4.661	0.663	5.062	0.621	4.464
24	0.428	4.097	0.495	5.157	0.544	5.606	0.489	4.953
25	0.153	4.251	0.216	5.372	0.222	5.829	0.197	5.150
26	0.062	4.312	0.127	5.500	0.131	5.960	0.107	5.257
27	0.018	4.331	0.078	5.578	0.076	6.036	0.058	5.315
28	0.001	4.332	0.049	5.627	0.043	6.079	0.031	5.346
29	0.000	4.332	0.026	5.653	0.015	6.094	0.014	5.360
30	0.000	4.332	0.007	5.661	0.000	6.094	0.002	5.362
31	0.000	4.332	0.000	5.661	0.000	6.094	0.000	5.362
32	0.000	4.332	0.000	5.661	0.000	6.094	0.000	5.362
33	0.000	4.332	0.000	5.661	0.000	6.094	0.000	5.362
34	0.000	4.332	0.000	5.661	0.000	6.094	0.000	5.362
35	0.000	4.332	0.000	5.661	0.000	6.094	0.000	5.362
36	0.000	4.332	0.000	5.661	0.000	6.094	0.000	5.362
37	0.000	4.332	0.000	5.661	0.000	6.094	0.000	5.362

Table C.2 (continued)

2002 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
38	0.049	4.381	0.154	5.815	0.128	6.222	0.110	5.473
39	0.023	4.403	0.141	5.956	0.129	6.351	0.097	5.570
40	0.000	4.403	0.065	6.021	0.056	6.407	0.040	5.610
41	0.000	4.403	0.029	6.050	0.018	6.425	0.016	5.626
42	0.000	4.403	0.065	6.115	0.050	6.475	0.038	5.664
43	0.000	4.403	0.021	6.136	0.010	6.484	0.010	5.674
44	0.001	4.405	0.001	6.136	0.000	6.484	0.001	5.675
45	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
46	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
47	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
48	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
49	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
50	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
51	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
52	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
53	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
54	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
55	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
56	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
57	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
58	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
59	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
60	0.000	4.405	0.000	6.136	0.000	6.484	0.000	5.675
61	0.001	4.405	0.000	6.136	0.000	6.484	0.000	5.675
62	1.228	5.633	1.359	7.495	1.448	7.932	1.345	7.020
63	0.219	5.852	0.314	7.809	0.390	8.322	0.308	7.328
64	0.071	5.923	0.148	7.957	0.168	8.490	0.129	7.457
65	0.016	5.939	0.079	8.036	0.082	8.572	0.059	7.516
66	0.000	5.939	0.034	8.070	0.028	8.600	0.021	7.536
67	0.000	5.939	0.005	8.075	0.000	8.600	0.002	7.538
68	0.000	5.939	0.000	8.075	0.000	8.600	0.000	7.538
69	0.000	5.939	0.000	8.075	0.000	8.600	0.000	7.538
70	0.000	5.939	0.000	8.075	0.000	8.600	0.000	7.538
71	0.000	5.939	0.000	8.075	0.000	8.600	0.000	7.538
72	0.003	5.942	0.034	8.109	0.009	8.610	0.015	7.553
73	0.028	5.970	0.109	8.218	0.078	8.688	0.072	7.625
74	0.000	5.970	0.038	8.256	0.027	8.715	0.022	7.647
75	0.000	5.970	0.004	8.260	0.000	8.715	0.001	7.648
76	0.000	5.970	0.000	8.260	0.000	8.715	0.000	7.648

Table C.2 (continued)

2002 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
77	0.000	5.970	0.000	8.260	0.000	8.715	0.000	7.648
78	0.000	5.970	0.000	8.260	0.000	8.715	0.000	7.648
79	0.000	5.971	0.000	8.260	0.000	8.715	0.000	7.649
80	0.000	5.971	0.037	8.297	0.016	8.731	0.018	7.667
81	0.001	5.972	0.064	8.361	0.016	8.748	0.027	7.694
82	0.000	5.972	0.014	8.375	0.000	8.748	0.005	7.698
83	0.000	5.972	0.000	8.375	0.000	8.748	0.000	7.698
84	0.000	5.972	0.000	8.375	0.000	8.748	0.000	7.698
85	0.000	5.973	0.000	8.375	0.000	8.748	0.000	7.698
86	0.578	6.551	0.675	9.050	0.728	9.476	0.661	8.359
87	0.221	6.772	0.308	9.358	0.351	9.828	0.294	8.653
88	0.064	6.837	0.126	9.484	0.135	9.963	0.109	8.761
89	0.030	6.866	0.077	9.561	0.073	10.035	0.060	8.821
90	0.313	7.180	0.325	9.886	0.316	10.352	0.318	9.139
91	1.130	8.310	1.276	11.163	1.270	11.622	1.225	10.365
92	0.206	8.516	0.267	11.429	0.309	11.930	0.260	10.625
93	0.104	8.620	0.163	11.593	0.160	12.090	0.143	10.768
94	0.243	8.863	0.285	11.878	0.293	12.383	0.274	11.041
95	0.067	8.930	0.111	11.989	0.112	12.495	0.096	11.138
96	0.019	8.949	0.053	12.042	0.048	12.543	0.040	11.178
97	0.002	8.951	0.024	12.066	0.017	12.560	0.014	11.192
98	0.000	8.951	0.012	12.078	0.004	12.564	0.005	11.197
99	0.000	8.951	0.004	12.081	0.000	12.564	0.001	11.199
100	0.000	8.951	0.002	12.084	0.000	12.564	0.001	11.199
101	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.199
102	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.199
103	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.199
104	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.199
105	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.199
106	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.199
107	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.200
108	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.200
109	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.200
110	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.200
111	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.200
112	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.200
113	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.200
114	0.000	8.951	0.000	12.084	0.000	12.564	0.000	11.200
115	0.000	8.951	0.000	12.085	0.000	12.564	0.000	11.200

Table C.2 (continued)

2002 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
116	0.000	8.951	0.000	12.085	0.000	12.564	0.000	11.200
117	0.000	8.951	0.000	12.085	0.000	12.564	0.000	11.200
118	0.000	8.951	0.000	12.085	0.000	12.564	0.000	11.200
119	0.000	8.951	0.000	12.085	0.000	12.564	0.000	11.200
120	0.000	8.951	0.000	12.085	0.000	12.564	0.000	11.200
121	0.000	8.951	0.000	12.085	0.000	12.564	0.000	11.200
122	0.000	8.951	0.000	12.085	0.000	12.564	0.000	11.200
123	0.000	8.951	0.000	12.085	0.000	12.564	0.000	11.200
124	0.000	8.952	0.000	12.085	0.000	12.564	0.000	11.200
125	0.000	8.952	0.000	12.085	0.000	12.564	0.000	11.200
126	0.000	8.952	0.000	12.085	0.000	12.564	0.000	11.200
127	0.000	8.952	0.000	12.085	0.000	12.564	0.000	11.200
128	0.000	8.952	0.000	12.085	0.000	12.564	0.000	11.200
129	0.000	8.952	0.000	12.085	0.000	12.564	0.000	11.200
130	0.000	8.952	0.000	12.085	0.000	12.564	0.000	11.200
131	0.000	8.952	0.000	12.085	0.000	12.564	0.000	11.200
132	0.000	8.952	0.000	12.085	0.000	12.564	0.000	11.200
133	0.001	8.952	0.000	12.085	0.000	12.564	0.000	11.200
134	0.000	8.952	0.000	12.085	0.000	12.564	0.000	11.200
135	0.000	8.952	0.000	12.085	0.000	12.564	0.000	11.200
136	0.000	8.952	0.000	12.085	0.000	12.564	0.000	11.200
137	0.000	8.952	0.000	12.085	0.000	12.564	0.000	11.200
138	0.001	8.953	0.000	12.085	0.000	12.564	0.000	11.201
139	0.000	8.953	0.000	12.085	0.000	12.564	0.000	11.201
140	0.000	8.953	0.000	12.085	0.000	12.564	0.000	11.201
141	0.000	8.953	0.000	12.085	0.000	12.564	0.000	11.201
142	0.001	8.954	0.002	12.087	0.000	12.564	0.001	11.202
143	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
144	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
145	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
146	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
147	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
148	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
149	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
150	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
151	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
152	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
153	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
154	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202

Table C.2 (continued)

2002 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
155	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
156	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
157	0.000	8.954	0.000	12.087	0.000	12.564	0.000	11.202
158	0.001	8.955	0.000	12.087	0.000	12.564	0.000	11.202
159	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
160	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
161	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
162	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
163	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
164	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
165	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
166	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
167	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
168	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
169	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
170	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
171	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
172	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
173	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
174	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
175	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
176	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
177	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
178	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
179	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
180	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
181	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
182	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
183	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
184	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
185	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
186	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
187	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
188	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
189	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
190	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
191	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
192	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
193	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202

Table C.2 (continued)

2002 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
194	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
195	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
196	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
197	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
198	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
199	0.000	8.955	0.000	12.087	0.000	12.564	0.000	11.202
200	0.059	9.014	0.067	12.154	0.069	12.633	0.065	11.267
201	0.414	9.428	0.575	12.729	0.604	13.237	0.531	11.798
202	0.133	9.561	0.244	12.973	0.275	13.512	0.217	12.015
203	0.000	9.561	0.003	12.975	0.005	13.516	0.002	12.018
204	0.009	9.571	0.048	13.023	0.095	13.611	0.051	12.068
205	0.337	9.907	0.438	13.461	0.533	14.144	0.436	12.504
206	0.207	10.114	0.307	13.768	0.383	14.527	0.299	12.803
207	0.589	10.704	0.693	14.461	0.827	15.354	0.703	13.506
208	0.236	10.939	0.334	14.794	0.393	15.747	0.321	13.827
209	0.020	10.959	0.074	14.868	0.123	15.870	0.072	13.899
210	0.000	10.959	0.013	14.881	0.054	15.923	0.022	13.921
211	0.000	10.959	0.000	14.881	0.016	15.939	0.005	13.927
212	0.027	10.986	0.113	14.994	0.092	16.032	0.077	14.004
213	0.000	10.986	0.025	15.019	0.034	16.065	0.020	14.023
214	0.000	10.986	0.000	15.019	0.000	16.065	0.000	14.023
215	0.000	10.986	0.000	15.019	0.000	16.065	0.000	14.023
216	0.000	10.986	0.000	15.019	0.000	16.065	0.000	14.023
217	0.000	10.986	0.000	15.019	0.000	16.065	0.000	14.023
218	0.000	10.986	0.000	15.019	0.000	16.065	0.000	14.023
219	0.000	10.986	0.000	15.019	0.000	16.065	0.000	14.023
220	0.000	10.986	0.000	15.019	0.000	16.065	0.000	14.023
221	0.000	10.986	0.000	15.019	0.000	16.065	0.000	14.023
222	0.000	10.986	0.000	15.019	0.000	16.065	0.000	14.023
223	0.000	10.986	0.000	15.019	0.000	16.065	0.000	14.023
224	0.000	10.986	0.000	15.019	0.000	16.065	0.000	14.023
225	0.000	10.986	0.000	15.019	0.000	16.065	0.000	14.023
226	0.000	10.986	0.000	15.019	0.000	16.065	0.000	14.023
227	0.001	10.987	0.000	15.019	0.001	16.066	0.001	14.024
228	0.000	10.987	0.000	15.019	0.000	16.066	0.000	14.024
229	0.000	10.987	0.000	15.019	0.000	16.066	0.000	14.024
230	0.000	10.987	0.000	15.019	0.000	16.066	0.000	14.024
231	0.000	10.987	0.000	15.019	0.000	16.066	0.000	14.024
232	0.000	10.987	0.000	15.019	0.000	16.066	0.000	14.024

Table C.2 (continued)

2002 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)	Flow (cm)	Total Flow (cm)
233	0.000	10.987	0.000	15.019	0.000	16.066	0.000	14.024
234	0.000	10.987	0.000	15.019	0.000	16.066	0.000	14.024
235	0.000	10.987	0.000	15.019	0.000	16.066	0.000	14.024
236	0.000	10.987	0.000	15.019	0.000	16.066	0.000	14.024
237	0.000	10.987	0.000	15.019	0.000	16.066	0.000	14.024
238	0.629	11.616	0.775	15.794	0.793	16.859	0.732	14.757
239	0.474	12.091	0.664	16.458	0.697	17.556	0.612	15.368
240	0.061	12.152	0.172	16.630	0.375	17.931	0.203	15.571
241	0.000	12.152	0.033	16.663	0.063	17.994	0.032	15.603
242	1.784	13.935	1.959	18.623	1.975	19.968	1.906	17.509
243	0.850	14.785	1.050	19.673	1.124	21.092	1.008	18.517
244	0.203	14.989	0.308	19.981	0.335	21.428	0.282	18.799
245	0.048	15.036	0.132	20.114	0.141	21.569	0.107	18.906
246	0.003	15.039	0.048	20.162	0.048	21.618	0.033	18.939
247	0.000	15.039	0.006	20.168	0.004	21.622	0.003	18.943
248	0.000	15.039	0.000	20.168	0.000	21.622	0.000	18.943
249	0.000	15.039	0.000	20.168	0.000	21.622	0.000	18.943
250	0.000	15.039	0.000	20.168	0.000	21.622	0.000	18.943
251	0.000	15.039	0.000	20.168	0.000	21.622	0.000	18.943
252	0.000	15.039	0.000	20.168	0.000	21.622	0.000	18.943
253	0.001	15.039	0.000	20.168	0.000	21.622	0.000	18.943
254	0.000	15.039	0.000	20.168	0.000	21.622	0.000	18.943
255	0.000	15.040	0.000	20.168	0.000	21.622	0.000	18.943
256	0.000	15.040	0.000	20.168	0.000	21.622	0.000	18.943
257	0.000	15.040	0.000	20.168	0.000	21.622	0.000	18.943
258	0.000	15.040	0.000	20.168	0.000	21.622	0.000	18.943
259	0.210	15.250	0.347	20.516	0.345	21.967	0.301	19.244
260	0.272	15.522	0.483	20.999	0.535	22.502	0.430	19.674
261	0.089	15.611	0.224	21.223	0.226	22.728	0.180	19.854
262	0.178	15.789	0.280	21.503	0.199	22.927	0.219	20.073
263	0.038	15.827	0.099	21.602	0.052	22.979	0.063	20.136
264	0.000	15.827	0.019	21.622	0.001	22.980	0.007	20.143
265	0.000	15.827	0.000	21.622	0.000	22.980	0.000	20.143
266	0.000	15.827	0.000	21.622	0.000	22.980	0.000	20.143
267	0.000	15.827	0.000	21.622	0.000	22.980	0.000	20.143
268	0.000	15.827	0.003	21.625	0.000	22.980	0.001	20.144
269	0.031	15.858	0.146	21.771	0.048	23.029	0.075	20.219
270	0.002	15.859	0.068	21.839	0.019	23.047	0.029	20.249
271	0.000	15.859	0.006	21.845	0.000	23.047	0.002	20.251

Table C.2 (continued)

2002 Flow - Plot 2 (shallow drains)

Drain Depth = 0.70 m Drain Spacing = 12.5 m

Estimated flow

	P2A		P2B		P2C		Average Plot 2	
Julian day	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**	**Flow (cm)**	**Total Flow (cm)**
272	0.000	15.859	0.000	21.845	0.000	23.047	0.000	20.251
273	0.000	**15.859**	0.021	**21.866**	0.000	**23.047**	0.007	**20.258**

APPENDIX 1-D

Methods for Estimating Missed Drainage Events

Gaps in the flow data from the drains occurred because of flooding of the manholes from heavy rainfall events, clogged outlet piping, or power outages during storms that stopped pumping from the outlet sumps. Gaps in the flow data were also caused by tipping bucket and datalogger malfunctions.

Estimates were made in the following manner:

A. If the Blue Earth microprocessor malfunctioned, flow data from the HOBO datalogger was used.

B. If both dataloggers malfunctioned or if the tipping bucket malfunctioned in one manhole, flow during that period for that drain was estimated based on a linear flow relationship with the other drains in that plot that successfully collected flow data during that period.

Figures D.1 and D.2 show the linear relationship of drain P1A to P1B and P1C in 2001 and 2002 respectively. If drainage data from P1A was available, then drainage data for the P1B or P1C drain could be calculated from the equations given in Figures D.1 and D.2, and vice-versa. Drain P1A was chosen to be the basis of these relationships because there were the fewest holes in its flow record. The P1A relationship with other Plot 1 drains was based on daily flow from several events in 2001, since the data was in that form when the method was developed. The P1A relationship with the other Plot 1 drains in 2002 was based on hourly flow data from several events that year.

Figures D.3 and D.4 show the linear relationship of drain P2B to P2A and P2C in 2001 and 2002 respectively. If drainage data from P2B was available, then drainage data for the P2A or P2C drain could be calculated from the equations given in Figures D.3 and D.4, and vice-versa. Drain P2B was chosen to be the basis of these relationships because it was the most isolated of the Plot 2 drains, and its flow record was the most complete. 2001 was very dry year with limited flow data in the shallow drains, so the relationship for that year was based on hourly data from a July event only. The relationship in 2002 was based on hourly data from several events that year.

C. If all manholes were flooded, flow was estimated in the P1A drain in Plot 1, and the P2B drain in Plot 2. This was accomplished using a water balance based on rainfall, water table depth, the volume drained (V_d) vs. water table depth (WTD) relationship for the soil, and potential evaporation during that period.

The water balance was based on the equation

$$\Delta S = R - ET - D - Seepage$$

where:

ΔS = Change in water stored in the soil profile (cm)

R = Rainfall (cm)

ET = Evapotranspiration (cm)

D = Drainage during the period (cm)

Seepage = Vertical or lateral seepage losses during he period (cm).

Generally, some drainage was measured before and after flooding occurred, so $D = D_i + D_m$, where D_i was the drainage measured just before or after flooding, and D_m was the missing drainage. Seepage losses were assumed to be negligible during these short periods. The drainage missed during the period of flooding can be estimated by replacing D with $D_i + D_m$ and rearranging the above equation to obtain

$$D_m = R - \Delta S - D_i - ET$$

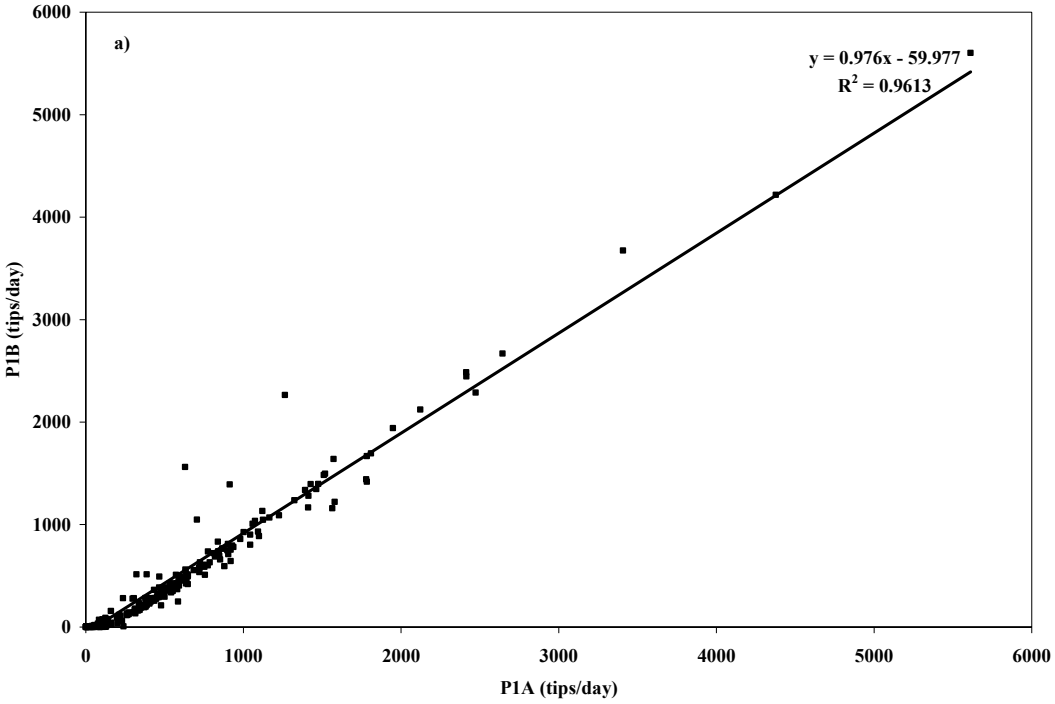
The interval used in the estimate of missed drainage was between the maximum water table elevation during the flooding event (Point A) until after the flooding event was complete (Point B), when the flow data was again measured reliably. During this period, rainfall and D_i, was measured at the site, and ET was estimated with weather data from the site with the Penman-Montieth Combination equation (see reference in Chapter 2). ΔS was estimated with the use of water table data and the V_d vs. WTD relationship (Figure D5), created from the SWC data from the soils in Plot 1. The water table elevation at Point A and Point B was used to obtain the V_d at Point A and B using Figure D.5, and the difference between those volume drained values was equal to ΔS. With all of those factors, the missing drainage could be estimated.

This water balance method was far from perfect. The major assumption is that this estimate was made during drained to equilibrium conditions. Sharp decreases in WTD after a rainfall events are accompanied by an increase of water above the drain tile lines. This depth of water will greatly increase the flow to the drain when compared to drained to equilibrium conditions. This depth was not measured in this study; only the midpoint WTD.

Therefore, estimation of the missed flow by using a water balance was imperfect because it was impossible to estimate the hourly WTD above the drains. This made it impossible to estimate when drained to equilibrium conditions began. With a WTD recorder at ¼ distance between the drains, or directly over the drain, water table depth over the drain could have been measured, and other methods could be used to estimate flow to the drain during this period. Further, heavy rainfall almost certainly caused ponded conditions to occur, which made it difficult to estimate how much rainfall had actually infiltrated into the soil matrix at any given time.

D. If the water balance approach was not satisfactory in estimating flow, a regression curve was created using flow data collected after the flooding subsided, and this was used to estimate the data at the beginning of the event for P1A and P2B. On a few occasions, estimates using the water balance method yielded values for drainage that were much too high or too low. In these cases, a quadratic curve was fitted to drainage flow versus time after the flooding event. The curve was extended back to the beginning of the flood event to estimate missed drainage. This most likely resulted in an underestimation of flow because the quadratic expression probably underestimated the peak flow.

E. After flow was estimated in P1A for a manhole flood event using Method C or D above, flow in the other drains in Plot 1 were estimated based on their relationship to the flow in P1A. After flow was estimated in P2B for a manhole flood event, flow in the other drains in Plot 2 was estimated based on their relationship to the flow in P2B. This was previously described in Method B above.



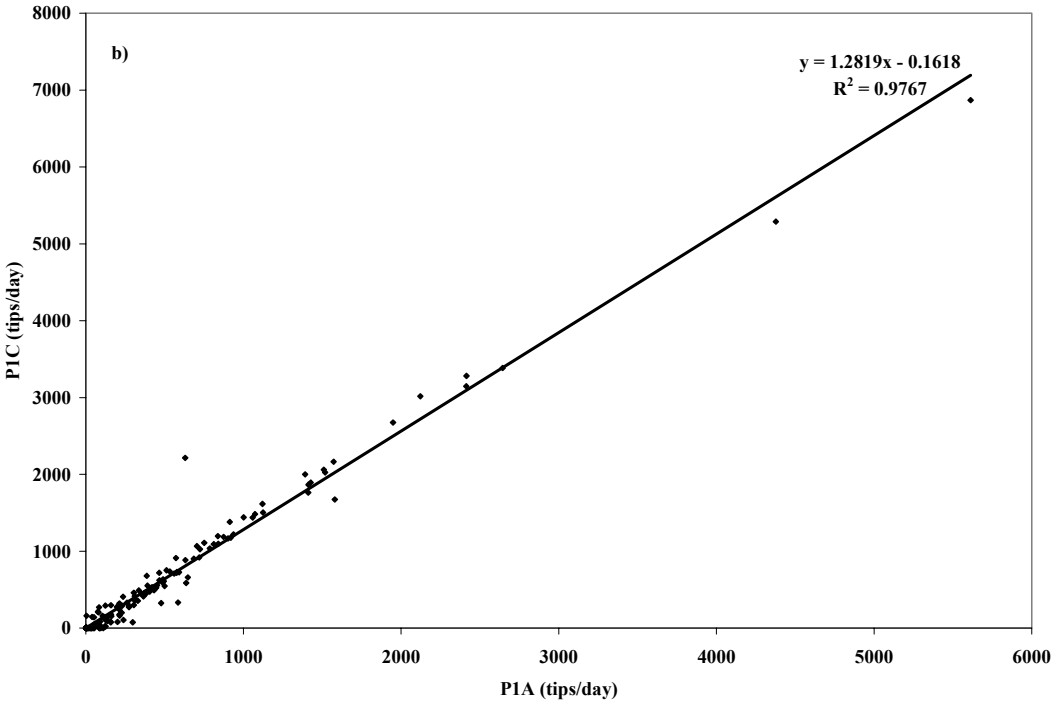
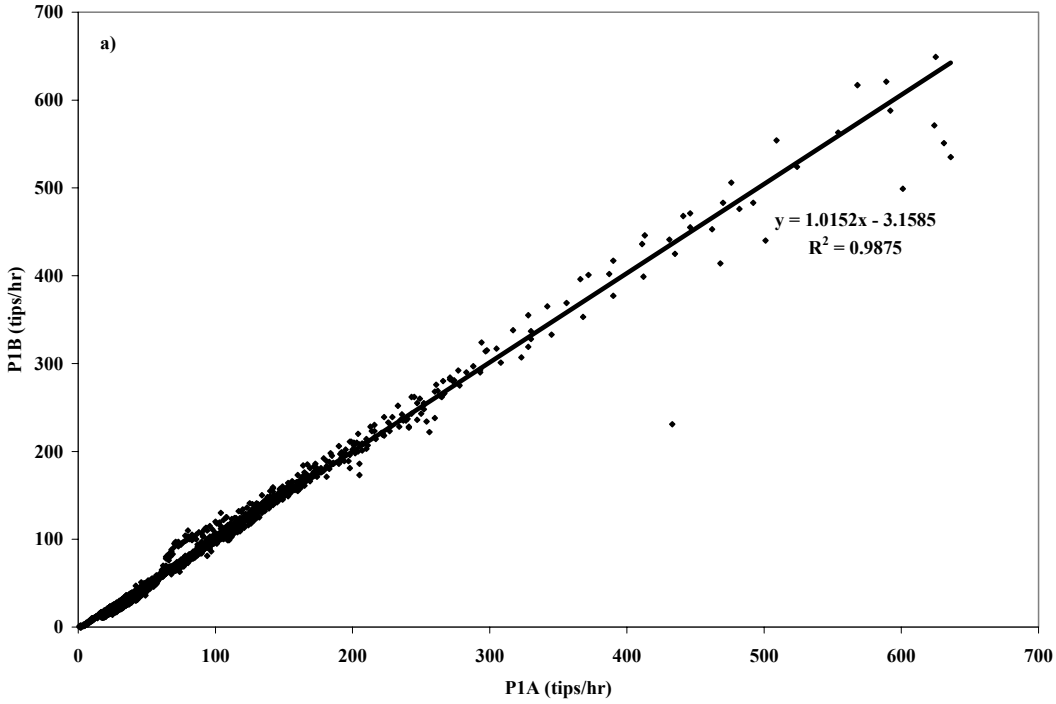


Figure D.1. Relationship of P1A and **a)** P1B and **b)** P1C in 2001



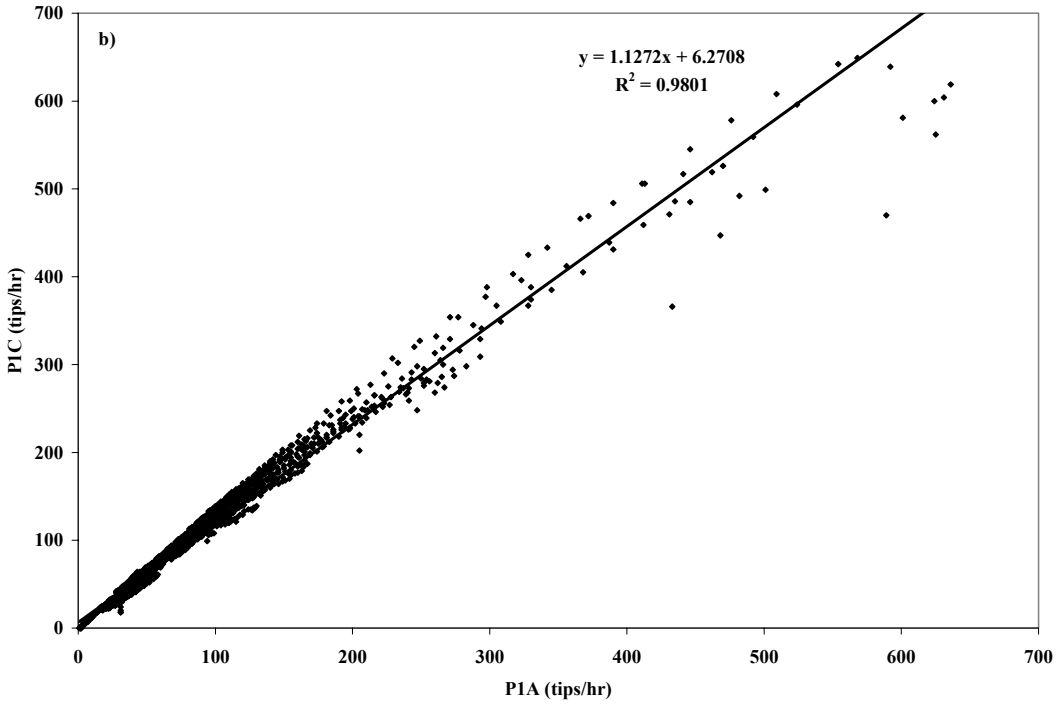
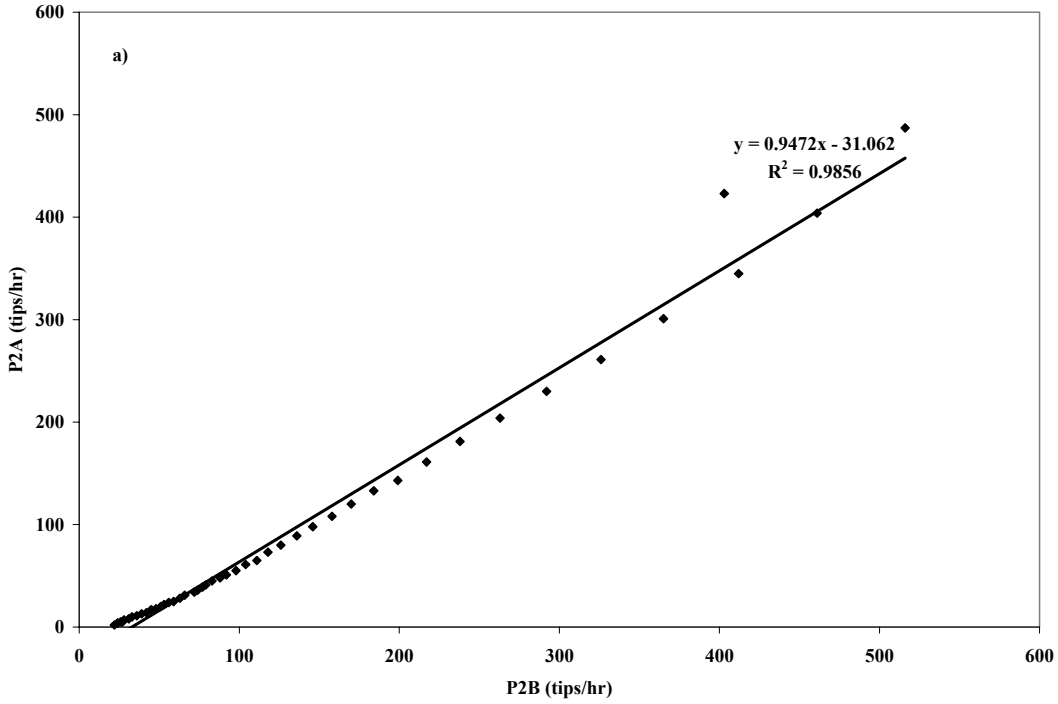


Figure D.2. Relationship of P1A and **a)** P1B and **b)** P1C in 2002



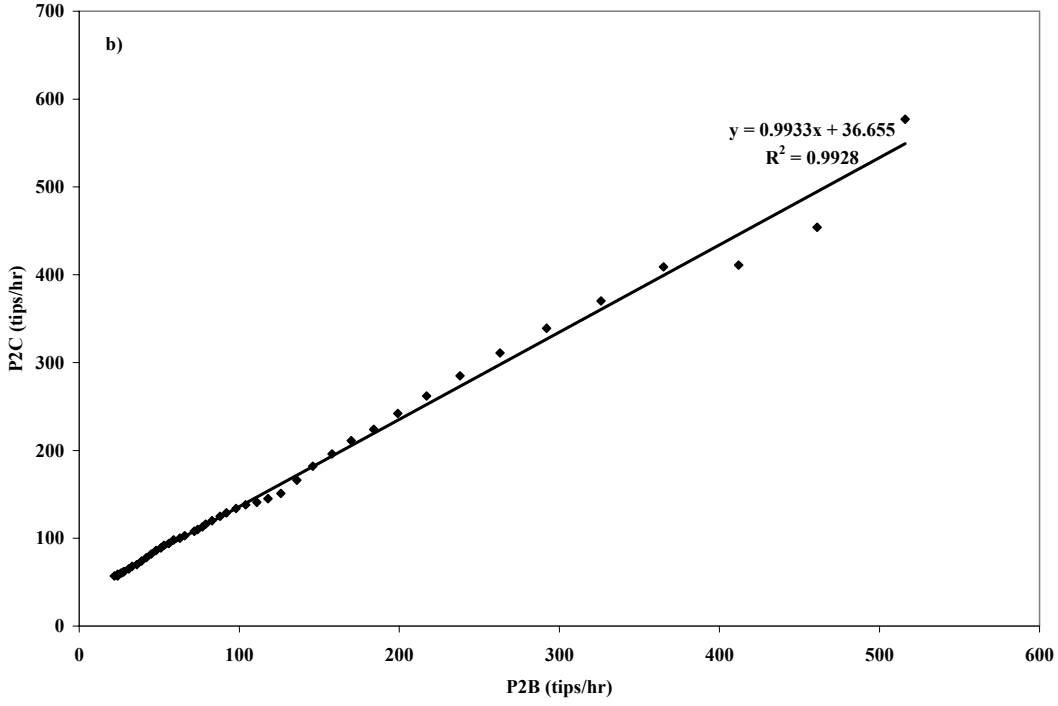
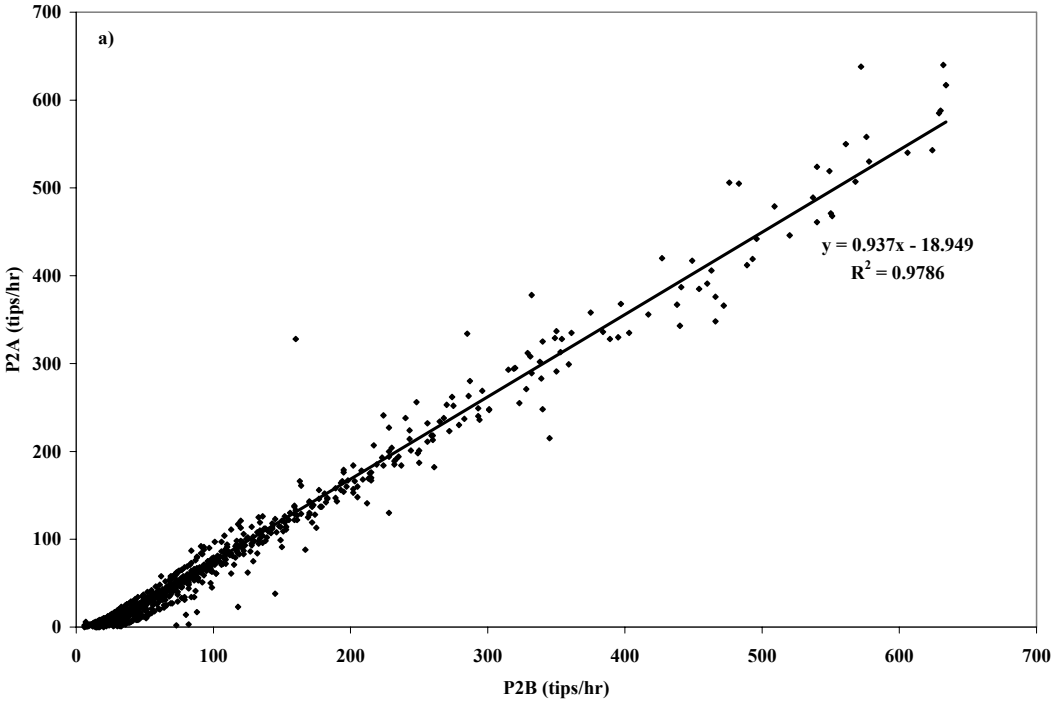


Figure D.3. Relationship of P2B and **a)** P2A and **b)** P2C in 2001



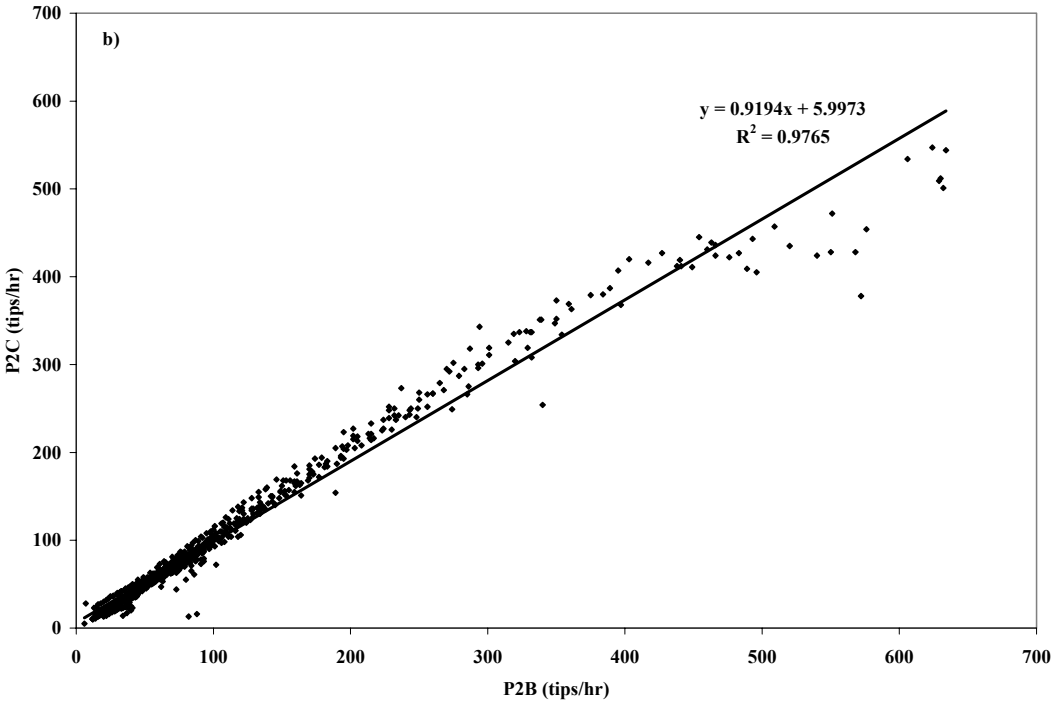


Figure D.4. Relationship of P2B and **a)** P2A and **b)** P2C in 2002

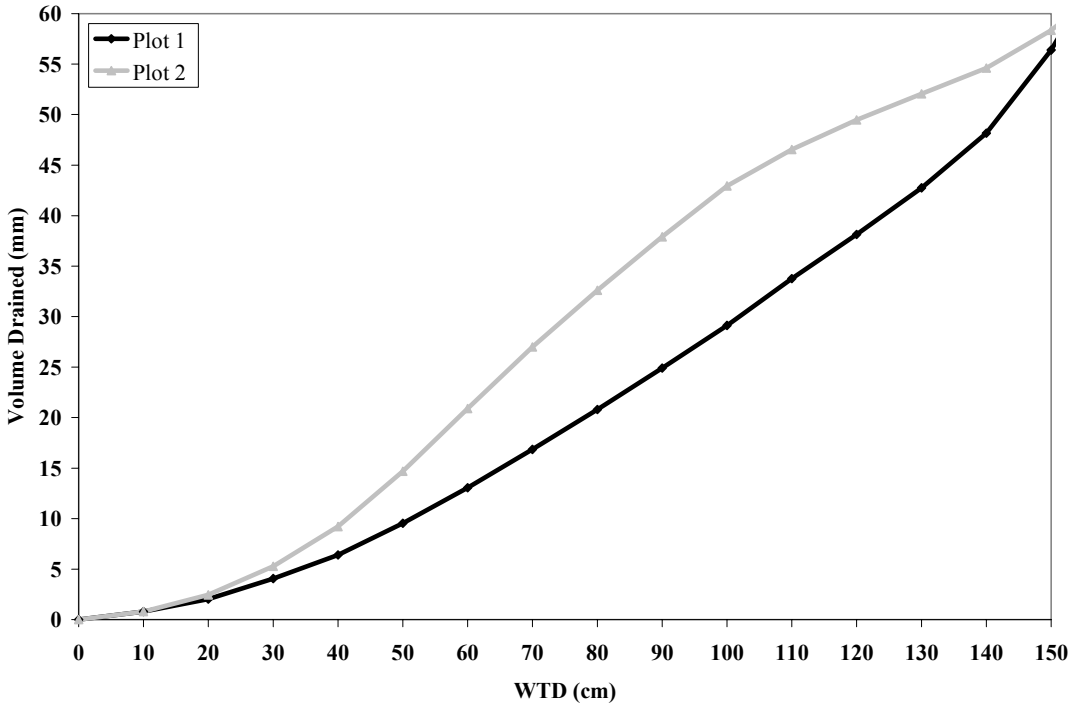


Figure D.5. Volume drained vs. water table depth relationship developed from the soil water characteristic of the soils in Plot 1 and Plot 2

APPENDIX 1-E

Swine Waste Irrigation Data

Table E.1. Swine waste irrigation depth, estimate of plant available nitrogen (PAN) reaching the plots during each irrigation, and amount of PAN applied to the plots in 2001 and 2002

2001 Date	Irrigation Depth (cm)	PAN lb/1000gal	PAN Applied lbs/ac	PAN Applied kg/ha
14-Mar	0.79	3.21	27.22	30.51
19-Apr	0.91	3.54	34.50	38.67
23-May	0.89	2.92	27.68	31.02
28-Jun	0.78	2.80	23.34	26.16
18-Jul	0.92	2.58	25.50	28.59
29-Aug	1.59	2.03	34.47	38.64
12-Sep	1.38	2.26	33.31	37.34
26-Sep	1.54	2.55	41.84	46.91
15-Nov	0.94	2.93	29.60	33.19
Sum	**9.75**		**277.45**	**311.02**
2002 Date	**Irrigation Depth (cm)**	**PAN lb/1000gal**	**PAN Applied lbs/ac**	**PAN Applied kg/ha**
24-Apr	1.24	2.49	33.02	37.01
22-May	1.31	2.46	34.43	38.60
19-Jun	1.48	2.52	39.76	44.57
31-Jul	1.43	1.82	27.75	31.11
18-Sep	1.51	1.53	24.72	27.71
26-Sep	1.39	1.31	19.50	21.86
Sum	**8.37**		**179.18**	**200.86**

APPENDIX 1-F

Well Water Quality Data

Table F.1. Shallow groundwater quality in well nest W1A located in Plot 1 in **a)** 2001 and **b)** 2002

a) 2001

W1A (30-60 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
No Samples collected					

W1A (90-120 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC43	0.30	1.60	0.15	11.00
21-Mar-01	MBC67	0.10	2.00	0.14	3.00
16-May-01	MBC148	0.00	1.50	0.16	8.00
22-Aug-01	MBC311	0.05	4.16	0.15	6.00
5-Sep-01	MBC336	0.00	0.20	0.04	5.00

W1A (150-180 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC44	0.10	0.20	0.06	10.00
21-Mar-01	MBC68	0.10	0.20	0.03	2.00
4-Apr-01	MBC129	0.10	0.00	0.03	5.00
18-Apr-01	MBC93	0.20	0.00	0.03	12.00
2-May-01	MBC111	0.10	0.10	0.04	10.00
16-May-01	MBC149	0.00	0.10	0.03	5.00
30-May-01	MBC170	0.10	0.00	0.60	5.00
13-Jun-01	MBC191	0.10	0.00	0.09	11.00
27-Jun-01	MBC212	0.10	0.00	0.07	5.00
11-Jul-01	MBC232	0.40	0.10	0.09	7.00
25-Jul-01	MBC267	0.20	0.10	0.09	5.30
8-Aug-01	MBC290	0.10	0.00	0.07	4.90
22-Aug-01	MBC312	0.03	0.19	0.04	4.00
5-Sep-01	MBC337	0.30	0.00	0.22	8.00
19-Sep-01	MBC357	0.09	0.00	0.09	6.00
3-Oct-01	MBC393	0.10	0.20	0.04	5.00
17-Oct-01	MBC408	0.02	0.07	0.08	4.00
15-Nov-01	MBC 433	0.10	0.03	0.22	6.00
28-Nov-01	MBC 448	0.09	0.07	0.09	3.00
12-Dec-01	MBC 460	0.06	0.00	0.06	4.70
26-Dec-01	MBC 472	0.03	0.01	0.03	2.20

W1A (210-240 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC45	0.30	0.00	0.09	12.00
21-Mar-01	MBC69	0.30	0.00	0.15	2.00
4-Apr-01	MBC130	0.40	0.10	0.09	8.00
18-Apr-01	MBC94	0.30	0.00	0.15	13.00
2-May-01	MBC112	0.30	0.00	0.20	11.00
16-May-01	MBC150	0.30	0.00	0.15	8.00
30-May-01	MBC171	0.30	0.00	0.18	8.00
13-Jun-01	MBC192	0.30	0.00	0.20	17.00
27-Jun-01	MBC213	0.40	0.10	0.28	12.00
11-Jul-01	MBC233	0.40	0.00	0.22	8.00
25-Jul-01	MBC268	0.30	0.00	0.22	6.90
8-Aug-01	MBC291	0.30	0.00	0.23	4.60
22-Aug-01	MBC313	0.26	0.02	0.18	8.00
5-Sep-01	MBC338	0.20	0.10	0.01	5.00
19-Sep-01	MBC358	0.31	0.00	0.21	8.00
3-Oct-01	MBC394	0.21	0.20	0.17	6.00
17-Oct-01	MBC409	0.24	0.04	0.22	7.00
31-Oct-01	MBC 422	0.30	0.04	0.17	8.00
15-Nov-01	MBC 434	0.24	0.03	0.06	5.00
28-Nov-01	MBC 449	0.20	0.03	0.09	5.00
12-Dec-01	MBC 461	0.34	0.00	0.13	7.90
26-Dec-01	MBC 473	0.27	0.00	0.09	4.50

b) 2002

W1A (30-60 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
23-Jan-02	MBC 528	0.0	43.3	2.28	8.81
6-Mar-02	MBC 609	0.58	40.02	2.31	

W1A (90-120 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 490	0.00	14.61	0.08	3.83
23-Jan-02	MBC 529	0.00	29.18	0.02	1.71
6-Feb-02	MBC 561	0.00	32.12	0.16	6.00
6-Mar-02	MBC 610	0.06	57.41	0.02	4.17
20-Mar-02	MBC 634	0.08	36.15	0.11	5.60
3-Apr-02	MBC 659	0.05	31.33	0.02	4.24
17-Apr-02	MBC 684	0.07	48.68	0.12	5.22
24-Jul-02	MBC 835	0.44	46.36	0.42	8.00
5-Sep-02	MBC 912	0.03	44.59	0.07	4.00
18-Sep-02	MBC 936	0.15	66.66	0.09	4.83
3-Oct-02	MBC 979	0.17	60.46	0.38	6.59

W1A (150-180 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 491	0.00	0.98	0.19	2.84
23-Jan-02	MBC 530	0.01	2.86	0.02	2.16
6-Feb-02	MBC 562	0.00	3.17	0.02	3.00
20-Feb-02	MBC 588	0.01	3.11	0.12	3.00
6-Mar-02	MBC 611	0.10	2.67	0.02	2.76
20-Mar-02	MBC 635	0.11	1.94	0.02	3.70
3-Apr-02	MBC 660	0.10	2.14	0.02	2.40
17-Apr-02	MBC 685	0.16	1.24	0.02	2.58
1-May-02	MBC 715	0.27	0.91	0.04	2.47
15-May-02	MBC 733	0.20	0.61	0.03	6.78
29-May-02	MBC 759	0.20	0.61	0.04	3.94
12-Jun-02	MBC 777	0.02	1.01	0.04	3.00
26-Jun-02	MBC 801	0.42	1.26	0.07	3.00
9-Jul-02	MBC 816	0.34	0.86	0.11	3.00
24-Jul-02	MBC 836	0.13	5.33	0.03	2.00
7-Aug-02	MBC 868	0.06	8.97	0.03	3.00
21-Aug-02	MBC 886	0.13	5.30	0.09	3.00
5-Sep-02	MBC 913	0.10	14.79	0.04	2.00
18-Sep-02	MBC 937	0.16	19.76	0.03	2.39
3-Oct-02	MBC 980	0.18	27.02	0.03	2.25

W1A (210-240 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 492	0.23	0.11	0.45	6.19
23-Jan-02	MBC 531	0.11	0.07	0.05	3.22
6-Feb-02	MBC 563	0.12	0.06	0.12	6.00
20-Feb-02	MBC 589	0.18	0.01	0.36	7.00
6-Mar-02	MBC 612	0.26	0.04	0.14	7.66
20-Mar-02	MBC 636	0.31	0.05	0.12	8.01
3-Apr-02	MBC 661	0.34	0.01	0.16	7.56
17-Apr-02	MBC 686	0.36	0.01	0.15	7.91
1-May-02	MBC 716	0.32	0.03	0.16	7.63
15-May-02	MBC 734	0.34	0.00	0.09	10.13
29-May-02	MBC 760	0.35	0.00	0.18	9.13
12-Jun-02	MBC 778	0.07	0.00	0.20	8.00
26-Jun-02	MBC 802	0.78	0.00	0.21	8.00
9-Jul-02	MBC 817	0.83	0.00	0.28	8.00
24-Jul-02	MBC 837	0.33	0.00	0.21	8.00
7-Aug-02	MBC 869	0.32	0.00	0.22	9.00
21-Aug-02	MBC 887	0.36	0.00	0.26	8.00
5-Sep-02	MBC 914	0.33	0.00	0.26	9.00
18-Sep-02	MBC 938	0.34	0.00	0.20	6.91
3-Oct-02	MBC 981	0.37	0.05	0.26	9.13

NH_4-N Ammonia - Nitrogen
NO_3-N Nitrate-Nitrogen
o-PO_4 Ortho-phosphate
DOC Dissolved Organic Carbon

Table F.2. Shallow groundwater quality in well nest W1B located in Plot 1 in **a)** 2001 and **b)** 2002

a) 2001

W1B (30-60 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
No Samples collected					

W1B (90-120cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC46	0.10	1.70	0.37	14.00
21-Mar-01	MBC70	0.10	1.20	0.50	5.00
16-May-01	MBC151	0.00	1.30	0.69	16.00
22-Aug-01	MBC314	0.02	14.30	0.73	10.00
5-Sep-01	MBC339	0.20	0.00	0.12	8.00

W1B (150-180 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC47	0.10	0.10	0.20	9.00
21-Mar-01	MBC71	0.10	0.00	0.02	2.00
4-Apr-01	MBC131	0.10	0.00	0.04	6.00
18-Apr-01	MBC95	0.20	0.00	0.04	11.00
2-May-01	MBC113	0.20	0.00	0.04	8.00
16-May-01	MBC152	0.10	0.10	0.02	5.00
30-May-01	MBC172	0.30	0.20	0.05	35.00
13-Jun-01	MBC193	0.10	0.40	0.05	13.00
27-Jun-01	MBC214	0.20	0.20	0.04	5.00
11-Jul-01	MBC234	0.40	0.00	0.06	6.00
25-Jul-01	MBC269	0.10	0.10	0.04	5.60
8-Aug-01	MBC292	0.10	0.40	0.02	7.80
22-Aug-01	MBC315	0.04	0.10	0.01	5.00
5-Sep-01	MBC340	0.10	0.00	0.03	4.00
19-Sep-01	MBC359	0.61	0.30	0.02	5.00
3-Oct-01	MBC395	0.10	0.30	0.01	5.00
17-Oct-01	MBC410	0.03	0.07	0.03	6.00
31-Oct-01	MBC 423	0.10	0.09	0.04	6.00
15-Nov-01	MBC 435	0.05	0.14	0.06	7.00
28-Nov-01	MBC 450	0.01	0.10	0.01	3.00
12-Dec-01	MBC 462	0.07	0.06	0.03	4.40
26-Dec-01	MBC 474	0.03	0.05	0.01	3.30

W1B (210-240 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC48	0.20	0.00	0.50	12.00
21-Mar-01	MBC72	0.20	0.00	0.11	3.00
4-Apr-01	MBC132	0.20	0.00	0.06	8.00
18-Apr-01	MBC96	0.30	0.00	0.10	13.00
2-May-01	MBC114	0.20	0.00	0.14	11.00
16-May-01	MBC153	0.20	0.00	0.09	8.00
30-May-01	MBC173	0.30	0.00	0.12	9.00
13-Jun-01	MBC194	0.20	0.10	0.13	18.00
27-Jun-01	MBC215	0.30	0.00	0.11	8.00
11-Jul-01	MBC235	0.30	0.00	0.13	8.00
25-Jul-01	MBC270	0.20	0.00	0.12	7.40
8-Aug-01	MBC293	0.30	0.00	0.13	1.40
22-Aug-01	MBC316	0.20	0.02	0.12	8.00
5-Sep-01	MBC341	0.30	0.00	0.20	5.00
19-Sep-01	MBC360	0.28	0.00	0.13	8.00
3-Oct-01	MBC396	0.20	0.20	0.12	7.00
17-Oct-01	MBC411	0.20	0.04	0.13	7.00
31-Oct-01	MBC 424	0.26	0.04	0.12	8.00
15-Nov-01	MBC 436	0.17	0.03	0.05	6.00
28-Nov-01	MBC 451	0.12	0.03	0.05	4.00
12-Dec-01	MBC 463	0.22	0.00	0.07	7.40
26-Dec-01	MBC 475	0.15	0.00	0.04	3.70

b) 2002

W1B (30-60 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
01/23/02	MBC 532	1.50	63.99	4.11	20.68

W1B (90-120cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 493	0.00	29.93	0.13	7.21
23-Jan-02	MBC 533	0.00	37.72	0.02	3.12
6-Feb-02	MBC 564	0.00	52.80	0.46	7.00
6-Mar-02	MBC 613	0.04	69.23	0.21	6.02
20-Mar-02	MBC 637	0.22	55.36	0.31	7.80
3-Apr-02	MBC 662	0.07	29.56	0.04	5.08
17-Apr-02	MBC 687	0.11	51.51	0.32	7.22
24-Jul-02	MBC 838	0.04	67.27	0.15	7.00
5-Sep-02	MBC 915	0.07	40.54	0.17	6.00
18-Sep-02	MBC 939	0.13	53.68	0.46	9.65
3-Oct-02	MBC 982	2.22	46.20	1.65	13.60

W1B (150-180 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 494	0.00	0.32	0.17	4.09
23-Jan-02	MBC 534	0.03	5.92	0.01	3.66
6-Feb-02	MBC 565	0.00	11.14	0.01	4.00
20-Feb-02	MBC 590	0.01	14.40	0.08	4.00
6-Mar-02	MBC 614	0.15	17.20	0.01	3.46
20-Mar-02	MBC 638	0.09	21.13	0.01	3.90
3-Apr-02	MBC 663	0.14	19.08	0.02	3.50
17-Apr-02	MBC 688	0.12	26.33	0.01	3.84
1-May-02	MBC 717	0.09	29.03	0.02	4.10
15-May-02	MBC 735	0.09	21.44	0.01	8.38
29-May-02	MBC 761	0.14	16.20	0.01	6.04
12-Jun-02	MBC 779	0.03	13.26	0.02	4.00
26-Jun-02	MBC 803	0.62	13.28	0.04	5.00
9-Jul-02	MBC 818	0.21	15.18	0.03	4.00
24-Jul-02	MBC 839	0.05	14.70	0.02	4.00
7-Aug-02	MBC 870	0.07	21.49	0.02	4.00
21-Aug-02	MBC 888	0.07	12.54	0.04	5.00
5-Sep-02	MBC 916	0.08	25.23	0.03	4.00
18-Sep-02	MBC 940	0.15	34.15	0.02	4.21
3-Oct-02	MBC 983	0.16	39.74	0.01	3.97

W1B (210-240 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 495	0.18	0.08	0.40	5.91
23-Jan-02	MBC 535	0.25	0.03	0.06	5.14
6-Feb-02	MBC 566	0.12	0.04	0.07	6.00
20-Feb-02	MBC 591	0.18	0.00	0.31	6.00
6-Mar-02	MBC 615	0.23	0.01	0.07	6.35
20-Mar-02	MBC 639	0.28	0.03	0.06	7.03
3-Apr-02	MBC 664	0.20	0.01	0.09	6.86
17-Apr-02	MBC 689	0.29	0.01	0.09	6.86
1-May-02	MBC 718	0.25	0.02	0.09	6.57
15-May-02	MBC 736	0.24	0.00	0.08	10.80
29-May-02	MBC 762	0.25	0.00	0.09	8.08
12-Jun-02	MBC 780	0.04	0.00	0.10	7.00
26-Jun-02	MBC 804	0.88	0.00	0.11	7.00
9-Jul-02	MBC 819	0.66	0.00	0.15	7.00
24-Jul-02	MBC 840	0.26	0.00	0.12	7.00
7-Aug-02	MBC 871	0.27	0.00	0.12	8.00
21-Aug-02	MBC 889	0.33	0.00	0.15	7.00
5-Sep-02	MBC 917	0.29	0.00	0.15	8.00
18-Sep-02	MBC 941	0.43	0.00	0.20	7.24
3-Oct-02	MBC 984	0.30	0.00	0.13	7.54

NH_4-N	Ammonia - Nitrogen
NO_3-N	Nitrate-Nitrogen
o-PO_4	Ortho-phosphate
DOC	Dissolved Organic Carbon

Table F.3. Shallow groundwater quality in well nest W1C located in Plot 1 in **a)** 2001 and **b)** 2002

a) 2001

W1C (30-60 cm depth)

Date	LabID	NH_4-N	NO_3-N	o-PO_4	DOC
		mg/L	mg/L	mg/L	mg/L
7-Mar-01	MBC49	0.10	2.10	0.50	21.00
21-Mar-01	MBC73	10.20	2.80	1.13	10.00

W1C (90-120 cm depth)

Date	LabID	NH_4-N	NO_3-N	o-PO_4	DOC
		mg/L	mg/L	mg/L	mg/L
7-Mar-01	MBC50	0.10	0.60	0.11	6.00
21-Mar-01	MBC74	0.30	0.20	0.10	3.00
16-May-01	MBC154	0.20	0.20	0.26	8.00
22-Aug-01	MBC317	0.25	0.87	1.36	10.00
5-Sep-01	MBC342	0.70	6.80	0.15	5.00
26-Sep-01	GMBC380	22.80	10.50	4.88	29.00

W1C (150-180 cm depth)

Date	LabID	NH_4-N	NO_3-N	o-PO_4	DOC
		mg/L	mg/L	mg/L	mg/L
7-Mar-01	MBC51	0.10	0.10	0.06	6.00
21-Mar-01	MBC75	0.20	0.00	0.03	3.00
4-Apr-01	MBC133	0.10	0.00	0.05	5.00
18-Apr-01	MBC97	0.30	0.00	0.06	10.00
2-May-01	MBC115	0.20	0.00	0.04	9.00
16-May-01	MBC155	0.10	0.10	0.02	4.00
30-May-01	MBC174	0.20	0.00	0.04	4.00
13-Jun-01	MBC195	0.10	0.10	0.04	13.00
27-Jun-01	MBC216	0.20	0.00	0.03	4.00
11-Jul-01	MBC236	0.30	0.00	0.09	5.00
25-Jul-01	MBC271	0.20	0.10	0.12	5.60
8-Aug-01	MBC294	0.10	0.10	0.04	4.60
22-Aug-01	MBC318	0.02	0.12	0.02	4.00
5-Sep-01	MBC343	0.10	0.00	0.29	4.00
19-Sep-01	MBC361	0.33	0.00	0.19	5.00
3-Oct-01	MBC397	0.30	0.20	0.04	5.00
17-Oct-01	MBC412	0.16	0.04	0.08	6.00
31-Oct-01	MBC 425	0.21	0.05	0.25	6.00
15-Nov-01	MBC 437	0.15	0.13	0.14	5.00
28-Nov-01	MBC 452	0.04	0.09	0.03	3.00
12-Dec-01	MBC 464	0.14	0.05	0.04	4.30
26-Dec-01	MBC 476	0.05	0.05	0.03	2.60

W1C (210-240 cm depth)

Date	LabID	NH_4-N	NO_3-N	o-PO_4	DOC
		mg/L	mg/L	mg/L	mg/L
7-Mar-01	MBC52	0.30	0.00	0.19	6.00
21-Mar-01	MBC76	0.30	0.00	0.08	6.00
4-Apr-01	MBC134	0.40	0.00	0.18	6.00
18-Apr-01	MBC98	0.30	0.00	0.22	10.00
2-May-01	MBC116	0.30	0.00	0.19	9.00
16-May-01	MBC156	0.20	0.00	0.16	6.00
30-May-01	MBC175	0.30	0.00	0.16	5.00
13-Jun-01	MBC196	0.30	0.10	0.21	13.00
27-Jun-01	MBC217	0.30	0.00	0.20	5.00
11-Jul-01	MBC237	0.40	0.00	0.25	6.00
25-Jul-01	MBC271	0.30	0.00	0.17	4.70
8-Aug-01	MBC295	0.30	0.00	0.20	4.10
22-Aug-01	MBC319	0.27	0.02	0.28	5.00
5-Sep-01	MBC344	0.30	0.00	0.41	6.00
19-Sep-01	MBC362	0.64	0.00	0.78	6.00
3-Oct-01	MBC398	0.30	0.20	0.21	5.00
31-Oct-01	MBC 426	0.29	0.03	0.30	6.00
15-Nov-01	MBC 438	0.27	0.03	0.19	4.00
28-Nov-01	MBC 453	0.13	0.03	0.07	3.00
12-Dec-01	MBC 465	0.31	0.00	0.16	5.00
26-Dec-01	MBC 477	0.25	0.00	0.20	3.20

Grab sample after irrigation

NH_4-N Ammonia - Nitrogen
NO_3-N Nitrate-Nitrogen
o-PO_4 Ortho-phosphate
DOC Dissolved Organic Carbon

b) 2002

W1C (30-60 cm depth)

Date	LabID	NH_4-N	NO_3-N	o-PO_4	DOC
		mg/L	mg/L	mg/L	mg/L
7-Mar-01	MBC 49	0.15	2.12	0.50	21.00
21-Mar-01	MBC 73	10.23	2.83	1.13	10.00
23-Jan-02	MBC 536	0.05	43.30	1.95	9.10

W1C (90-120 cm depth)

Date	LabID	NH_4-N	NO_3-N	o-PO_4	DOC
		mg/L	mg/L	mg/L	mg/L
9-Jan-02	MBC 496	0.02	24.61	0.74	7.48
23-Jan-02	MBC 537	0.00	16.61	0.13	3.12
6-Feb-02	MBC 567	0.00	19.77	1.18	5.00
6-Mar-02	MBC 616	0.03	22.68	0.19	3.38
20-Mar-02	MBC 640	0.16	23.29	0.74	5.58
3-Apr-02	MBC 665	0.08	19.94	0.31	4.43
17-Apr-02	MBC 690	0.10	25.46	1.04	4.98
24-Jul-02	MBC 841	0.03	37.38	0.33	4.00
5-Sep-02	MBC 918	0.12	29.32	0.88	5.00
18-Sep-02	MBC 942	0.06	35.41	0.39	4.70
3-Oct-02	MBC 985	0.13	34.71	0.23	4.89

W1C (150-180 cm depth)

Date	LabID	NH_4-N	NO_3-N	o-PO_4	DOC
		mg/L	mg/L	mg/L	mg/L
9-Jan-02	MBC 497	0.00	2.94	0.14	2.79
23-Jan-02	MBC 538	0.00	10.33	0.01	1.20
6-Feb-02	MBC 568	0.00	13.16	0.04	3.00
20-Feb-02	MBC 592	0.00	15.20	0.08	3.00
6-Mar-02	MBC 617	0.02	19.45	0.02	2.95
20-Mar-02	MBC 641	0.07	21.60	0.02	4.11
3-Apr-02	MBC 666	0.09	19.76	0.01	2.83
17-Apr-02	MBC 691	0.04	29.65	0.03	2.81
1-May-02	MBC 719	0.45	30.53	0.04	2.82
15-May-02	MBC 737	0.04	22.48	0.02	7.32
29-May-02	MBC 763	0.09	26.12	0.02	4.65
12-Jun-02	MBC 781	0.03	24.85	0.41	3.00
26-Jun-02	MBC 805	0.23	24.33	0.31	4.00
9-Jul-02	MBC 820	0.21	24.93	0.09	4.00
24-Jul-02	MBC 842	0.01	29.88	0.02	3.00
7-Aug-02	MBC 872	0.07	29.05	0.05	3.00
21-Aug-02	MBC 890	0.14	13.42	0.44	4.00
5-Sep-02	MBC 919	0.00	30.98	0.03	3.00
18-Sep-02	MBC 943	0.06	35.71	0.11	3.53
3-Oct-02	MBC 986	0.12	29.60	0.02	3.33

W1C (210-240 cm depth)

Date	LabID	NH_4-N	NO_3-N	o-PO_4	DOC
		mg/L	mg/L	mg/L	mg/L
9-Jan-02	MBC 498	0.23	0.03	0.34	3.70
23-Jan-02	MBC 539	0.13	0.09	0.06	2.34
6-Feb-02	MBC 569	0.14	0.07	0.14	4.00
20-Feb-02	MBC 593	0.21	0.03	0.37	4.00
6-Mar-02	MBC 618	0.23	0.02	0.17	4.11
20-Mar-02	MBC 642	0.27	0.01	0.14	5.27
3-Apr-02	MBC 667	0.27	0.02	0.19	4.30
17-Apr-02	MBC 692	0.37	0.02	0.14	4.13
1-May-02	MBC 720	0.31	0.02	0.17	4.06
15-May-02	MBC 738	0.28	0.00	0.14	7.71
29-May-02	MBC 764	0.41	0.00	0.14	5.51
12-Jun-02	MBC 782	0.08	0.04	0.25	5.00
26-Jun-02	MBC 806	0.86	0.00	0.34	5.00
9-Jul-02	MBC 821	0.88	0.00	0.75	5.00
24-Jul-02	MBC 843	0.32	0.00	0.21	4.00
7-Aug-02	MBC 873	0.34	0.00	0.23	4.00
21-Aug-02	MBC 891	0.36	0.00	0.38	4.00
5-Sep-02	MBC 920	0.35	0.27	0.19	4.00
18-Sep-02	MBC 944	0.88	0.00	1.02	5.84
3-Oct-02	MBC 987	0.42	0.00	0.38	6.41

Table F.4. Shallow groundwater quality in well nest W2A located in Plot 2 in **a)** 2001 and **b)** 2002

a) 2001

W2A (30-60 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
No Samples collected					

W2A (90-120 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC53	0.10	1.50	0.05	6.00
21-Mar-01	MBC77	7.80	2.70	0.11	13.00
4-Apr-01	MBC135	2.70	0.20	0.06	8.00
18-Apr-01	MBC99	2.20	0.10	0.17	12.00
2-May-01	MBC117	14.70	0.00	1.08	34.00
16-May-01	MBC157	1.80	2.20	0.35	14.00
30-May-01	MBC176	1.80	7.30	0.18	8.00
13-Jun-01	MBC197	1.10	13.60	0.20	15.00
27-Jun-01	MBC218	0.90	7.90	0.08	5.00
11-Jul-01	MBC238	1.00	4.70	0.25	7.00
25-Jul-01	MBC273	4.80	9.50	0.67	11.80
8-Aug-01	MBC296	1.00	7.20	0.49	7.00
22-Aug-01	MBC320	0.12	14.82	0.11	
5-Sep-01	MBC345	0.00	0.34	0.14	
19-Sep-01	MBC363	0.65	3.10	0.28	
26-Sep-01	GMBC381	2.20	44.70	0.73	
28-Sep-01	MBC 387	3.45	17.53	0.59	16.00
3-Oct-01	MBC 399	1.11	11.54	0.38	10.00

W2A (150-180 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC54	0.20	0.00	0.13	4.00
21-Mar-01	MBC78	0.20	0.00	0.17	4.00
4-Apr-01	MBC136	0.10	0.00	0.17	4.00
18-Apr-01	MBC100	0.20	0.00	0.15	10.00
2-May-01	MBC118	0.20	0.00	0.19	8.00
16-May-01	MBC158	0.10	0.00	0.18	4.00
30-May-01	MBC177	0.30	0.00	0.23	4.00
13-Jun-01	MBC198	0.20	0.00	0.24	9.00
27-Jun-01	MBC219	0.30	0.00	0.24	4.00
11-Jul-01	MBC239	0.30	0.00	0.22	5.00
25-Jul-01	MBC274	0.20	0.00	0.28	3.60
8-Aug-01	MBC297	0.20	0.00	0.26	4.50
22-Aug-01	MBC321	0.14	0.02	0.28	
5-Sep-01	MBC346	0.10	0.00	0.14	
19-Sep-01	MBC364	0.20	0.00	0.29	
3-Oct-01	MBC 400	0.17	0.21	0.25	4.00
31-Oct-01	MBC 427	0.15	0.03	0.15	4.00
15-Nov-01	MBC 439	0.20	0.03	0.16	4.00
28-Nov-01	MBC 454	0.08	0.04	0.06	2.00
12-Dec-01	MBC 466	0.19	0.00	0.17	3.40
26-Dec-01	MBC 478	0.11	0.00	0.10	2.40

W2A (210-240 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC55	0.30	0.00	0.23	6.00
21-Mar-01	MBC79	0.20	0.00	0.24	5.00
4-Apr-01	MBC137	0.40	0.00	0.16	5.00
18-Apr-01	MBC101	0.40	0.00	0.30	10.00
2-May-01	MBC119	0.30	0.00	0.28	9.00
16-May-01	MBC159	0.40	0.10	0.13	5.00
30-May-01	MBC178	0.40	0.00	0.23	6.00
13-Jun-01	MBC199	0.30	0.10	0.39	13.00
27-Jun-01	MBC220	0.40	0.10	0.46	7.00
11-Jul-01	MBC240	0.60	0.10	0.45	6.00
25-Jul-01	MBC275	0.30	0.00	0.42	5.20
8-Aug-01	MBC298	0.30	0.00	0.38	5.30
22-Aug-01	MBC322	0.23	0.02	0.44	
5-Sep-01	MBC347	0.20	0.00	0.29	
19-Sep-01	MBC365	0.34	0.00	0.38	
3-Oct-01	MBC 401	0.30	0.22	0.36	6.00
17-Oct-01	MBC 414	0.12	0.04	0.18	4.00
31-Oct-01	MBC 428	0.25	0.03	0.31	6.00
15-Nov-01	MBC 440	0.17	0.04	0.10	3.00
28-Nov-01	MBC 455	0.25	0.03	0.12	3.00
12-Dec-01	MBC 467	0.25	0.00	0.24	5.30
26-Dec-01	MBC 479	0.23	0.00	0.21	4.30

b) 2002

W2A (30-60 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
23-Jan-02	MBC 540	0.06	46.36	0.92	9.21
6-Mar-02	MBC 619	0.39	39.44	1.01	

W2A (90-120 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 499	0.04	22.41	0.13	5.61
23-Jan-02	MBC 541	0.00	26.61	0.07	2.58
6-Feb-02	MBC 570	0.02	31.97	0.18	5.00
20-Feb-02	MBC 594	0.10	21.50	0.23	4.00
6-Mar-02	MBC 620	0.06	52.07	0.05	3.60
20-Mar-02	MBC 643	0.10	30.87	0.14	4.42
3-Apr-02	MBC 669	0.13	72.16	0.03	4.57
17-Apr-02	MBC 693	0.14	49.93	0.06	3.55
1-May-02	MBC 721	0.18	45.36	0.06	3.75
15-May-02	MBC 739	0.13	34.91	0.14	8.83
29-May-02	MBC 765	10.62	26.02	0.58	13.54
12-Jun-02	MBC 783	0.75	17.23	0.75	14.00
24-Jul-02	MBC 844	0.44	50.64	0.68	9.00
7-Aug-02	MBC 874	1.72	41.64	0.81	8.00
21-Aug-02	MBC 892	2.36	19.66	2.49	12.00
5-Sep-02	MBC 921	0.57	23.16	0.68	8.00
18-Sep-02	MBC 945	0.77	23.78	0.85	8.21
3-Oct-02	MBC 988	21.30	14.30	3.72	43.00

W2A (150-180 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 500	0.15	0.03	0.42	2.96
23-Jan-02	MBC 542	0.03	0.03	0.05	1.58
6-Feb-02	MBC 571	0.08	0.04	0.08	3.00
20-Feb-02	MBC 595	0.13	0.00	0.27	3.00
6-Mar-02	MBC 621	0.16	0.08	0.07	3.00
20-Mar-02	MBC 644	0.28	0.06	0.06	3.81
3-Apr-02	MBC 670	0.17	0.06	0.10	3.19
17-Apr-02	MBC 694	0.19	0.05	0.08	3.00
1-May-02	MBC 722	0.22	0.02	0.07	2.50
15-May-02	MBC 740	0.17	0.00	0.05	5.77
29-May-02	MBC 766	0.22	0.02	0.09	4.01
12-Jun-02	MBC 784	0.03	0.00	0.11	3.00
26-Jun-02	MBC 807	0.71	0.00	0.14	3.00
9-Jul-02	MBC 822	0.79	0.00	0.13	3.00
24-Jul-02	MBC 845	0.25	0.30	0.16	4.00
7-Aug-02	MBC 875	0.23	0.00	0.17	4.00
21-Aug-02	MBC 893	0.33	0.00	0.21	3.00
5-Sep-02	MBC 922	0.28	0.00	0.19	4.00
18-Sep-02	MBC 946	0.32	0.00	0.24	4.11
3-Oct-02	MBC 989	0.26	0.01	0.14	3.52

W2A (210-240 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 501	0.24	0.08	0.56	4.96
23-Jan-02	MBC 543	0.09	0.07	0.13	2.72
6-Feb-02	MBC 572	0.15	0.06	0.22	5.00
20-Feb-02	MBC 596	0.20	0.01	0.48	5.00
6-Mar-02	MBC 622	0.23	0.03	0.22	4.93
20-Mar-02	MBC 645	0.28	0.01	0.22	5.65
3-Apr-02	MBC 671	0.26	0.01	0.29	5.45
17-Apr-02	MBC 695	0.30	0.03	0.27	4.83
1-May-02	MBC 723	0.30	0.04	0.28	4.77
15-May-02	MBC 741	0.29	0.00	0.24	8.29
29-May-02	MBC 767	0.38	0.00	0.30	6.64
12-Jun-02	MBC 785	0.07	0.00	0.36	6.00
26-Jun-02	MBC 808	0.72	0.00	0.35	6.00
9-Jul-02	MBC 823	0.76	0.00	0.33	6.00
24-Jul-02	MBC 846	0.33	0.01	0.28	6.00
7-Aug-02	MBC 876	0.38	0.00	0.32	6.00
21-Aug-02	MBC 894	0.33	0.00	0.38	4.00
5-Sep-02	MBC 923	0.32	0.00	0.51	7.00
18-Sep-02	MBC 947	0.42	0.00	0.47	6.53
3-Oct-02	MBC 990	0.42	0.00	0.37	6.47

Samples in Grey are Grab Samples After Irrigation

NH_4-N Ammonia - Nitrogen
NO_3-N Nitrate-Nitrogen
o-PO_4 Ortho-phosphate
DOC Dissolved Organic Carbon

Table F.5. Shallow groundwater quality in well nest W2B located in Plot 2 in **a)** 2001 and **b)** 2002

a) 2001

W2B (30-60 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
No Samples collected					

W2B (90-120 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC56	0.20	0.10	0.02	5.00
21-Mar-01	MBC80	0.10	0.10	0.06	5.00
4-Apr-01	MBC138	0.10	0.10	0.07	5.00
18-Apr-01	MBC102	0.20	0.00	0.17	11.00
2-May-01	MBC120	0.20	0.10	0.18	12.00
16-May-01	MBC160	0.20	0.30	0.12	6.00
30-May-01	MBC179	1.10	0.00	0.14	8.00
13-Jun-01	MBC200	0.50	0.80	0.21	15.00
27-Jun-01	MBC221	0.20	0.90	0.24	6.00
11-Jul-01	MBC241	0.60	0.50	0.21	7.00
25-Jul-01	MBC276	0.10	2.30	0.21	7.80
8-Aug-01	MBC299	0.10	1.70	0.25	5.70
22-Aug-01	MBC323	0.02	0.79	0.12	
5-Sep-01	MBC348	0.00	0.10	0.15	
19-Sep-01	MBC366	0.04	0.30	0.14	
26-Sep-01	GMBC382	0.10	0.80	0.09	
28-Sep-01	MBC 388	0.09	1.07	0.10	6.00
3-Oct-01	MBC 402	0.00	0.94	0.08	6.00
17-Oct-01	MBC 415	0.18	0.05	0.08	4.00

W2B (150-180 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC57	0.10	0.00	0.04	4.00
21-Mar-01	MBC81	0.10	0.00	0.05	4.00
4-Apr-01	MBC139	0.00	0.00	0.05	4.00
18-Apr-01	MBC103	0.10	0.00	0.03	9.00
2-May-01	MBC121	0.10	0.10	0.04	7.00
16-May-01	MBC161	0.10	0.00	0.05	5.00
30-May-01	MBC180	0.20	0.00	0.09	6.00
13-Jun-01	MBC201	0.10	0.10	0.10	12.00
27-Jun-01	MBC222	0.20	0.00	0.12	5.00
11-Jul-01	MBC242	0.30	0.00	0.16	5.00
25-Jul-01	MBC277	0.10	0.10	0.17	4.60
8-Aug-01	MBC300	0.20	0.00	0.14	4.90
22-Aug-01	MBC324	0.19	0.05	0.13	
5-Sep-01	MBC349	0.10	0.00	0.01	
19-Sep-01	MBC367	0.51	0.00	0.13	
3-Oct-01	MBC 403	0.06	0.21	0.07	5.00
17-Oct-01	MBC 416	0.03	0.04	0.06	4.00
31-Oct-01	MBC 429	0.15	0.03	0.12	6.00
15-Nov-01	MBC 441	0.18	0.03	0.24	6.00
28-Nov-01	MBC 456	0.06	0.04	0.23	4.00
12-Dec-01	MBC 468	0.17	0.00	0.16	5.30
26-Dec-01	MBC 480	0.14	0.00	0.14	3.80

W2B (210-240 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC58	0.20	0.00	0.21	5.00
21-Mar-01	MBC82	0.20	0.00	0.22	5.00
4-Apr-01	MBC140	0.30	0.00	0.20	5.00
18-Apr-01	MBC104	0.20	0.00	0.23	11.00
2-May-01	MBC122	0.20	0.00	0.24	8.00
16-May-01	MBC162	0.20	0.00	0.23	6.00
30-May-01	MBC181	0.20	0.00	0.27	6.00
13-Jun-01	MBC202	0.20	0.10	0.30	13.00
27-Jun-01	MBC223	0.20	0.00	0.30	6.00
11-Jul-01	MBC243	0.20	0.10	0.14	8.00
25-Jul-01	MBC278	0.20	0.00	0.29	4.80
8-Aug-01	MBC301	0.20	0.00	0.29	5.70
22-Aug-01	MBC325	0.17	0.02	0.26	
5-Sep-01	MBC350	0.10	0.00	0.23	
19-Sep-01	MBC368	0.25	0.00	0.32	
3-Oct-01	MBC 404	0.21	0.21	0.28	5.00
17-Oct-01	MBC 417	0.14	0.04	0.25	6.00
31-Oct-01	MBC 430	0.21	0.03	0.18	6.00
15-Nov-01	MBC 442	0.15	0.03	0.05	4.00
28-Nov-01	MBC 457	0.06	0.03	0.03	2.00
12-Dec-01	MBC 469	0.20	0.00	0.18	5.70
26-Dec-01	MBC 481	0.21	0.00	0.13	4.40

b) 2002

W2B (30-60 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
23-Jan-02	MBC 544	0.00	42.91	0.50	4.15

W2B (90-120 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 502	0.00	15.61	0.03	4.64
23-Jan-02	MBC 545	0.00	16.25	0.02	2.38
6-Feb-02	MBC 573	0.00	18.01	0.03	4.00
20-Feb-02	MBC 597	0.02	16.20	0.15	4.00
6-Mar-02	MBC 623	0.03	42.67	0.03	4.52
20-Mar-02	MBC 646	0.05	38.56	0.03	4.76
3-Apr-02	MBC 672	0.03	62.46	0.02	4.87
17-Apr-02	MBC 696	0.07	40.49	0.04	3.88
1-May-02	MBC 724	0.06	23.97	0.07	4.00
15-May-02	MBC 742	0.96	15.62	0.07	7.88
29-May-02	MBC 768	0.06	12.94	0.07	5.64
12-Jun-02	MBC 786	0.06	10.58	0.06	4.00
24-Jul-02	MBC 847	1.01	28.93	1.25	9.00
7-Aug-02	MBC 877	2.92	25.57	1.87	10.00
21-Aug-02	MBC 895	1.16	15.48	1.40	7.00
5-Sep-02	MBC 924	2.27	9.54	1.70	11.00
18-Sep-02	MBC 948	1.03	14.54	1.35	11.02
3-Oct-02	MBC 991	2.72	10.98	0.86	16.60

W2B (150-180 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 503	0.09	0.07	0.36	3.69
23-Jan-02	MBC 546	0.01	0.11	0.06	2.66
6-Feb-02	MBC 574	0.00	0.12	0.02	4.00
20-Feb-02	MBC 598	0.02	0.11	0.19	3.00
6-Mar-02	MBC 624	0.11	0.07	0.02	3.33
20-Mar-02	MBC 647	0.09	0.36	0.03	4.05
3-Apr-02	MBC 673	0.05	0.09	0.03	3.30
17-Apr-02	MBC 697	0.07	0.06	0.02	3.32
1-May-02	MBC 725	0.09	0.05	0.02	3.22
15-May-02	MBC 743	0.11	0.00	0.02	6.18
29-May-02	MBC 769	0.21	0.00	0.02	4.39
12-Jun-02	MBC 787	0.03	0.02	0.04	4.00
26-Jun-02	MBC 809	0.38	0.00	0.04	4.00
9-Jul-02	MBC 824	0.48	0.00	0.06	6.00
24-Jul-02	MBC 848	0.20	0.00	0.06	5.00
7-Aug-02	MBC 878	0.22	0.00	0.07	5.00
21-Aug-02	MBC 896	0.23	0.00	0.14	4.00
5-Sep-02	MBC 925	0.21	0.56	0.09	5.00
18-Sep-02	MBC 949	0.37	0.38	0.07	2.93
3-Oct-02	MBC 992	0.19	0.43	0.03	4.81

W2B (210-240 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 504	0.15	0.07	0.55	5.01
23-Jan-02	MBC 547	0.06	0.13	0.10	2.72
6-Feb-02	MBC 575	0.09	0.05	0.15	5.00
20-Feb-02	MBC 599	0.19	0.00	0.42	6.00
6-Mar-02	MBC 625	0.16	0.02	0.15	5.49
20-Mar-02	MBC 648	0.19	0.01	0.15	6.24
3-Apr-02	MBC 674	0.21	0.01	0.17	5.77
17-Apr-02	MBC 698	0.29	0.05	0.16	6.12
1-May-02	MBC 726	0.22	0.02	0.18	5.20
15-May-02	MBC 744	0.24	0.00	0.15	9.34
29-May-02	MBC 770	0.21	0.00	0.18	7.05
12-Jun-02	MBC 788	0.04	0.00	0.22	6.00
26-Jun-02	MBC 810	0.59	0.00	0.23	6.00
9-Jul-02	MBC 825	0.64	0.00	0.25	6.00
24-Jul-02	MBC 849	0.27	0.00	0.24	6.00
7-Aug-02	MBC 879	0.29	0.00	0.27	7.00
21-Aug-02	MBC 897	0.27	0.00	0.30	4.00
5-Sep-02	MBC 926	0.28	0.00	0.27	7.00
18-Sep-02	MBC 950	0.29	0.00	0.29	5.00
3-Oct-02	MBC 993	0.34	0.00	0.23	7.80

Samples in Grey are Grab Samples After Irrigation

NH_4-N Ammonia - Nitrogen
NO_3-N Nitrate-Nitrogen
o-PO_4 Ortho-phosphate
DOC Dissolved Organic Carbon

Table F.6. Shallow groundwater quality in well nest W2C located in Plot 2 in **a)** 2001 and **b)** 2002

a) 2001

W2C (30-60 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
21-Mar-01	MBC83	22.20	3.80	5.43	29.00

W2C (90-120 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC59	0.20	0.20	0.05	4.00
21-Mar-01	MBC84	0.20	0.00	0.20	8.00
4-Apr-01	MBC141	0.10	0.00	0.11	7.00
18-Apr-01	MBC105	0.20	0.10	0.23	14.00
2-May-01	MBC123	0.10	0.20	0.11	12.00
16-May-01	MBC163	0.20	0.00	0.26	11.00
30-May-01	MBC182	0.30	0.10	0.16	7.00
13-Jun-01	MBC203	0.10	0.20	0.14	18.00
27-Jun-01	MBC224	0.10	0.10	0.11	6.00
11-Jul-01	MBC244	0.40	0.00	0.04	5.00
25-Jul-01	MBC279	0.00	0.20	0.14	8.90
8-Aug-01	MBC302	0.30	0.10	0.09	7.20
22-Aug-01	MBC326	0.05	0.13	0.12	
19-Sep-01	MBC369	0.48	0.20	0.12	
26-Sep-01	GMBC383	0.10	0.20	0.07	
28-Sep-01	MBC 389	0.11	0.38	0.06	6.00
3-Oct-01	MBC 405	0.04	0.41	0.13	7.00

W2C (150-180 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC60	0.10	0.00	0.05	2.00
21-Mar-01	MBC85	0.10	0.00	0.03	5.00
4-Apr-01	MBC142	0.10	0.00	0.02	5.00
18-Apr-01	MBC106	0.20	0.00	0.03	9.00
2-May-01	MBC124	0.10	0.00	0.04	8.00
16-May-01	MBC164	0.10	0.00	0.04	5.00
30-May-01	MBC183	0.20	0.00	0.03	5.00
13-Jun-01	MBC204	0.10	0.10	0.05	11.00
27-Jun-01	MBC225	0.10	0.00	0.03	5.00
11-Jul-01	MBC245	0.30	0.00	0.05	5.00
25-Jul-01	MBC280	0.10	0.00	0.02	4.70
8-Aug-01	MBC303	0.10	0.00	0.02	4.80
22-Aug-01	MBC327	0.09	0.09	0.02	
19-Sep-01	MBC370	0.21	0.00	0.05	
3-Oct-01	MBC 406	0.19	0.22	0.04	5.00
17-Oct-01	MBC 418	0.11	0.07	0.03	5.00
31-Oct-01	MBC 431	0.19	0.04	0.03	5.00
15-Nov-01	MBC 443	0.17	0.04	0.02	5.00
28-Nov-01	MBC 458	0.11	0.04	0.02	4.00
12-Dec-01	MBC 470	0.27	0.00	0.02	5.20
26-Dec-01	MBC 482	0.13	0.00	0.01	3.60

W2C (210-240 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
7-Mar-01	MBC61	0.20	0.00	0.13	3.00
21-Mar-01	MBC86	0.20	0.00	0.13	6.00
4-Apr-01	MBC143	0.30	0.00	0.14	7.00
18-Apr-01	MBC107	0.30	0.00	0.10	13.00
2-May-01	MBC125	0.10	0.00	0.04	9.00
30-May-01	MBC184	0.20	0.00	0.17	7.00
13-Jun-01	MBC205	0.20	0.10	0.19	14.00
27-Jun-01	MBC226	0.20	0.00	0.20	6.00
11-Jul-01	MBC246	0.40	0.00	0.20	6.00
25-Jul-01	MBC281	0.10	0.00	0.19	6.50
8-Aug-01	MBC304	0.20	0.00	0.19	6.20
22-Aug-01	MBC328	0.13	0.02	0.17	
19-Sep-01	MBC371	0.15	0.00	0.22	
3-Oct-01	MBC 407	0.15	0.21	0.18	6.00
17-Oct-01	MBC 419	0.12	0.08	0.17	6.00
31-Oct-01	MBC 432	0.15	0.03	0.12	6.00
15-Nov-01	MBC 444	0.15	0.08	0.09	6.00
28-Nov-01	MBC 459	0.09	0.05	0.01	3.00
12-Dec-01	MBC 471	0.19	0.00	0.14	6.10
26-Dec-01	MBC 483	0.17	0.00	0.13	5.80

b) 2002

W2C (30-60 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
23-Jan-02	MBC 548	0.0	10.9	0.41	5.32

W2C (90-120 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 505	0.03	11.08	0.28	7.75
23-Jan-02	MBC 549	0.00	8.82	0.13	3.77
6-Feb-02	MBC 576	0.00	8.90	0.44	7.00
20-Feb-02	MBC 600	0.07	7.66	0.49	7.00
6-Mar-02	MBC 626	0.10	16.69	0.29	6.43
20-Mar-02	MBC 649	0.07	12.99	0.34	7.05
3-Apr-02	MBC 675	0.05	15.81	0.14	6.51
17-Apr-02	MBC 699	0.05	14.26	0.20	6.45
1-May-02	MBC 727	0.18	8.35	0.73	10.60
15-May-02	MBC 745	0.29	3.99	0.17	10.27
29-May-02	MBC 771	0.18	3.61	0.38	10.78
12-Jun-02	MBC 789	0.04	3.80	0.18	7.00
24-Jul-02	MBC 850	0.03	29.29	0.08	6.00
7-Aug-02	MBC 880	0.07	19.43	0.16	6.00
21-Aug-02	MBC 898	0.06	9.47	0.18	6.00
5-Sep-02	MBC 927	0.10	13.61	0.32	7.00
18-Sep-02	MBC 951	0.22	13.26	0.31	8.37
3-Oct-02	MBC 994	0.15	14.33	0.23	6.31

W2C (150-180 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 506	0.15	0.07	0.21	4.10
23-Jan-02	MBC 550	0.12	0.09	0.02	3.10
6-Feb-02	MBC 577	0.10	0.05	0.01	4.00
20-Feb-02	MBC 601	0.16	0.02	0.14	4.00
6-Mar-02	MBC 627	0.20	0.03	0.02	4.65
20-Mar-02	MBC 650	0.22	0.03	0.02	5.66
3-Apr-02	MBC 676	0.20	0.02	0.02	4.65
17-Apr-02	MBC 700	0.23	0.03	0.01	4.40
1-May-02	MBC 728	0.25	0.04	0.02	4.59
15-May-02	MBC 746	0.29	0.00	0.01	7.02
29-May-02	MBC 772	0.21	0.00	0.01	5.86
12-Jun-02	MBC 790	0.05	0.00	0.02	5.00
26-Jun-02	MBC 811	0.65	0.00	0.04	5.00
9-Jul-02	MBC 826	0.45	0.00	0.03	5.00
24-Jul-02	MBC 851	0.16	0.00	0.04	5.00
7-Aug-02	MBC 881	0.18	0.00	0.03	5.00
21-Aug-02	MBC 899	0.19	0.00	0.05	3.00
5-Sep-02	MBC 928	0.21	0.00	0.04	5.00
18-Sep-02	MBC 952	0.28	0.00	0.07	5.04
3-Oct-02	MBC 995	0.24	0.01	0.03	3.74

W2C (210-240 cm depth)

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 507	0.12	0.03	0.53	5.13
23-Jan-02	MBC 551	0.09	0.03	0.11	4.01
6-Feb-02	MBC 578	0.06	0.04	0.13	6.00
20-Feb-02	MBC 602	0.12	0.00	0.43	5.00
6-Mar-02	MBC 628	0.15	0.01	0.13	5.40
20-Mar-02	MBC 651	0.28	0.01	0.12	6.26
3-Apr-02	MBC 677	0.15	0.01	0.16	5.55
17-Apr-02	MBC 701	0.18	0.04	0.13	5.51
1-May-02	MBC 729	0.19	0.02	0.14	6.00
15-May-02	MBC 747	0.18	0.01	0.09	7.49
29-May-02	MBC 773	0.26	0.00	0.14	6.64
12-Jun-02	MBC 791	0.02	0.00	0.17	6.00
26-Jun-02	MBC 812	0.48	0.00	0.18	6.00
9-Jul-02	MBC 827	0.48	0.00	0.19	6.00
24-Jul-02	MBC 852	0.20	0.00	0.21	6.00
7-Aug-02	MBC 882	0.22	0.00	0.19	7.00
21-Aug-02	MBC 900	0.22	0.00	0.24	4.00
5-Sep-02	MBC 929	0.24	0.00	0.24	7.00
18-Sep-02	MBC 953	0.27	0.00	0.30	6.37
3-Oct-02	MBC 996	0.18	0.00	0.13	3.88

Samples in Grey are Grab Samples After Irrigation

NH_4-N Ammonia - Nitrogen
NO_3-N Nitrate-Nitrogen
o-PO_4 Ortho-phosphate
DOC Dissolved Organic Carbon

APPENDIX 1-G

Drainage Water Quality Data

Table G.1. Drain P1A drainage water quality data in **a)** 2001 and **b)** 2002

a) 2001

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
10-Jan-01	MBC18	0.30	1.20	0.01	7.00
24-Jan-01	MBC23	0.30	1.30	0.02	6.00
8-Feb-01	MBC29	0.20	1.30	0.01	6.00
21-Feb-01	MBC33	0.20	1.00	0.01	11.00
7-Mar-01	MBC40	0.20	1.00	0.01	5.00
21-Mar-01	MBC62	2.90	0.20	0.67	13.00
4-Apr-01	MBC126	0.50	0.30	0.36	14.00
18-Apr-01	MBC90	3.70	0.20	0.03	10.00
16-May-01	MBC144	0.70	1.10	0.03	11.00
30-May-01	MBC167	1.30	1.60	0.03	8.00
13-Jun-01	MBC185	0.40	4.60	0.04	20.00
27-Jun-01	MBC206	0.50	2.60	0.02	6.00
11-Jul-01	MBC230	1.00	2.30	0.03	8.00
25-Jul-01	MBC264	0.50	2.90	0.04	8.60
8-Aug-01	MBC285	0.30	6.00	0.02	6.10
22-Aug-01	MBC305	0.22	7.67	0.02	6.00
5-Sep-01	MBC332	0.30	3.00	0.02	9.00
19-Sep-01	MBC354	0.58	3.50	0.01	7.00
26-Sep-01	GMBC375	0.90	7.00	0.04	7.00
28-Sep-01	GMBC384	0.30	6.80	0.04	7.00
3-Oct-01	MBC390	1.2	6.6	0.04	7

Samples in Grey are Grab Samples

NH_4-N	Ammonia - Nitrogen
NO_3-N	Nitrate-Nitrogen
o-PO_4	Ortho-phosphate
DOC	Dissolved Organic Carbon

b) 2002

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 484	0.13	26.06	0.12	4.98
16-Jan-02	MBC 508	0.07	10.62	0.01	3.60
23-Jan-02	MBC 514	0.07	11.23	0.01	2.28
23-Jan-02	MBC 522	0.07	21.33	0.04	4.33
30-Jan-02	MBC 552	0.18	11.58	0.03	2.81
6-Feb-02	MBC 558	0.19	11.65	0.04	5.70
13-Feb-02	MBC 579	0.27	13.23	0.01	5.00
20-Feb-02	MBC 585	0.19	12.60	0.06	5.00
6-Mar-02	MBC 603	0.21	10.92	0.04	6.38
20-Mar-02	MBC 629	0.25	9.11	0.04	5.77
3-Apr-02	MBC 652	0.22	7.31	0.05	7.49
17-Apr-02	MBC 678	0.29	5.03	0.03	6.44
25-Apr-02	MBC 707	16.94	6.11	0.38	25.49
1-May-02	MBC 712	0.93	2.89	0.04	7.71
15-May-02	MBC 730	0.26	1.55	0.02	9.77
24-May-02	MBC 751	15.47	10.46	0.34	23.10
29-May-02	MBC 756	1.51	5.17	0.04	10.37
12-Jun-02	MBC 774	0.28	9.24	0.05	10.00
19-Jun-02	MBC 795	61.91			121.00
26-Jun-02	MBC 798	2.91	12.32	0.17	18.00
9-Jul-02	MBC 813	2.29	13.27	0.04	11.00
24-Jul-02	MBC 828	0.17	13.58	0.05	7.00
31-Jul-02	MBC 856	4.69	12.43	0.32	16.00
7-Aug-02	MBC 862	0.98	11.41	0.02	7.00
21-Aug-02	MBC 883	0.50	9.14	0.13	19.00
28-Aug-02	MBC 901	0.28	9.34	0.08	7.00
5-Sep-02	MBC 906	0.15	10.59	0.03	5.00
18-Sep-02	MBC 930	0.33	6.43	0.02	6.71
18-Sep-02	MBC 956	0.69	5.83	0.02	6.49
19-Sep-02	MBC 963	0.99	7.75	0.08	9.10
3-Oct-02	MBC 973	0.40	5.61	0.02	7.03

Table G.2. Drain P1B drainage water quality data in **a)** 2001 and **b)** 2002

a) 2001

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
10-Jan-01	MBC19	0.10	0.90	0.23	11.00
24-Jan-01	MBC24	0.10	0.70	0.59	16.00
8-Feb-01	MBC30	0.10	1.10	0.04	7.00
21-Feb-01	MBC34	0.10	0.60	0.08	8.00
7-Mar-01	MBC41	0.10	1.00	0.02	6.00
21-Mar-01	MBC63	0.50	0.40	0.24	4.00
4-Apr-01	MBC127	0.20	0.50	0.27	11.00
18-Apr-01	MBC91	0.20	0.50	0.12	14.00
16-May-01	MBC145	0.50	0.90	0.16	16.00
30-May-01	MBC168	0.80	1.40	0.07	9.00
13-Jun-01	MBC186	0.40	2.80	0.08	23.00
27-Jun-01	MBC207	0.30	3.50	0.09	8.00
11-Jul-01	MBC231	1.60	2.50	5.75	102.00
25-Jul-01	MBC265	0.00	4.70	0.08	7.10
8-Aug-01	MBC286	0.70	8.40	0.06	7.20
22-Aug-01	MBC306	0.15	7.67	0.06	7.00
5-Sep-01	MBC333	0.30	4.80	0.11	10.00
19-Sep-01	MBC355	4.48	6.00	0.63	24.00
26-Sep-01	GMBC376	15.20	14.10	0.84	21.00
28-Sep-01	GMBC385	0.30	9.10	0.04	6.00
3-Oct-01	MBC391	3.90	9.20	0.33	13.00

Samples in Grey are Grab Samples

NH_4-N	Ammonia - Nitrogen
NO_3-N	Nitrate-Nitrogen
o-PO_4	Ortho-phosphate
DOC	Dissolved Organic Carbon

b) 2002

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 485	0.34	30.70	0.13	6.54
16-Jan-02	MBC 509	0.01	20.00	0.03	3.75
23-Jan-02	MBC 515	0.00	13.08	0.02	2.63
23-Jan-02	MBC 523	0.00	15.39	0.03	3.11
30-Jan-02	MBC 553	0.02	16.67	0.02	3.04
6-Feb-02	MBC 559	0.00	17.38	0.03	6.10
13-Feb-02	MBC 580	0.03	17.56	0.04	5.00
20-Feb-02	MBC 586	0.01	18.70	0.08	6.00
6-Mar-02	MBC 604	0.07	17.95	0.08	6.41
20-Mar-02	MBC 630	0.05	13.57	0.03	5.90
3-Apr-02	MBC 653	0.13	10.95	0.06	5.80
17-Apr-02	MBC 679	0.11	8.47	0.04	7.42
25-Apr-02	MBC 708	14.45	9.56	1.04	20.14
1-May-02	MBC 713	3.85	7.03	0.49	13.74
15-May-02	MBC 731	0.66	9.60	0.30	35.11
24-May-02	MBC 752	39.56	15.66	1.20	35.43
29-May-02	MBC 757	1.33	7.93	0.35	14.63
12-Jun-02	MBC 775	0.14	13.31	0.16	14.00
19-Jun-02	MBC 796	37.98			100.00
26-Jun-02	MBC 799	24.30	20.64	2.54	108.00
9-Jul-02	MBC 814	1.24	17.86	0.16	16.00
24-Jul-02	MBC 829	0.11	17.50	0.06	7.00
31-Jul-02	MBC 857	17.27	19.12	1.26	24.00
7-Aug-02	MBC 863	0.21	15.29	0.06	7.00
21-Aug-02	MBC 884	0.26	15.64	0.16	20.00
28-Aug-02	MBC 902	0.19	13.18	0.08	6.00
5-Sep-02	MBC 907	0.16	12.36	0.12	6.00
18-Sep-02	MBC 931	0.15	10.70	0.06	7.20
18-Sep-02	MBC 957	11.84	11.71	0.88	13.95
19-Sep-02	MBC 964	17.59	12.64	1.83	20.92
3-Oct-02	MBC 974	4.98	11.00	1.65	23.84

Table G.3. Drain P1C drainage water quality data in **a)** 2001 and **b)** 2002

a) 2001

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
10-Jan-01	MBC20	0.20	0.50	0.05	7.00
24-Jan-01	MBC25	0.20	0.40	0.08	7.00
8-Feb-01	MBC31	0.10	0.50	0.02	6.00
21-Feb-01	MBC35	0.10	0.40	0.04	8.00
7-Mar-01	MBC42	0.10	0.50	0.01	6.00
21-Mar-01	MBC64	0.40	0.10	0.26	5.00
4-Apr-01	MBC128	0.20	0.20	0.24	13.00
18-Apr-01	MBC92	0.20	0.20	0.06	11.00
16-May-01	MBC146	0.30	0.40	0.05	6.00
30-May-01	MBC169	1.30	0.40	0.08	12.00
13-Jun-01	MBC187	0.40	2.30	0.05	20.00
27-Jun-01	MBC208	0.30	1.30	0.03	7.00
25-Jul-01	MBC266	1.70	0.90	0.14	14.00
8-Aug-01	MBC287	0.40	5.00	0.02	7.00
22-Aug-01	MBC307	0.41	4.32	0.03	6.00
5-Sep-01	MBC334	1.00	2.60	0.02	7.00
19-Sep-01	MBC356	2.31	2.90	0.23	15.00
26-Sep-01	GMBC377	3.90	7.70	0.23	12.00
28-Sep-01	GMBC386	0.50	4.20	0.14	8.00
3-Oct-01	MBC392	2.90	4.20	0.06	15.00

Samples in Grey are Grab Samples

NH_4-N Ammonia - Nitrogen
NO_3-N Nitrate-Nitrogen
o-PO_4 Ortho-phosphate
DOC Dissolved Organic Carbon

b) 2002

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 486	0.03	16.88	0.02	4.01
16-Jan-02	MBC 510	0.33	25.17	0.02	3.73
23-Jan-02	MBC 516	0.02	9.77	0.01	1.97
23-Jan-02	MBC 524	0.00	10.31	0.02	2.77
30-Jan-02	MBC 554	0.00	15.16	0.02	2.82
6-Feb-02	MBC 560	0.00	18.91	0.02	5.00
13-Feb-02	MBC 581	0.03	17.24	0.01	5.00
20-Feb-02	MBC 587	0.04	22.20	0.06	5.00
6-Mar-02	MBC 605	0.14	18.59	0.02	5.39
20-Mar-02	MBC 631	0.20	13.38	0.03	6.82
3-Apr-02	MBC 654	0.06	9.60	0.02	5.70
17-Apr-02	MBC 680	0.13	9.41	0.02	5.90
25-Apr-02	MBC 709	2.13	6.70	0.11	10.28
1-May-02	MBC 714	0.99	11.72	0.03	8.56
15-May-02	MBC 732	0.37	5.46	0.02	10.16
24-May-02	MBC 753	5.36	11.25	0.13	17.29
29-May-02	MBC 758	1.83	9.96	0.04	10.14
12-Jun-02	MBC 776	0.26	13.74	0.03	10.00
19-Jun-02	MBC 797	15.34			81.00
26-Jun-02	MBC 800	17.99	20.75	0.98	50.00
9-Jul-02	MBC 815	2.76	20.48	0.08	15.00
24-Jul-02	MBC 830	0.13	10.49	0.03	5.00
31-Jul-02	MBC 858	1.25	12.50	0.08	10.00
7-Aug-02	MBC 864	0.44	12.10	0.03	7.00
21-Aug-02	MBC 885	0.77	11.77	0.11	14.00
28-Aug-02	MBC 903	0.31	9.14	0.05	6.00
5-Sep-02	MBC 908	0.20	9.32	0.03	5.00
18-Sep-02	MBC 932	0.55	7.41	0.04	5.90
18-Sep-02	MBC 958	3.74	8.30	0.35	12.58
19-Sep-02	MBC 965	0.49	8.93	0.04	7.43
3-Oct-02	MBC 975	0.76	8.06	0.05	7.66

Table G.4. Drain P2A drainage water quality data in **a)** 2001 and **b)** 2002

a) 2001

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
10-Jan-01	MBC21	2.90	7.20	0.97	35.00
7-Mar-01	MBC37	0.60	0.90	0.81	29.00
21-Mar-01	MBC65	39.80	0.10	2.30	11.00
13-Jun-01	MBC188	1.00	8.40	0.48	34.00
27-Jun-01	MBC209	0.90	11.40	1.19	17.00
22-Aug-01	MBC308	5.96	28.07	3.18	36.00
26-Sep-01	GMBC378	137.00	24.70	4.58	3.00

Samples in Grey are Grab Samples

NH_4-N Ammonia - Nitrogen
NO_3-N Nitrate-Nitrogen
o-PO_4 Ortho-phosphate
DOC Dissolved Organic Carbon

b) 2002

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 487	2.83	54.64	1.85	35.30
16-Jan-02	MBC 511	0.07	29.46	0.27	6.52
23-Jan-02	MBC 517	0.00	18.17	0.06	3.35
23-Jan-02	MBC 525	0.00	23.56	0.03	4.17
30-Jan-02	MBC 555	0.00	22.13	0.06	4.39
13-Feb-02	MBC 582	0.23	19.90	0.21	17.00
6-Mar-02	MBC 606	0.38	18.75	0.22	10.35
3-Apr-02	MBC 655	0.14	10.11	0.12	9.92
17-Apr-02	MBC 681	0.21	10.39	0.14	10.42
25-Apr-02	MBC 710	21.16	9.45	2.09	55.52
24-May-02	MBC 754	41.27	33.01	4.84	124.70
24-Jul-02	MBC 831	1.30	21.85	0.65	14.00
31-Jul-02	MBC 859	13.03	22.24	1.29	30.00
7-Aug-02	MBC 865	0.45	17.82	0.20	11.00
28-Aug-02	MBC 904	0.39	10.76	0.68	12.00
5-Sep-02	MBC 909	0.76	13.20	0.13	10.00
18-Sep-02	MBC 933	0.24	9.58	0.30	11.79
18-Sep-02	MBC 959	22.52	11.96	2.20	25.87
19-Sep-02	MBC 966	4.29	12.09	0.52	17.94
3-Oct-02	MBC 976	4.04	11.47	0.77	27.31

Table G.5. Drain P2B drainage water quality data in **a)** 2001 and **b)** 2002

a) 2001

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
24-Jan-01	MBC26	0.40	2.10	2.49	52.00
8-Feb-01	MBC31	0.10	2.70	0.26	19.00
7-Mar-01	MBC38	0.30	0.70	0.23	17.00
21-Mar-01	MBC66	19.90	0.70	1.29	8.00
16-May-01	MBC166	6.30	9.90	1.44	38.00
13-Jun-01	MBC189	2.30	13.00	0.54	35.00
27-Jun-01	MBC210	0.80	9.80	0.18	11.00
8-Aug-01	MBC288	2.10	23.60	1.57	19.50
22-Aug-01	MBC309	0.78	19.20	0.35	10.00
26-Sep-01	GMBC379	103.70	72.30	1.50	94.00

Samples in Grey are Grab Samples

NH_4-N Ammonia - Nitrogen
NO_3-N Nitrate-Nitrogen
o-PO_4 Ortho-phosphate
DOC Dissolved Organic Carbon

b) 2002

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 488	0.41	44.77	0.48	8.46
16-Jan-02	MBC 512	0.13	29.63	0.17	5.72
23-Jan-02	MBC 518	0.01	10.42	0.08	3.12
23-Jan-02	MBC 526	0.00	15.73	0.03	3.97
30-Jan-02	MBC 556	0.08	22.18	0.06	5.05
13-Feb-02	MBC 583	0.10	23.60	0.26	14.00
6-Mar-02	MBC 607	0.29	16.69	0.15	8.67
20-Mar-02	MBC 632	0.17	11.09	0.24	14.69
3-Apr-02	MBC 656	0.15	8.21	0.13	10.53
17-Apr-02	MBC 682	0.20	7.74	0.08	10.00
25-Apr-02	MBC 711	22.08	14.18	0.49	41.63
24-May-02	MBC 755	250.04	19.27	9.36	6.28
24-Jul-02	MBC 832	0.93	18.80	0.31	11.00
31-Jul-02	MBC 860	4.72	15.70	0.46	18.00
7-Aug-02	MBC 866	1.46	14.84	0.07	12.00
28-Aug-02	MBC 905	0.32	9.43	0.39	9.00
5-Sep-02	MBC 910	0.28	11.01	0.24	10.00
18-Sep-02	MBC 934	0.35	7.83	0.15	9.83
18-Sep-02	MBC 960	8.66	7.07	0.85	17.20
19-Sep-02	MBC 967	13.79	7.78	0.85	18.01
3-Oct-02	MBC 977	7.00	7.87	1.14	20.25

Table G.6. Drain P2C drainage water quality data in **a)** 2001 and **b)** 2002

a) 2001

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
10-Jan-01	MBC22	0.10	2.20	0.02	9.00
24-Jan-01	MBC27	0.00	2.90	0.06	9.00
8-Feb-01	MBC32	0.00	2.00	0.06	7.00
21-Feb-01	MBC36	0.00	0.70	0.03	11.00
7-Mar-01	MBC39	0.10	0.40	0.02	10.00
21-Mar-01	MBC88	22.50	2.10	2.39	32.00
16-May-01	MBC147	2.10	4.40	0.45	23.00
13-Jun-01	MBC190	3.40	12.40	2.96	60.00
27-Jun-01	MBC211	0.20	1.60	0.37	14.00
8-Aug-01	MBC289	0.20	12.60	0.30	10.30
22-Aug-01	MBC310	0.00	9.05	0.07	9.00
5-Sep-01	MBC335	0.30	4.80	0.07	14.00

Samples in Grey are Grab Samples

NH_4-N Ammonia - Nitrogen
NO_3-N Nitrate-Nitrogen
o-PO_4 Ortho-phosphate
DOC Dissolved Organic Carbon

b) 2002

Date	LabID	NH_4-N mg/L	NO_3-N mg/L	o-PO_4 mg/L	DOC mg/L
9-Jan-02	MBC 489	0.31	33.89	0.33	7.84
16-Jan-02	MBC 513	0.12	19.66	0.06	4.87
23-Jan-02	MBC 519	0.00	16.35	0.06	3.60
23-Jan-02	MBC 527	0.00	16.11	0.05	4.15
30-Jan-02	MBC 557	0.02	18.80	0.04	4.46
13-Feb-02	MBC 584	0.00	17.40	0.03	6.00
6-Mar-02	MBC 608	0.09	11.54	0.40	9.60
20-Mar-02	MBC 633	0.07	5.34	0.10	9.12
3-Apr-02	MBC 657	0.04	4.44	0.08	10.06
17-Apr-02	MBC 683	0.07	3.28	0.05	9.57
24-Jul-02	MBC 833	0.29	10.87	0.84	19.00
31-Jul-02	MBC 861	2.32	6.78	0.20	14.00
7-Aug-02	MBC 867	1.40	8.27	0.18	12.00
5-Sep-02	MBC 911	0.17	4.98	0.88	13.00
18-Sep-02	MBC 935	0.27	3.79	0.08	7.77
18-Sep-02	MBC 961	2.51	2.70	0.21	12.37
19-Sep-02	MBC 968	0.48	3.00	0.07	10.08
3-Oct-02	MBC 978	1.19	3.32	0.19	17.17

APPENDIX 1-H

NH_4^+ - N Data from Plot 1 and 2

Table H.1. Average of NH_4^+-N concentrations measured in Plot 1 and Plot 2

Plot	2001 NH_4^+- N (mg/L)	2002 NH_4^+- N (mg/L)	Overall (mg/L)
Plot 1	0.8 (0 - 4.5)[1]	1.1 (0 - 24.3)	1.0 (0 - 24.3)
Plot 2	5.3 (0.1 - 39.8)	0.6 (0 - 7.0)	2.4 (0 - 39.8)

1 - Range of concentrations

Table H.2. Average of NH_4^+-N export observed from Plot 1 and Plot 2

a) Plot 1 - Drain depth = 1.5 m, Spacing = 25 m

Drain	2001 NH_4^+- N kg/ha	2002[1] NH_4^+- N kg/ha	Study NH_4^+- N kg/ha
P1A	1.1	0.93	2.03
P1B	0.83	1.21	2.04
P1C	0.895	0.95	1.845
Avg	0.94	1.03	1.97
Std Dev	0.14	0.16	0.11

b) Plot 2 - Drain depth = 0.75 m, Spacing = 12.5 m

Drain	2001 NH_4^+- N kg/ha	2002[1] NH_4^+- N kg/ha	Study NH_4^+- N kg/ha
P2A	1.35	0.77	2.12
P2B	1.54	1.22	2.76
P2C	0.59	0.73	1.32
Avg	1.16	0.91	2.07
Std Dev	0.50	0.27	0.72

1 - Through September

APPENDIX 1-I

Experimental Challenges

Initial Design

The original design of the drainage systems was to include subsurface tile drains that *averaged* 1.5 m deep in Plot 1 and 0.75 m deep in Plot 2. Because of limited depth the machine could install the drain tile, and the wet conditions the installers were forced to contend with, a depth of 1.5 m was the maximum the drain tile could be installed at one end. To achieve a depth of 50% of the deep drain, the maximum depth the shallow drains could be installed at one end was 0.75 m. With the 0.07% slope of each of the drains, the average drain depth was slightly less that the original goal. Also, a tree in the middle of Plot 1, used as shade for the cattle, required that the middle drain in Plot 1, P1B, need to be bowed around the tree to avoid the rooting system. The drain was also wrapped in copper wire to discourage roots from penetrating the drain lines during the study.

The main drainage lines that carried the drainage water from the laterals was a much more critical problem for two reasons. First, to achieve adequate drop in the observation manholes to install the tipping bucket flow measuring devices, the main for Plot 1 needed to be installed at a depth of over 2.1 m. Because the maximum depth of the drain tile could be installed with our equipment was about 1.5 m, a 60 cm trench was excavated above where the main was to be installed. As in the lateral installation, wet conditions again limited the installation of the main to a depth adequate for clearance of the tipping buckets in the observation manholes. Lateral drains entering the observation manholes in P1A and P1C then had to be raised 6-8 cm, effectively raising the depth of the drains by that amount. Secondly, *perforated* mains instead of solid mains were installed due to high water table

conditions. This helped maintain the grade of the mains because as groundwater flowed into the trench during installation, it also flowed into the drain, preventing it from floating upward before the trench was backfilled. The problem is that the main also carried groundwater from the adjacent field, as well as a small percentage of the groundwater from beneath the research plots. This put an extra requirement on the outlet pumps because of the extra volume of water entering the sumps, and also made it difficult to quantify seepage from the research plots.

Observation Manhole Flooding

Flooding of the observation manholes occurred on several occasions following large rainfall events. Flow into the mains from outside the plots through the perforated mains, exceeding the designed pumping capacity, seemed to be the major culprit. Pump malfunctions, mainly from clogging with debris such as gravel, frogs, and rabbits, caused water to back up into the manholes on several occasions. Loss in electrical power to the pumps during storms also caused water to back into the observation manholes. Formation of ion ochre in the PVC lines leading away from the sumps backed water up into the sumps and observation manholes on at least one occasion.

Drainage Flow and Water Table Measurements

The tipping buckets, made of PVC, worked well, but occasionally became stuck, especially after an observation manhole was flooded. The receding water would leave the tipping bucket balanced with water flowing into both sides equally, resulting in no tips. The

tipping bucket in P1C manhole was especially prone to this. Flow from these drains had to be estimated after flooding and/or tipping bucket malfunction.

Data collection was occasionally compromised due to malfunctions in the dataloggers and/or power supplies. Both dataloggers would occasionally stop collecting data and would need to be reset. Battery power to the dataloggers and automatic samplers would drop below 12 V, causing the dataloggers to miss data and water sample collection periods.

There were water table recorder problems on a couple of occasions. The dataloggers only malfunctioned twice in over 2-1/2 years of service. During several rainfall events in 2001, the counterweight attachment on the pulley and float system bottomed out on soil, which had flowed into the uncapped counterweight well. This caused the water table profile to appear to be lower than it actually was, because the float rising toward the soil surface was limited by the counterweight.

APPENDIX 2

APPENDIX 2-A

Procedures for Estimating Lateral Saturated Hydraulic Conductivity (K_{sat}) in Plot 1 and Plot 2

Field estimates of K_{sat} using the auger hole method were not satisfactory, so a method was employed that used water table data and measured flow data to estimate the value of K_{sat} for the various soil layers in Plot 1 and Plot 2. Observations of the soil profile revealed it could be described with four layers. The depth to the impervious layer was estimated to be 300 cm. To estimate K_{sat}, the general form of the Hooghoudt equation was modified to reflect the various layers in the soil profile in order to solve for the K_{sat} of each of the four soil layers observed:

$$q = \frac{4m^2\left(\frac{K_1d_1 + K_2d_2 + K_3d_3 + K_4d_4}{d_1 + d_2 + d_3 + d_4}\right) + 8K_4d_em}{L^2}$$

where

q = drainage flux (cm/hr)

d_e = the equivalent depth from the drain to the impermeable layer (cm)

m = the midpoint elevation of the water table above the drain (cm)

L = drain spacing (cm)

d_1 = thickness of layer 1 (0-40 cm) contributing to flow

d_2 = thickness of layer 2 (40-100 cm) contributing to flow

d_3 = thickness of layer 3 (100-135 cm) contributing to flow

d_4 = thickness of layer 4 (135-300 cm) contributing to flow

K_1……K_4 = represent the lateral saturated hydraulic conductivity of layers 1-4.

The K_{sat} estimate for Plot 1 was attempted first. Figure A.1 shows the schematic of the Plot 1 drains within the four layered soil. The effective depth to the impermeable layer, d_e (required to account for head losses due to convergence), was calculated using the equation

$$d_e = \frac{d}{1 + \frac{d}{L}\left(\frac{8}{\pi} ln \frac{d}{r_e} - 3.4\right)}$$

For Plot 1, d (the distance of the drain to the impermeable layer) = 156 cm, r_e (the effective radius of the drain) = 1.5 cm, and L = 2500 cm. This resulted in a d_e = 102 cm.

Observed values for m were obtained from water table data, collected at the midpoint between the drains in Plot 1. Observed values for q were obtained from drain P1B drainage data, avoiding data that had been estimated. A scatter plot of the observed q vs. m relationship for drain P1B was then generated. A spreadsheet was developed to generate a q vs. m curve using the modified version of the Hooghoudt equation. The goal was to produce a curve that closely matched the observed q vs. m relationship by manipulating K_{sat} for the various layers. If this curve matched the observed relationship, those values of K_{sat} should be representative of the various soil layers.

This curve was developed for m values from 0 - 140 cm, with the value for q calculated at 0.5 cm intervals of water table drop. The estimate for q began at m = 140 cm, or 36 cm within Layer 1 (0-40 cm depth). Therefore, d_1 = 36 cm. Layer 2 (40-100 cm), Layer 3 (100-135 cm) and Layer 4 (135 – 144 cm to drain) all contributed to the flow to the drain so d_2 = 60 cm, d_3 = 35 cm, and d_4 = 9 cm. As the water table fall was simulated

through the various layers at 0.5 cm intervals, the d value for the layer in which the water table was residing also reduced by subtracting 0.5 cm during each interval, until the value reached 0 cm. Then, the d value for the next layer was reduced by subtracting 0.5 cm from its value while the water table resided in that layer. For example, for an m value of 30 cm, $d_1 = 0$ cm, $d_2 = 0$ cm, $d_3 = 21$ cm, and $d_4 = 9$ cm (see Figure A.1).

The values for q were generated in this spreadsheet initially by substituting K_{sat} values that had been estimated using the auger hole method. The K_{sat} values for each layer were adjusted iteratively until the q vs. m curve adequately matched the observed q vs. m relationship. Initially, the fit of this curve was poor, especially at m values between 80 and 105 cm. This was rectified by adding an additional soil layer at the 40 to 65 cm depth. The new profile is shown in Figure A.2. The spreadsheet was adjusted, and the curve fit the observed data much more smoothly, as shown in Figure A.3. The resulting estimated values of K_{sat} are located in Chapter 2, Table 3.

Even though both drainage plots were located immediately adjacent to one another, K_{sat} was also estimated for Plot 2 based on water table and flow data recorded in that drainage system. Figure A.4 shows the setup of the Plot 2 drainage system, with a 5-layer soil system. K_{sat} values for Plot 2 were estimated in a similar manner as in Plot 1, except an equivalent depth, D', was calculated to represent the layer that the shallow drains resided (Layer 3) and the layers below the drains (Layer 4 and 5), as one layer. The K_{sat} values for Plot 1 were needed to make this estimate. The calculation was as follows

$K_d D' = K_3 d_3 + K_4 d_4 + K_4 d_4$

$(1.1)D' = (1.1)(35) + (1.6)(35) + 0.1\ (265)$

$D' = 110$ cm.

The soil profile in Plot 2 and was then reduced to a three layer profile, with Layer 1 and Layer 2 unchanged, but and equivalent Layer 3 extended to the impervious layer. The equivalent depth to the impermeable layer (d_e) was then calculated to be 66 cm. Estimates for K_{sat} in Plot 2 were then calculated iteratively as in Plot 1. Values of K_{sat} estimated for Plot 2 are located in Chapter 2, Table 3. The resulting q vs. m curve and observed q vs. m values can be found in Chapter 2, Figure 3.

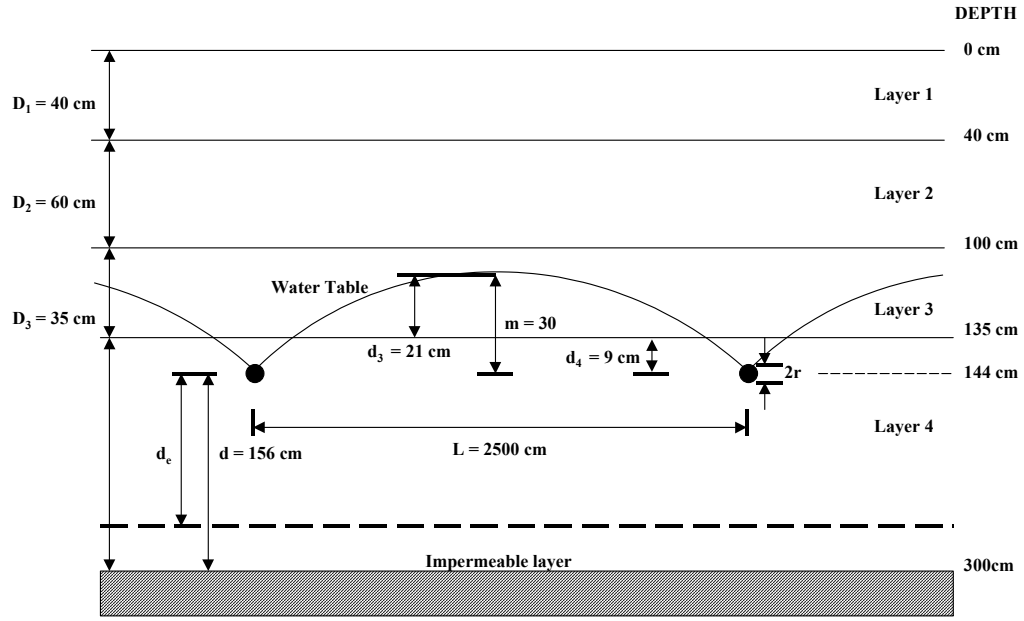


Figure A.1. Plot 1 4- layered soil profile

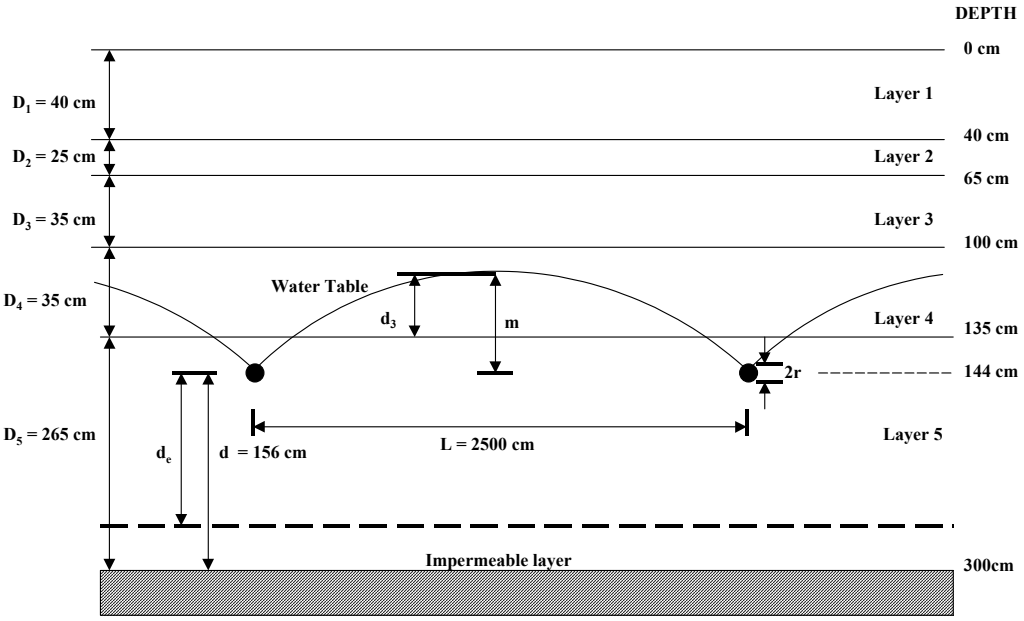


Figure A.2. Plot 1 5- layered soil profile

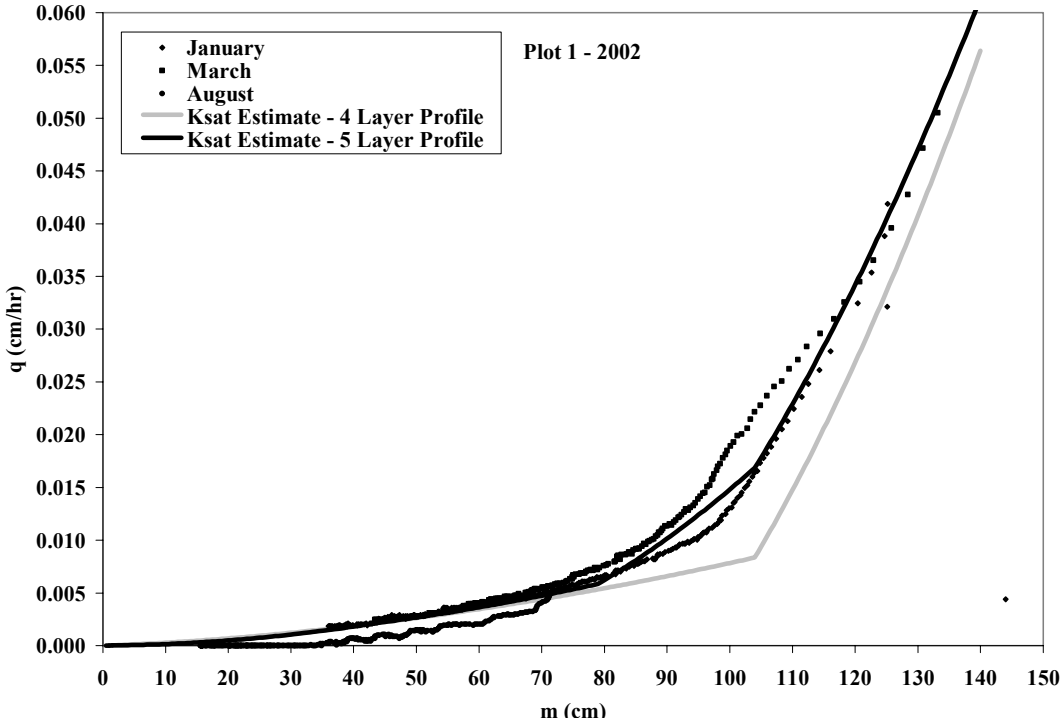


Figure A.3. Comparison of 4-layered and 5-layered soil system in q vs. m relationship generated

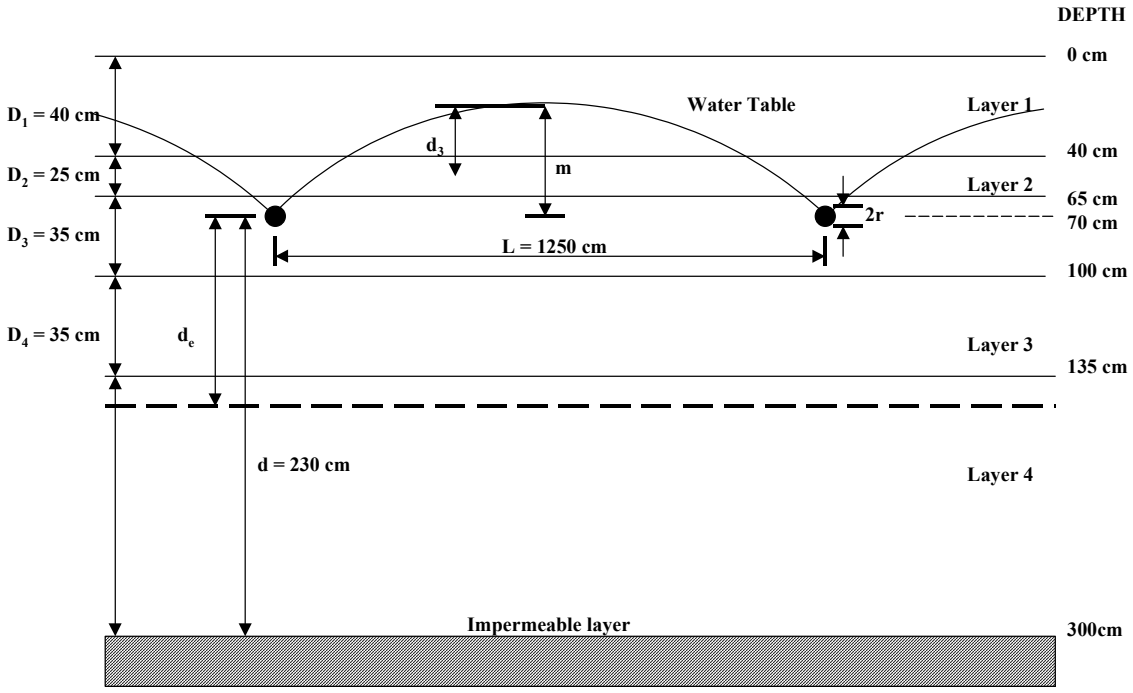


Figure A.4. Plot 2 5 – layered soil profile

APPENDIX 2-B

Effective Rooting Depth Estimates

The rooting depths of the common bermuda/rye grass rotation in place on the drainage plots were challenging to estimate. Maximum rooting depths observed in the field were approximately 80 cm. Assuming effective rooting depths to be 50% of maximum rooting depth, the maximum effective rooting depth used in DRAINMOD simulations was 40 cm. Data for seasonal rooting depths for these two grasses were unavailable, so rooting depths were initially estimated using crop growth stage coefficients. However, this was complicated by the early growth of one grass during the die-back of the other. This was further complicated by heavy grazing in both years of the study in April- June, which also corresponded to the die-back of the winter rye and the emergence of the common bermuda grass. Table B.1 shows the grazing schedule on the research plots by beef cattle in 2001 and 2002.

When the effective rooting depths generated using crop growth stage coefficients were used in calibration of DRAINMOD to the observed data in Plot 1 and 2, simulated water table depths were much lower than observed values. This indicated that rooting depths were too deep, creating an overestimation of ET. Grazing can reduce rooting depths substantially as the vegetation tries to produce more above-ground biomass in the following period. Therefore, the initial estimates of rooting depths were reduced to 5 cm during this period to account for grazing during this period. This increased the agreement between the observed and simulated water table depths substantially during this period. Conversely, the initial rooting depth estimate seemed to underestimate rooting depths during the Fall,

resulting in higher simulated water table depths that were observed. Therefore, rooting depths were increased during DRAINMOD calibration for this period. Figure B.1 shows graphically the comparison of the initial effective rooting depth estimates and the final effective rooting depths used in calibrating DRAINMOD.

Table B.1. Grazing record of beef cattle on Plots 1 and 2

2001 Month	Dates	Type	#days
March	23-27	Cows	5
April	16-17	Heifers	2
May	1	Heifers	1
May	26-28	Heifers	3
July	7-9	Cows	2
Aug	17-20	Cows	4
Sept	21-25	Cows	4
2002 Month	**Dates**	**Type**	**#days**
April	5-8	Cows	4
April	17-18	Cows	2
May	3-4	Heifers	2
May	24	Cows	1
May	31	Cows	1
June	1	Cows	1
July	11-14	Heifers	4
August	19-24	Heifers	6
Sept	6-11	Calves	6

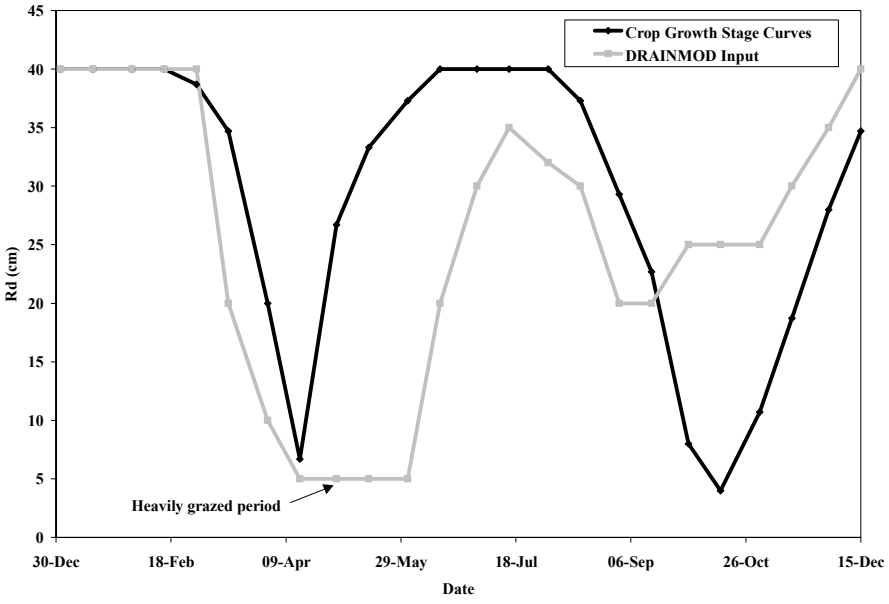


Figure B.1. Effective rooting depth estimated with crop growth stage curves compared to final DRAINMOD inputs

APPENDIX 2-C

DRAINMOD Seepage Diagrams

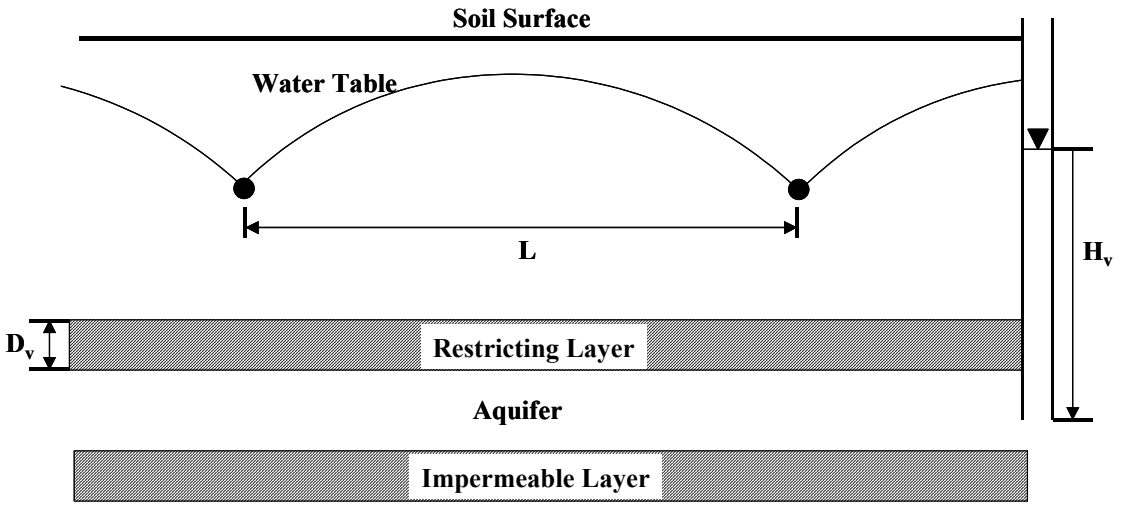


Figure C.1. Schematic of vertical seepage inputs required for DRAINMOD

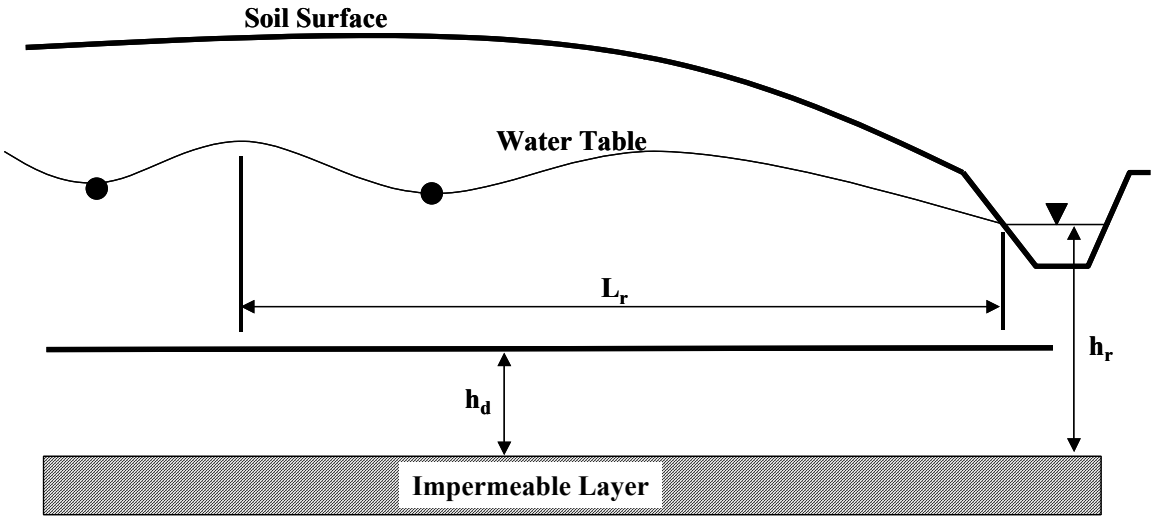


Figure C.2. Schematic of lateral seepage inputs required for DRAINMOD

APPENDIX 2-D

Summary of DRAINMOD Input Parameters for Plot 1 Long-Term Simulation

```
**************************************************************************

                          D R A I N M O D  5.1

              Copyright 1980-99 North Carolina State University
                           LAST UPDATE: SEPT 1999
                             LANGUAGE FORTRAN 77/90

          DRAINMOD IS A FIELD-SCALE HYDROLOGIC MODEL DEVELOPED FOR
          THE DESIGN OF SUBSURFACE DRAINAGE SYSTEMS. THE MODEL WAS
          DEVELOPED BY RESEARCHERS AT THE DEPT. OF BIOLOGICAL AND
          AGRICULTURAL ENGINEERING, NORTH CAROLINA STATE UNIVERSITY
          UNDER THE DIRECTION OF R. W. SKAGGS.

**************************************************************************


 DATA READ FROM INPUT FILE: F:\DRAINMOD\INPUTS\Study\Plot1_LTS.prj
 Cream selector (0=no, 1=yes) =  0

                        TITLE OF RUN
                        ************


 CONVENTIONAL DRAINAGE,  NO YIELD, Cape Fear Loam
 Plymouth, NC, Plot 1, Drains 1.5 m deep, 25 m spacing


                       CLIMATE INPUTS
                       ******* ******

     DESCRIPTION                                (VARIABLE)     VALUE   UNIT
 ------------------------------------------------------------------------------
 FILE FOR RAINDATA ..............F:\DRAINMOD\WEATHER\PLYMOUTH.RAI
 FILE FOR TEMPERATURE/PET DATA ..F:\DRAINMOD\WEATHER\PLYMOUTH.TEM
 RAINFALL STATION NUMBER.........................(RAINID)          1
 TEMPERATURE/PET STATION NUMBER..................(TEMPID)          1
 STARTING YEAR OF SIMULATION.................(START YEAR)       1933   YEAR
 STARTING MONTH OF SIMULATION................(START MONTH)         1   MONTH
 ENDING YEAR OF SIMULATION...................(END YEAR)         1999   YEAR
 ENDING MONTH OF SIMULATION..................(END MONTH)          12   MONTH
 TEMPERATURE STATION LATITUDE................(TEMP LAT)        35.43   DEG.MIN
 HEAT INDEX..........................................(HID)      76.00
```

ET MULTIPLICATION FACTOR FOR EACH MONTH

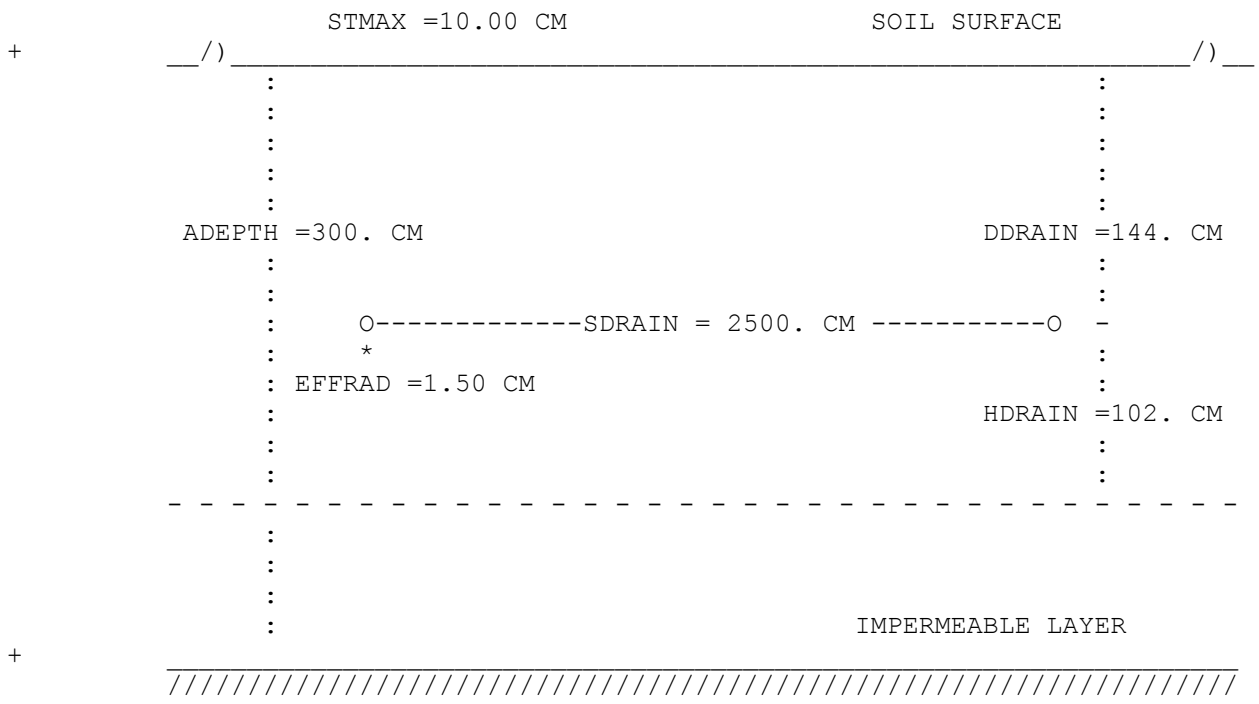
2.01	2.32	2.10	1.72	1.23	1.00	.86	.82	.92	1.05	1.22	1.44

DRAINAGE SYSTEM DESIGN
****

*** CONVENTIONAL DRAINAGE ***

JOB TITLE:

CONVENTIONAL DRAINAGE, NO YIELD, Cape Fear Loam
Plymouth, NC 2001-2002, Plot 1, Drains 1.5 m deep, 25 m spac



DEPTH (CM)	SATURATED HYDRAULIC CONDUCTIVITY (CM/HR)
.0 - 40.0	20.000
40.0 - 65.0	6.000
65.0 - 100.0	1.100
100.0 - 135.0	1.600
135.0 - 300.0	.100

DEPTH TO DRAIN = 144.0 CM
EFFECTIVE DEPTH FROM DRAIN TO IMPERMEABLE LAYER = 102.5 CM
DISTANCE BETWEEN DRAINS = 2500.0 CM

```
MAXIMUM DEPTH OF SURFACE PONDING = 10.00 CM
EFFECTIVE DEPTH TO IMPERMEABLE LAYER =  246.5 CM
DRAINAGE COEFFICIENT(AS LIMITED BY SUBSURFACE OUTLET) =  2.50 CM/DAY
MAXIMUM PUMPING CAPACITY (SUBIRRIGATION MODE) =   2.50 CM/DAY
ACTUAL DEPTH FROM SURFACE TO IMPERMEABLE LAYER = 300.0 CM
SURFACE STORAGE THAT MUST BE FILLED BEFORE WATER
  CAN MOVE TO DRAIN = 1.50 CM
FACTOR -G- IN KIRKHAM EQ. 2-17 =10.94

  *** SEEPAGE LOSS INPUTS ***

   No seepage due to field slope

   Vertical Deep Seepage
      hydraulic head in aquifer (cm)=    0.000000E+00
      thickness of impeading layer (cm)=     1000.000000
      vertical conductivity of impeading layer (cm/hr)=    5.000000E-04

   No seepage due to lateral deep seepage

 *** end of seepage inputs ***

WIDTH OF DITCH BOTTOM = 200.0 CM
SIDE SLOPE OF DITCH (HORIZ:VERT) =   .50 : 1.00

INITIAL WATER TABLE DEPTH = 112.0 CM


    DEPTH OF WEIR FROM THE SURFACE
    ------------------------------
DATE         1/  1   2/  1   3/  1   4/  1   5/  1   6/  1
WEIR DEPTH   144.0   144.0   144.0   144.0   144.0   144.0

DATE         7/  1   8/  1   9/  1   10/  1  11/  1  12/  1
WEIR DEPTH   144.0   144.0   144.0   144.0   144.0   144.0
```

SOIL INPUTS
****

TABLE 1

DRAINAGE TABLE

VOID VOLUME (CM)	WATER TABLE DEPTH (CM)
.0	.0
1.0	35.3
2.0	58.4
3.0	77.7
4.0	98.6
5.0	119.3
6.0	136.9
7.0	151.9
8.0	159.8
9.0	167.6
10.0	175.4
11.0	183.2
12.0	191.0
13.0	198.8
14.0	204.1
15.0	208.9
16.0	213.7
17.0	218.5
18.0	223.3
19.0	228.1
20.0	232.9
21.0	237.7
22.0	242.6
23.0	247.4
24.0	252.2
25.0	257.0
26.0	261.8
27.0	266.6
28.0	271.4
29.0	276.2
30.0	281.0
35.0	305.1
40.0	329.1
45.0	353.1
50.0	377.2
60.0	425.3
70.0	473.3
80.0	591.1
90.0	795.6

TABLE 2

SOIL WATER CHARACTERISTIC VS VOID VOLUME VS UPFLUX

HEAD (CM)	WATER CONTENT (CM/CM)	VOID VOLUME (CM)	UPFLUX (CM/HR)
.0	.4930	.00	.5000
10.0	.4835	.07	.5000
20.0	.4790	.27	.1218
30.0	.4740	.69	.0323
40.0	.4690	1.31	.0101
50.0	.4640	1.73	.0045
60.0	.4590	2.05	.0016
70.0	.4541	2.60	.0011
80.0	.4494	3.11	.0007
90.0	.4446	3.58	.0005
100.0	.4399	4.07	.0004
110.0	.4374	4.55	.0002
120.0	.4364	5.04	.0001
130.0	.4354	5.61	.0001
140.0	.4344	6.18	.0000
150.0	.4334	6.75	.0000
160.0	.4324	8.03	.0000
170.0	.4314	9.31	.0000
180.0	.4304	10.59	.0000
190.0	.4294	11.87	.0000
200.0	.4284	13.15	.0000
210.0	.4279	15.23	.0000
220.0	.4278	17.31	.0000
230.0	.4276	19.39	.0000
240.0	.4274	21.47	.0000
250.0	.4273	23.55	.0000
260.0	.4271	25.63	.0000
270.0	.4270	27.71	.0000
280.0	.4268	29.79	.0000
290.0	.4267	31.87	.0000
300.0	.4265	33.95	.0000
350.0	.4257	44.35	.0000
400.0	.4249	54.75	.0000
450.0	.4242	65.14	.0000
500.0	.4234	75.54	.0000
600.0	.4218	80.44	.0000
700.0	.4203	85.33	.0000
800.0	.4187	90.22	.0000
900.0	.4171	95.11	.0000

GREEN AMPT INFILTRATION PARAMETERS

W.T.D. (CM)	A (CM)	B (CM)
.000	.000	3.000
10.000	.270	3.000
20.000	.420	3.000
40.000	.590	2.500
60.000	.830	2.500
80.000	1.070	2.500
100.000	1.250	2.500
150.000	2.210	2.500
200.000	2.210	2.500
1000.000	2.210	2.500

TRAFFICABILITY

REQUIREMENTS	FIRST PERIOD	SECOND PERIOD
-MINIMUM AIR VOLUME IN SOIL (CM):	3.90	3.90
-MAXIMUM ALLOWABLE DAILY RAINFALL(CM):	1.20	1.20
-MINIMUM TIME AFTER RAIN BEFORE TILLING CAN CONTINUE:	2.00	2.00
WORKING TIMES		
-DATE TO BEGIN COUNTING WORK DAYS:	4/ 1	12/32
-DATE TO STOP COUNTING WORK DAYS:	5/ 1	12/32
-FIRST WORK HOUR OF THE DAY:	8	8
-LAST WORK HOUR OF THE DAY:	20	20

CROP

SOIL MOISTURE AT WILTING POINT = .20

HIGH WATER STRESS: BEGIN STRESS PERIOD ON 4/10
END STRESS PERIOD ON 8/18
CROP IS IN STRESS WHEN WATER TABLE IS ABOVE 40.0 CM

DROUGHT STRESS: BEGIN STRESS PERIOD ON 4/10
END STRESS PERIOD ON 8/18

MO	DAY	ROOTING DEPTH(CM)
1	1	40.0
1	15	40.0
2	1	40.0
2	15	40.0
3	1	40.0
3	15	20.0
4	1	10.0
4	15	5.0
5	1	5.0
5	15	5.0
6	1	5.0
6	15	20.0
7	1	30.0
7	15	35.0
8	1	32.0
8	15	30.0
9	1	20.0
9	15	20.0
10	1	25.0
10	15	25.0
11	1	25.0
11	15	30.0
12	1	35.0
12	15	40.0

Fixed Monthly Pet Values

1 1.00 2 1.00 3 1.00 4 1.00 5 1.00 6 1.00 7 1.00 8 1.00
9 1.00 10 1.00 11 1.00 12 1.00

Mrank indicator = 0

********** END OF INPUTS **********

----------RUN STATISTICS ----------
time: 1/17/2003 @ 11:47
input file: F:\DRAINMOD\INPUTS\Study\Plot1_LTS.prj
parameters: free drainage and yields not calculated
drain spacing = 2500. cm drain depth = 144.0 cm

FOR 8/1948, NUMBER DAYS MISSING TEMPERATURE= 1
*** ERROR IN TEMPERATURE FILE ***
MONTH 2, YEAR 1950 NOT FOUND
PET VALUE = 5.000000E-02 SUBSTITUTED (WILSON, NC)
FOR 2/1951, NUMBER DAYS MISSING TEMPERATURE= 8
FOR 4/1954, NUMBER DAYS MISSING TEMPERATURE= 1
TERMINATE SIMULATION DUE TO END OF LOOP
> Computational Statistics <
**> Start Computations = 707.347
**> End Computations = 707.758
**> Total simulation time = 24.7 seconds.

APPENDIX 2-E

Summary of DRAINMOD Input Parameters for Plot 2 Long-Term Simulation

```
**************************************************************************

                          D R A I N M O D  5.1

              Copyright 1980-99 North Carolina State University
                          LAST UPDATE: SEPT 1999
                            LANGUAGE FORTRAN 77/90

          DRAINMOD IS A FIELD-SCALE HYDROLOGIC MODEL DEVELOPED FOR
          THE DESIGN OF SUBSURFACE DRAINAGE SYSTEMS. THE MODEL WAS
          DEVELOPED BY RESEARCHERS AT THE DEPT. OF BIOLOGICAL AND
          AGRICULTURAL ENGINEERING, NORTH CAROLINA STATE UNIVERSITY
          UNDER THE DIRECTION OF R. W. SKAGGS.

**************************************************************************


 DATA READ FROM INPUT FILE: F:\DRAINMOD\INPUTS\Study\plot2LTS.prj
 Cream selector (0=no, 1=yes) =  0

                         TITLE OF RUN
                         ************


 CONVENTIONAL DRAINAGE,  NO YIELD, Cape Fear Loam
 Plymouth, NC 2001-2002, Plot 2, Drains 0.75 m deep, 12.5 m spacing



                        CLIMATE INPUTS
                        ******* ******

     DESCRIPTION                                (VARIABLE)     VALUE   UNIT
 ------------------------------------------------------------------------------
 FILE FOR RAINDATA ..............F:\DRAINMOD\WEATHER\PLYMOUTH.RAI
 FILE FOR TEMPERATURE/PET DATA ..F:\DRAINMOD\WEATHER\PLYMOUTH.TEM
 RAINFALL STATION NUMBER.........................(RAINID)          1
 TEMPERATURE/PET STATION NUMBER..................(TEMPID)          1
 STARTING YEAR OF SIMULATION.................(START YEAR)       1933   YEAR
 STARTING MONTH OF SIMULATION................(START MONTH)         1   MONTH
 ENDING YEAR OF SIMULATION...................(END YEAR)         1994   YEAR
 ENDING MONTH OF SIMULATION..................(END MONTH)          12   MONTH
 TEMPERATURE STATION LATITUDE................(TEMP LAT)        35.43   DEG.MIN
 HEAT INDEX..................................(HID)            76.00
```

ET MULTIPLICATION FACTOR FOR EACH MONTH

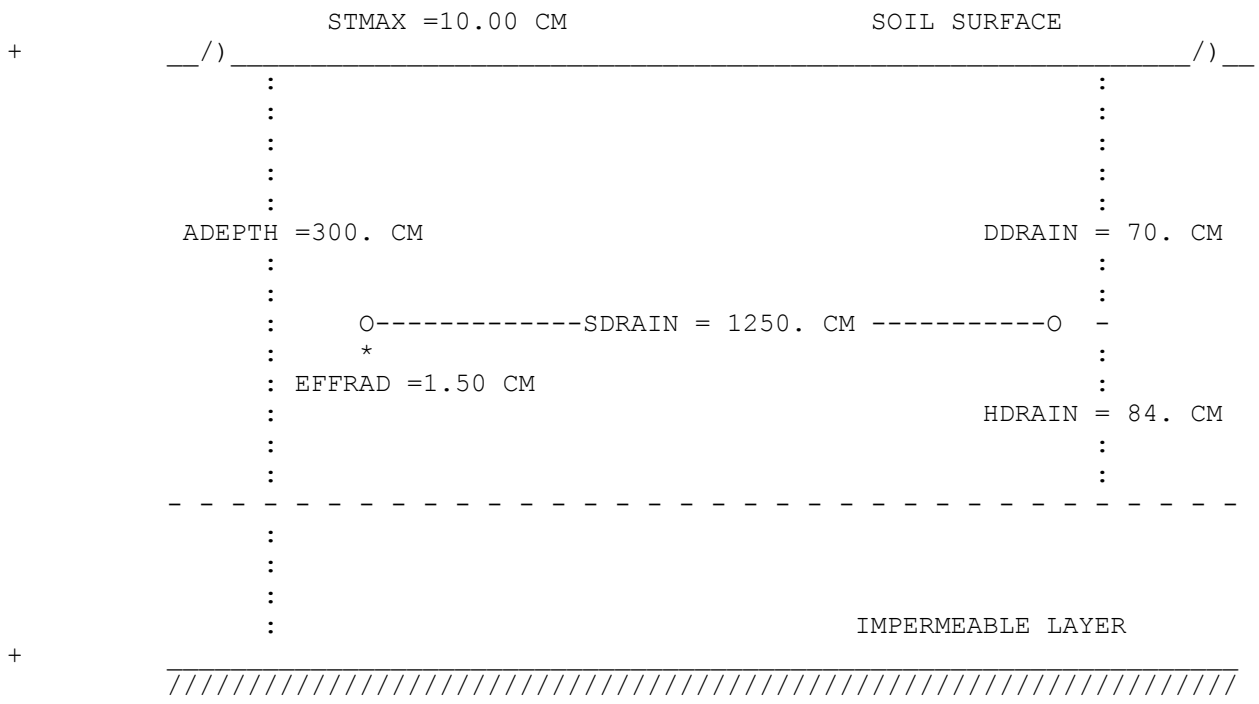
2.01	2.32	2.10	1.72	1.23	1.00	.86	.82	.92	1.05	1.22	1.44

DRAINAGE SYSTEM DESIGN
****

*** CONVENTIONAL DRAINAGE ***

JOB TITLE:

CONVENTIONAL DRAINAGE, NO YIELD, Cape Fear Loam
Plymouth, NC 2001-2002, Plot 2, Drains 0.75 m deep, 12.5 m s



DEPTH (CM)	SATURATED HYDRAULIC CONDUCTIVITY (CM/HR)
.0 - 40.0	20.000
40.0 - 65.0	6.000
65.0 - 100.0	1.100
100.0 - 135.0	1.600
135.0 - 300.0	.100

DEPTH TO DRAIN = 70.0 CM
EFFECTIVE DEPTH FROM DRAIN TO IMPERMEABLE LAYER = 83.7 CM
DISTANCE BETWEEN DRAINS = 1250.0 CM

```
MAXIMUM DEPTH OF SURFACE PONDING = 10.00 CM
EFFECTIVE DEPTH TO IMPERMEABLE LAYER =  153.7 CM
DRAINAGE COEFFICIENT(AS LIMITED BY SUBSURFACE OUTLET) =  2.50 CM/DAY
MAXIMUM PUMPING CAPACITY (SUBIRRIGATION MODE) =   2.50 CM/DAY
ACTUAL DEPTH FROM SURFACE TO IMPERMEABLE LAYER = 300.0 CM
SURFACE STORAGE THAT MUST BE FILLED BEFORE WATER
  CAN MOVE TO DRAIN = 1.50 CM
FACTOR -G- IN KIRKHAM EQ. 2-17 = 9.14

  *** SEEPAGE LOSS INPUTS ***

   No seepage due to field slope

   No seepage due to vertical deep seepage

   Lateral Deep Seepage
       thickness of convenance layer (cm)=    0.000000E+00
       hydraulic head at offsite sink/source (cm)=       83.000000
       distance to offsite sink/source (cm)=     3500.000000
       lateral conductivity of conveyance layer (cm/hr)=        1.100000

 *** end of seepage inputs ***

WIDTH OF DITCH BOTTOM = 200.0 CM
SIDE SLOPE OF DITCH (HORIZ:VERT) =   .50 : 1.00

INITIAL WATER TABLE DEPTH =  75.0 CM


    DEPTH OF WEIR FROM THE SURFACE
    ------------------------------
DATE         1/  1   2/  1   3/  1   4/  1   5/  1   6/  1
WEIR DEPTH    70.0    70.0    70.0    70.0    70.0    70.0

DATE         7/  1   8/  1   9/  1   10/  1  11/  1  12/  1
WEIR DEPTH    70.0    70.0    70.0    70.0    70.0    70.0
```

SOIL INPUTS
****

TABLE 1

DRAINAGE TABLE

VOID VOLUME (CM)	WATER TABLE DEPTH (CM)
.0	.0
1.0	35.3
2.0	58.4
3.0	77.7
4.0	98.6
5.0	119.3
6.0	136.9
7.0	151.9
8.0	159.8
9.0	167.6
10.0	175.4
11.0	183.2
12.0	191.0
13.0	198.8
14.0	204.1
15.0	208.9
16.0	213.7
17.0	218.5
18.0	223.3
19.0	228.1
20.0	232.9
21.0	237.7
22.0	242.6
23.0	247.4
24.0	252.2
25.0	257.0
26.0	261.8
27.0	266.6
28.0	271.4
29.0	276.2
30.0	281.0
35.0	305.1
40.0	329.1
45.0	353.1
50.0	377.2
60.0	425.3
70.0	473.3
80.0	591.1
90.0	795.6

TABLE 2

SOIL WATER CHARACTERISTIC VS VOID VOLUME VS UPFLUX

HEAD (CM)	WATER CONTENT (CM/CM)	VOID VOLUME (CM)	UPFLUX (CM/HR)
.0	.4930	.00	.5000
10.0	.4835	.07	.5000
20.0	.4790	.27	.1218
30.0	.4740	.69	.0323
40.0	.4690	1.31	.0101
50.0	.4640	1.73	.0045
60.0	.4590	2.05	.0016
70.0	.4541	2.60	.0011
80.0	.4494	3.11	.0007
90.0	.4446	3.58	.0005
100.0	.4399	4.07	.0004
110.0	.4374	4.55	.0002
120.0	.4364	5.04	.0001
130.0	.4354	5.61	.0001
140.0	.4344	6.18	.0000
150.0	.4334	6.75	.0000
160.0	.4324	8.03	.0000
170.0	.4314	9.31	.0000
180.0	.4304	10.59	.0000
190.0	.4294	11.87	.0000
200.0	.4284	13.15	.0000
210.0	.4279	15.23	.0000
220.0	.4278	17.31	.0000
230.0	.4276	19.39	.0000
240.0	.4274	21.47	.0000
250.0	.4273	23.55	.0000
260.0	.4271	25.63	.0000
270.0	.4270	27.71	.0000
280.0	.4268	29.79	.0000
290.0	.4267	31.87	.0000
300.0	.4265	33.95	.0000
350.0	.4257	44.35	.0000
400.0	.4249	54.75	.0000
450.0	.4242	65.14	.0000
500.0	.4234	75.54	.0000
600.0	.4218	80.44	.0000
700.0	.4203	85.33	.0000
800.0	.4187	90.22	.0000
900.0	.4171	95.11	.0000

GREEN AMPT INFILTRATION PARAMETER

W.T.D. (CM)	A (CM)	B (CM)
.000	.000	3.000
10.000	.270	3.000
20.000	.420	3.000
40.000	.590	2.500
60.000	.830	2.500
80.000	1.070	2.500
100.000	1.250	2.500
150.000	2.210	2.500
200.000	2.210	2.500
1000.000	2.210	2.500

TRAFFICABILITY

REQUIREMENTS	FIRST PERIOD	SECOND PERIOD
-MINIMUM AIR VOLUME IN SOIL (CM):	3.90	3.90
-MAXIMUM ALLOWABLE DAILY RAINFALL(CM):	1.20	1.20
-MINIMUM TIME AFTER RAIN BEFORE TILLING CAN CONTINUE:	2.00	2.00
WORKING TIMES		
-DATE TO BEGIN COUNTING WORK DAYS:	4/ 1	12/32
-DATE TO STOP COUNTING WORK DAYS:	5/ 1	12/32
-FIRST WORK HOUR OF THE DAY:	8	8
-LAST WORK HOUR OF THE DAY:	20	20

CROP

SOIL MOISTURE AT WILTING POINT = .20

HIGH WATER STRESS: BEGIN STRESS PERIOD ON 4/10
END STRESS PERIOD ON 8/18
CROP IS IN STRESS WHEN WATER TABLE IS ABOVE 40.0 CM

DROUGHT STRESS: BEGIN STRESS PERIOD ON 4/10
END STRESS PERIOD ON 8/18

MO	DAY	ROOTING DEPTH(CM)
1	1	40.0
1	15	40.0
2	1	40.0
2	15	40.0
3	1	40.0
3	15	20.0
4	1	10.0
4	15	5.0
5	1	5.0
5	15	5.0
6	1	5.0
6	15	20.0
7	1	30.0
7	15	35.0
8	1	32.0
8	15	30.0
9	1	20.0
9	15	20.0
10	1	25.0
10	15	30.0
11	1	35.0
11	15	40.0
12	1	40.0
12	15	40.0

```
Fixed Monthly Pet Values

1 1.00    2 1.00    3 1.00    4 1.00    5 1.00    6 1.00    7 1.00    8 1.00
9 1.00   10 1.00   11 1.00   12 1.00

Mrank indicator =  0

 ****************************** END OF INPUTS ******************************

  ----------RUN STATISTICS ----------          time:  1/17/2003  @ 11:59
 input file:   F:\DRAINMOD\INPUTS\Study\plot2LTS.prj
 parameters:    free drainage              and yields not calculated
               drain spacing =    1250. cm   drain depth =   70.0 cm
--------------------------------------------------------------------------

 FOR  8/1948, NUMBER DAYS MISSING TEMPERATURE=     1
*** ERROR IN TEMPERATURE FILE ***
  MONTH           2, YEAR        1950 NOT FOUND
  PET VALUE =   5.000000E-02 SUBSTITUTED (WILSON, NC)
 FOR  2/1951, NUMBER DAYS MISSING TEMPERATURE=     8
FOR  4/1954, NUMBER DAYS MISSING TEMPERATURE=     1
TERMINATE SIMULATION DUE TO END OF LOOP
**> Computational Statistics       <**
**> Start Computations    = 719.336
**> End Computations      = 719.787
**> Total simulation time =    27.1 seconds.
```

APPENDIX 2-F

Results of DRAINMOD Simulations for Plot 1 and Plot 2

Table F.1. Yearly output generated in DRAINMOD simulations for Plot 1

YEAR	RAINFALL (cm)	INFILTRATION (cm)	ET (cm)	DRAINAGE (cm)	RUNOFF (cm)	SEW (cm)	TWLOSS (cm)	PUMPV (cm)	SLOPSP (cm)	VERTSP (cm)	LATSP (cm)	DRN+SP (cm)
1933	123.55	123.55	87.95	40.14	0.00	7.37	40.16	0.00	0.00	5.20	0.00	45.33
1934	128.37	128.37	85.74	30.42	0.00	6.92	30.47	0.00	0.00	5.15	0.00	35.57
1935	106.43	106.43	76.70	21.73	0.00	0.00	21.76	0.00	0.00	5.16	0.00	26.89
1936	139.65	139.65	68.84	65.13	0.00	4.09	65.14	0.00	0.00	5.27	0.00	70.39
1937	125.43	125.43	79.99	39.65	0.00	16.69	39.70	0.00	0.00	5.21	0.00	44.87
1938	150.70	144.67	85.36	52.97	6.03	44.64	59.02	0.00	0.00	5.23	0.00	58.20
1939	124.41	124.41	79.54	39.61	0.00	8.64	39.65	0.00	0.00	5.20	0.00	44.81
1940	107.37	107.37	69.98	34.69	0.00	68.01	34.72	0.00	0.00	5.20	0.00	39.89
1941	91.54	91.54	58.70	28.57	0.00	4.03	28.60	0.00	0.00	5.15	0.00	33.72
1942	112.09	112.09	72.40	32.25	0.00	4.25	32.27	0.00	0.00	5.17	0.00	37.42
1943	99.01	99.01	64.70	27.73	0.00	63.26	27.74	0.00	0.00	5.15	0.00	32.88
1944	128.50	128.50	69.35	53.95	0.00	0.00	53.98	0.00	0.00	5.23	0.00	59.18
1945	144.04	144.04	77.78	59.64	0.00	213.99	59.67	0.00	0.00	5.22	0.00	64.86
1946	143.87	143.87	91.62	52.56	0.00	146.88	52.56	0.00	0.00	5.24	0.00	57.79
1947	146.15	146.15	80.13	57.23	0.00	60.37	57.25	0.00	0.00	5.23	0.00	62.46
1948	159.28	159.28	78.67	73.26	0.00	101.96	73.29	0.00	0.00	5.25	0.00	78.50
1949	156.57	156.57	91.44	62.71	0.00	290.02	62.71	0.00	0.00	5.25	0.00	67.96
1950	137.31	137.31	77.96	54.91	0.00	448.95	54.94	0.00	0.00	5.17	0.00	60.08
1951	101.60	101.60	81.84	14.88	0.00	8.62	14.91	0.00	0.00	5.16	0.00	20.04
1952	151.74	151.74	83.66	58.78	0.00	97.62	58.81	0.00	0.00	5.25	0.00	64.03
1953	134.32	134.32	87.03	43.50	0.00	148.47	43.52	0.00	0.00	5.21	0.00	48.71
1954	104.42	104.42	76.43	25.93	0.00	0.46	25.97	0.00	0.00	5.17	0.00	31.10
1955	141.58	141.58	81.21	56.17	0.00	189.17	56.21	0.00	0.00	5.21	0.00	61.38
1956	125.83	125.83	83.00	39.29	0.00	17.43	39.32	0.00	0.00	5.25	0.00	44.54
1957	117.60	117.60	66.63	40.85	0.00	0.00	40.86	0.00	0.00	5.16	0.00	46.00
1958	132.66	132.66	76.54	50.16	0.00	3.48	50.18	0.00	0.00	5.22	0.00	55.38
1959	118.90	118.90	80.81	34.30	0.00	71.19	34.33	0.00	0.00	5.19	0.00	39.49
1960	150.57	150.57	75.81	69.88	0.00	1.36	69.89	0.00	0.00	5.25	0.00	75.13
1961	148.87	148.87	86.55	56.82	0.00	164.34	56.84	0.00	0.00	5.25	0.00	62.07
1962	144.73	144.73	73.51	65.12	0.00	320.02	65.14	0.00	0.00	5.24	0.00	70.36
1963	123.22	123.22	68.43	50.12	0.00	107.58	50.15	0.00	0.00	5.20	0.00	55.32
1964	147.95	147.95	73.67	68.20	0.00	0.00	68.20	0.00	0.00	5.23	0.00	73.43
1965	113.44	113.44	72.42	46.88	0.00	290.51	46.91	0.00	0.00	5.18	0.00	52.07
1966	132.77	132.77	71.60	46.68	0.00	140.67	46.70	0.00	0.00	5.19	0.00	51.87
1967	126.97	126.97	70.76	49.09	0.00	116.50	49.11	0.00	0.00	5.19	0.00	54.28
1968	107.16	107.16	73.74	29.06	0.00	13.63	29.07	0.00	0.00	5.16	0.00	34.22
1969	123.67	123.67	77.62	40.80	0.00	0.00	40.83	0.00	0.00	5.21	0.00	46.01
1970	90.73	90.73	73.92	15.97	0.00	0.00	16.01	0.00	0.00	5.11	0.00	21.08
1971	159.72	159.72	83.46	71.01	0.00	1.76	71.02	0.00	0.00	5.24	0.00	76.25
1972	133.88	133.88	84.08	39.07	0.00	7.76	39.09	0.00	0.00	5.23	0.00	44.29
1973	134.95	134.95	85.95	44.02	0.00	11.06	44.04	0.00	0.00	5.21	0.00	49.23
1974	130.58	130.58	92.30	35.29	0.00	43.95	35.32	0.00	0.00	5.21	0.00	40.50
1975	130.53	130.53	76.50	45.31	0.00	112.46	45.32	0.00	0.00	5.22	0.00	50.53
1976	117.60	117.60	78.84	35.51	0.00	85.14	35.55	0.00	0.00	5.21	0.00	40.71
1977	152.86	152.86	80.29	65.96	0.00	135.51	65.98	0.00	0.00	5.24	0.00	71.20
1978	137.29	137.29	73.08	62.39	0.00	230.61	62.41	0.00	0.00	5.21	0.00	67.60
1979	156.64	156.64	81.13	69.73	0.00	155.72	69.74	0.00	0.00	5.26	0.00	74.98
1980	110.74	110.74	69.28	35.92	0.00	2.81	35.94	0.00	0.00	5.16	0.00	41.09
1981	103.07	103.07	72.60	27.25	0.00	40.11	27.28	0.00	0.00	5.15	0.00	32.40
1982	127.74	127.74	74.89	44.27	0.00	0.00	44.30	0.00	0.00	5.22	0.00	49.49
1983	154.64	154.64	77.01	73.21	0.00	96.54	73.23	0.00	0.00	5.26	0.00	78.47
1984	137.36	137.36	81.92	59.56	0.00	201.79	59.58	0.00	0.00	5.24	0.00	64.80
1985	114.17	114.17	69.80	32.04	0.00	0.00	32.06	0.00	0.00	5.13	0.00	37.18
1986	102.03	102.03	79.41	15.55	0.00	0.00	15.57	0.00	0.00	5.14	0.00	20.70
1987	132.97	132.97	78.80	48.14	0.00	25.37	48.17	0.00	0.00	5.22	0.00	53.37
1988	103.05	103.05	83.22	18.26	0.00	21.52	18.28	0.00	0.00	5.13	0.00	23.39
1989	175.97	175.97	94.20	73.19	0.00	124.01	73.19	0.00	0.00	5.27	0.00	78.46
1990	126.95	126.95	100.62	25.09	0.00	102.80	25.15	0.00	0.00	5.17	0.00	30.25
1991	134.95	134.95	82.21	44.92	0.00	59.86	44.94	0.00	0.00	5.22	0.00	50.13
1992	111.73	111.73	67.59	37.28	0.00	108.76	37.30	0.00	0.00	5.23	0.00	42.51
1993	95.15	95.15	54.34	36.74	0.00	0.05	36.76	0.00	0.00	5.16	0.00	41.90
1994	134.95	134.95	82.21	48.06	0.00	59.86	48.09	0.00	0.00	5.22	0.00	53.28
1995	136.80	136.80	79.61	47.86	0.00	118.87	47.91	0.00	0.00	5.20	0.00	53.06
1996	157.63	157.63	77.42	75.32	0.00	155.25	75.32	0.00	0.00	5.29	0.00	80.60
1997	104.55	104.55	83.50	13.74	0.00	0.00	13.75	0.00	0.00	5.12	0.00	18.86
1998	124.13	124.13	86.66	33.17	0.00	0.00	33.19	0.00	0.00	5.12	0.00	38.29
1999	132.64	126.97	73.13	50.48	5.66	0.00	56.15	0.00	0.00	5.17	0.00	55.65
Avg	**128.93**	**128.75**	**78.15**	**45.34**	**0.17**	**75.86**	**45.54**	**0.00**	**0.00**	**5.20**	**0.00**	**50.54**

Table F.2. Yearly output generated in DRAINMOD simulations for Plot 2

YEAR	RAINFALL (cm)	INFILTRATION (cm)	ET (cm)	DRAINAGE (cm)	RUNOFF (cm)	SEW (cm)	TWLOSS (cm)	PUMPV (cm)	SLOPSP (cm)	VERTSP (cm)	LATSP (cm)	DRN+SP (cm)
1933	123.55	123.55	88.87	30.58	0.00	24.98	30.58	0.00	0.00	0.00	15.01	45.59
1934	128.37	128.37	86.92	22.76	0.00	10.66	22.76	0.00	0.00	0.00	12.45	35.20
1935	106.43	106.43	78.73	12.66	0.00	1.74	12.66	0.00	0.00	0.00	12.83	25.48
1936	139.65	139.65	69.51	50.90	0.00	6.28	50.90	0.00	0.00	0.00	17.19	68.09
1937	125.43	125.43	80.47	28.50	0.00	37.81	28.50	0.00	0.00	0.00	15.59	44.09
1938	150.70	144.60	85.87	41.53	6.10	80.29	47.63	0.00	0.00	0.00	16.79	58.32
1939	124.41	124.41	80.41	29.23	0.00	20.29	29.23	0.00	0.00	0.00	14.74	43.97
1940	107.37	107.37	70.99	24.51	0.00	80.31	24.51	0.00	0.00	0.00	14.15	38.66
1941	91.54	91.54	61.71	21.04	0.00	8.80	21.04	0.00	0.00	0.00	12.26	33.30
1942	112.09	112.09	73.05	20.93	0.00	13.94	20.93	0.00	0.00	0.00	12.84	33.77
1943	99.01	99.01	67.60	19.20	0.00	98.29	19.20	0.00	0.00	0.00	11.90	31.10
1944	128.50	128.50	70.07	42.35	0.00	0.00	42.35	0.00	0.00	0.00	15.48	57.83
1945	144.04	144.04	78.03	49.43	0.00	241.82	49.43	0.00	0.00	0.00	15.61	65.04
1946	143.87	143.87	92.08	39.43	0.00	192.29	39.43	0.00	0.00	0.00	16.77	56.20
1947	146.15	146.15	80.69	46.71	0.00	68.86	46.71	0.00	0.00	0.00	16.09	62.81
1948	159.28	159.28	79.23	62.70	0.00	113.69	62.70	0.00	0.00	0.00	15.70	78.41
1949	156.57	156.57	92.21	48.67	0.00	347.62	48.67	0.00	0.00	0.00	17.30	65.97
1950	137.31	137.31	79.10	46.25	0.00	494.64	46.25	0.00	0.00	0.00	13.22	59.47
1951	101.60	101.60	82.91	5.63	0.00	23.64	5.63	0.00	0.00	0.00	13.22	18.85
1952	151.74	151.38	83.97	47.09	0.00	137.71	47.09	0.00	0.00	0.00	16.63	63.72
1953	134.32	134.68	88.17	32.53	0.00	153.26	32.53	0.00	0.00	0.00	15.57	48.11
1954	104.42	104.42	77.13	16.33	0.00	7.14	16.33	0.00	0.00	0.00	13.15	29.48
1955	141.58	141.58	81.81	46.03	0.00	224.69	46.03	0.00	0.00	0.00	15.37	61.39
1956	125.83	125.83	83.71	26.96	0.00	45.87	26.96	0.00	0.00	0.00	16.37	43.33
1957	117.60	117.60	67.04	32.43	0.00	0.00	32.43	0.00	0.00	0.00	13.46	45.89
1958	132.66	132.66	77.61	38.80	0.00	14.43	38.80	0.00	0.00	0.00	15.93	54.73
1959	118.90	118.90	82.44	23.18	0.00	106.60	23.18	0.00	0.00	0.00	14.16	37.34
1960	150.57	149.93	76.41	56.49	0.65	13.28	57.13	0.00	0.00	0.00	16.83	73.32
1961	148.87	148.87	87.12	45.01	0.00	225.16	45.01	0.00	0.00	0.00	16.98	62.00
1962	144.73	144.73	74.10	53.59	0.00	342.50	53.59	0.00	0.00	0.00	16.65	70.23
1963	123.22	123.22	69.04	40.41	0.00	127.49	40.41	0.00	0.00	0.00	14.05	54.47
1964	147.95	147.95	74.25	57.61	0.00	0.00	57.61	0.00	0.00	0.00	15.60	73.21
1965	113.44	113.44	72.96	37.83	0.00	346.62	37.83	0.00	0.00	0.00	13.73	51.56
1966	132.77	132.77	72.29	36.46	0.00	155.82	36.46	0.00	0.00	0.00	14.19	50.65
1967	126.97	126.97	71.34	40.28	0.00	134.35	40.28	0.00	0.00	0.00	13.91	54.19
1968	107.16	107.16	75.87	20.26	0.00	31.57	20.26	0.00	0.00	0.00	12.18	32.44
1969	123.67	123.67	78.39	29.80	0.00	8.32	29.80	0.00	0.00	0.00	15.07	44.87
1970	90.73	90.73	75.68	9.21	0.00	0.00	9.21	0.00	0.00	0.00	11.03	20.23
1971	159.72	159.72	84.12	57.05	0.00	12.46	57.05	0.00	0.00	0.00	16.66	73.71
1972	133.88	133.88	84.30	29.14	0.00	21.43	29.14	0.00	0.00	0.00	15.43	44.58
1973	134.95	134.95	87.50	32.96	0.00	34.32	32.96	0.00	0.00	0.00	14.96	47.92
1974	130.58	130.58	92.78	24.68	0.00	84.76	24.68	0.00	0.00	0.00	14.99	39.66
1975	130.53	130.53	77.19	34.88	0.00	141.76	34.88	0.00	0.00	0.00	15.78	50.66
1976	117.60	117.60	79.77	25.59	0.00	113.84	25.59	0.00	0.00	0.00	13.81	39.40
1977	152.86	152.86	81.65	53.30	0.00	160.23	53.30	0.00	0.00	0.00	16.87	70.16
1978	137.29	137.29	73.96	51.59	0.00	285.92	51.59	0.00	0.00	0.00	14.95	66.54
1979	156.64	156.64	82.15	55.69	0.00	213.17	55.69	0.00	0.00	0.00	17.42	73.12
1980	110.74	110.74	69.92	27.71	0.00	16.63	27.71	0.00	0.00	0.00	12.70	40.41
1981	103.07	103.07	74.87	19.54	0.00	52.60	19.54	0.00	0.00	0.00	12.69	32.22
1982	127.74	127.74	76.04	30.90	0.00	2.09	30.90	0.00	0.00	0.00	15.66	46.57
1983	154.64	154.64	77.59	61.05	0.00	129.66	61.05	0.00	0.00	0.00	16.96	78.01
1984	137.36	137.36	83.05	48.56	0.00	251.88	48.56	0.00	0.00	0.00	15.60	64.16
1985	114.17	114.17	70.18	24.24	0.00	0.00	24.24	0.00	0.00	0.00	11.43	35.67
1986	102.03	102.03	83.49	7.83	0.00	0.00	7.83	0.00	0.00	0.00	11.92	19.75
1987	132.97	132.97	79.77	34.42	0.00	56.75	34.42	0.00	0.00	0.00	15.77	50.19
1988	103.05	103.05	83.85	11.34	0.00	45.96	11.34	0.00	0.00	0.00	11.40	22.73
1989	175.97	175.97	94.90	59.75	0.00	181.21	59.75	0.00	0.00	0.00	17.81	77.56
1990	126.95	126.95	103.81	16.25	0.00	125.26	16.25	0.00	0.00	0.00	12.43	28.68
1991	134.95	134.95	83.12	31.96	0.00	86.22	31.96	0.00	0.00	0.00	15.28	47.24
1992	111.73	111.73	67.84	26.81	0.00	136.53	26.81	0.00	0.00	0.00	16.11	42.92
1993	95.15	95.15	55.58	28.45	0.00	2.45	28.45	0.00	0.00	0.00	12.27	40.72
1994	134.95	134.95	83.12	36.03	0.00	86.22	36.03	0.00	0.00	0.00	15.62	51.64
1995	136.80	136.80	80.19	41.41	0.00	151.59	41.41	0.00	0.00	0.00	15.03	56.44
1996	157.63	157.63	77.80	61.91	0.00	188.97	61.91	0.00	0.00	0.00	18.21	80.13
1997	104.55	104.55	84.39	7.29	0.00	0.00	7.29	0.00	0.00	0.00	11.64	18.93
1998	124.13	124.13	87.68	25.61	0.00	3.34	25.61	0.00	0.00	0.00	11.38	36.99
1999	132.64	126.77	73.63	39.59	5.86	0.00	45.46	0.00	0.00	0.00	14.31	53.91
Avg	**128.93**	**128.74**	**79.13**	**34.91**	**0.19**	**97.40**	**35.10**	**0.00**	**0.00**	**0.00**	**14.70**	**49.61**

APPENDIX 3

APPENDIX 3-A

Evapotranspiration in Wetland Mesocosms

Evapotranspiration rates during the summer months were very high in the wetland mesocosms. Evapotranspiration in wetlands may be estimated by multiplying pan evaportation by 0.7-0.8, with wetland ET rates being similar to lake ET rates (see Kadlec and Knight, 1996 and Reed et al., 1995 referenced in Chapter 3). Based on this rule of thumb, maximum ET in wetlands located in Plymouth, N.C. would be about 0.5 – 0.7 cm/day during the summer. Wetland mesocosm ET rates measured in Batch 3 (conducted in August 2001) ranged from 1.4 – 2.0 cm/day. The small size of the wetlands mesocosms clearly had some effect on increasing ET rates. However, there is very little information available on how wetland size affects ET rates. From and energy balance standpoint, advection terms in the equation would be expected to play a larger role in ET rates in smaller wetlands, and conventional methods would tend to underestimate ET rates from these systems (see Kadlec and Knight, 1996, referenced in Chapter 3).

Table A.1 shows the average ET rates from the wetland mesocosms measured in Batches 3 and 4. Wetland mesocosm ET rates measured in Batch 4 (conducted in September/October 2001) ranged from 1.2 – 1.4 cm/day, and averaged 0.3 cm/day in the control. As mentioned in Chapter 3, reduced ET rates observed in the Fall may have reduced the amount of NO_3^--N translocated into the wetland substrate, reducing removal efficiency during that season.

Table A.1. Average wetland mesocosm ET rates measured in Batches 3 and 4

Treatment	Batch 3 L	Batch 3 cm/day	Batch 4 L	Batch 4 cm/day
Control			60.6	0.3
SS	317.9	1.4	295.2	1.3
SSB11%	370.9	1.7	287.7	1.3
SSB16%	340.7	1.5	268.7	1.2
DM	454.2	2.0	280.1	1.3
DMB18%	367.1	1.6	317.9	1.4
DMB22%	378.5	1.7	314.2	1.4
Average (Wetlands Only)	**371.6**	**1.7**	**294.0**	**1.3**

Batch 3 - August 15-29, 2001
Batch 4 - September 18 - October 3, 2001

APPENDIX 3-B

Nitrogen Content in Above-Ground *Scirpus validus* Harvested from the Wetland Mesocosms

Table B.1. Nitrogen content of above-ground *Scirpus validus* in 2000

2000 Treatment	Replicate	Biomass (g/m2)	N (%)	Mass N (g/m2)
SS	**A**	812.5	0.8	6.4
	B	918.5	0.7	6.1
	C	941.5	0.8	7.9
	AVG	**890.8**	**0.8**	**6.8**
	STDDEV	68.8	0.1	1.0
SSB11%	**A**	1332.5	1.7	22.1
	B	1279.0	1.2	15.8
	C	1234.5	1.6	20.1
	AVG	**1282.0**	**1.5**	**19.4**
	STDDEV	49.1	0.2	3.2
SSB16%	**A**	1374.5	1.3	17.7
	B	945.5	1.5	14.3
	C	1156.0	1.4	16.8
	AVG	**1158.7**	**1.4**	**16.3**
	STDDEV	214.5	0.1	1.7
DM	**A**	1205.0	1.4	17.1
	B	1297.5	1.3	16.6
	C	1212.0	1.3	15.7
	AVG	**1238.2**	**1.3**	**16.5**
	STDDEV	51.5	0.1	0.7
DMB18%	**A**	1727.5	1.4	24.8
	B	1626.0	1.2	19.7
	C	1553.5	1.4	21.2
	AVG	**1635.7**	**1.3**	**21.9**
	STDDEV	87.4	0.1	2.6
DMB22%	**A**	1782.5	1.6	29.1
	B	1319.5	1.7	22.7
	C	1355.5	1.6	22.3
	AVG	**1485.8**	**1.7**	**24.7**
	STDDEV	257.6	0.0	3.8

Table B.2. Nitrogen content of above-ground *Scirpus validus* in 2001

2001 Treatment	Replicate	Biomass (g/m2)	N (%)	Mass N (g/m2)
SS	**A**	1859.5	1.2	22.7
	B	2240.5	1.7	37.4
	C	2029.0	1.0	20.9
	AVG	**2043.0**	**1.3**	**27.0**
	STDDEV	190.9	0.3	9.1
SSB11%	**A**	2502.5	1.5	37.8
	B	2838.5	1.5	41.2
	C	2918.5	1.3	36.5
	AVG	**2753.2**	**1.4**	**38.5**
	STDDEV	220.7	0.1	2.4
SSB16%	**A**	2447.0	1.2	28.4
	B	2576.0	1.4	37.1
	C	2353.5	1.2	28.7
	AVG	**2458.8**	**1.3**	**31.4**
	STDDEV	111.7	0.1	4.9
DM	**A**	2144.5	1.5	32.0
	B	2361.0	1.3	31.6
	C	2298.0	1.4	31.5
	AVG	**2267.8**	**1.4**	**31.7**
	STDDEV	111.4	0.1	0.2
DMB18%	**A**	2746.5	1.3	35.4
	B	2905.0	1.3	36.6
	C	2394.0	1.1	26.3
	AVG	**2681.8**	**1.2**	**32.8**
	STDDEV	261.6	0.1	5.6
DMB22%	**A**	2081.5	1.5	31.4
	B	2719.5	1.7	46.2
	C	2815.5	1.5	43.1
	AVG	**2767.5**	**1.6**	**44.7**
	STDDEV	n/a	0.1	n/a

Replicate 7A leaked during the year, drying the wetland out, so this replicate was not used in biomass averages

Table B.3. Nitrogen content of above-ground *Scirpus validus* in 2002

2002 Treatment	Replicate	Biomass (g/m2)	N (%)	Mass N (g/m2)
SS	**A**	2080.5	1.7	35.1
	B	2274.5	1.3	30.7
	C	2443.0	1.5	37.7
	AVG	**2266.0**	**1.5**	**34.5**
	STDDEV	181.4	0.2	3.5
SSB11%	**A**	2577.5	1.8	46.7
	B	2249.0	1.5	33.4
	C	2597.0	1.7	43.2
	AVG	**2474.5**	**1.7**	**41.1**
	STDDEV	195.5	0.2	6.8
SSB16%	**A**	2448.5	1.3	31.9
	B	2376.0	1.7	40.8
	C	1850.5	1.8	33.3
	AVG	**2225.0**	**1.6**	**35.3**
	STDDEV	326.3	0.3	4.8
DM	**A**	2418.5	1.6	39.9
	B	2372.0	1.5	35.1
	C	2221.0	1.6	34.6
	AVG	**2337.2**	**1.6**	**36.5**
	STDDEV	103.3	0.1	2.9
DMB18%	**A**	2752.0	1.5	41.7
	B	2494.5	1.5	38.1
	C	2658.0	1.5	40.6
	AVG	**2634.8**	**1.5**	**40.1**
	STDDEV	130.3	0.0	1.8
DMB22%	**A**	2418.5	1.6	39.8
	B	2385.0	1.6	38.7
	C	2597.5	1.4	35.7
	AVG	**2467.0**	**1.5**	**38.1**
	STDDEV	114.3	0.2	2.1

APPENDIX 3-C

Estimate of Wetland Plant Nitrogen Uptake During 2002

Table C.1. Calculations used in estimating wetland plant N uptake in 2002

Treatment	Rep	Biomass (g/mesocosm)	N (%)	N (g/mesocosm)	N uptake (g/d)	NO_3-N Applied* (g)	Residual N Batch 6 (mg/L)	Residual N Batch 7 (mg/L)	Residual N Batch 8 (mg/L)	Residual N Batch 6 (g)	Residual N Batch 7 (g)	Residual N Batch 8 (g)	Maximum Plant uptake (g)	N removal (g)	Plant Uptake (%)	Unaccounted N (%)
SS	A	4161	1.69	70.24	0.32	99.35	0.70	6.20	2.70	0.33	2.93	1.28	16.39	94.81	17.29	82.71
	B	4549	1.35	61.33	0.28	99.35	0.00	3.10	0.00	0.00	1.47	0.00	14.31	97.88	14.62	85.38
	C	4886	1.54	75.30	0.34	99.35	0.20	7.50	5.30	0.09	3.55	2.51	17.57	93.20	18.85	81.15
	AVG	**4532**	**1.53**	**68.96**	**0.31**	**99.35**	**0.30**	**5.60**	**2.67**	**0.14**	**2.65**	**1.26**	**16.09**	**95.30**	**16.92**	**83.08**
	STDDEV	362.80	0.17	7.07	0.03	0.00	0.36	2.26	2.65	0.17	1.07	1.25	1.65	2.38	2.14	2.14
SSB11%	A	5155	1.81	93.34	0.42	99.35	0.00	0.00	0.00	0.00	0.00	0.00	21.78	99.35	21.92	78.08
	B	4498	1.49	66.90	0.30	99.35	0.00	0.00	0.00	0.00	0.00	0.00	15.61	99.35	15.71	84.29
	C	5194	1.66	86.32	0.39	99.35	0.00	0.00	0.00	0.00	0.00	0.00	20.14	99.35	20.27	79.73
	AVG	**4949**	**1.65**	**82.18**	**0.37**	**99.35**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**19.18**	**99.35**	**19.30**	**80.70**
	STDDEV	391.06	0.16	13.70	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.20	0.00	3.22	3.22
SSB16%	A	4897	1.30	63.74	0.29	99.35	0.00	0.30	0.00	0.00	0.14	0.00	14.87	99.21	14.99	85.01
	B	4752	1.72	81.65	0.37	99.35	0.00	1.60	0.00	0.00	0.76	0.00	19.05	98.59	19.32	80.68
	C	3701	1.80	66.59	0.30	99.35	0.00	0.00	0.00	0.00	0.00	0.00	15.54	99.35	15.64	84.36
	AVG	**4450**	**1.61**	**70.66**	**0.32**	**99.35**	**0.00**	**0.63**	**0.00**	**0.00**	**0.30**	**0.00**	**16.49**	**99.05**	**16.65**	**83.35**
	STDDEV	652.69	0.27	9.63	0.04	0.00	0.00	0.85	0.00	0.00	0.40	0.00	2.25	0.40	2.34	2.34
DM	A	4837	1.65	79.77	0.36	99.35	0.10	0.40	0.30	0.05	0.19	0.14	18.61	98.97	18.81	81.19
	B	4744	1.48	70.18	0.31	99.35	0.00	0.60	0.00	0.00	0.28	0.00	16.38	99.07	16.53	83.47
	C	4442	1.56	69.29	0.31	99.35	0.00	0.00	0.00	0.00	0.00	0.00	16.17	99.35	16.27	83.73
	AVG	**4674.333333**	**1.56**	**73.08**	**0.33**	**99.35**	**0.03**	**0.33**	**0.10**	**0.02**	**0.16**	**0.05**	**17.05**	**99.13**	**17.20**	**82.80**
	STDDEV	206.51	0.08	5.81	0.03	0.00	0.06	0.31	0.17	0.03	0.14	0.08	1.36	0.20	1.39	1.39
DMB18%	A	5504	1.51	83.30	0.37	99.35	0.80	4.80	1.40	0.38	2.27	0.66	19.44	96.04	20.24	79.76
	B	4989	1.53	76.21	0.34	99.35	0.00	0.30	0.00	0.00	0.14	0.00	17.78	99.21	17.92	82.08
	C	5316	1.53	81.23	0.36	99.35	0.60	1.30	0.00	0.28	0.62	0.00	18.95	98.45	19.25	80.75
	AVG	**5269.666667**	**1.52**	**80.25**	**0.36**	**99.35**	**0.47**	**2.13**	**0.47**	**0.22**	**1.01**	**0.22**	**18.72**	**97.90**	**19.14**	**80.86**
	STDDEV	260.61	0.01	3.65	0.02	0.00	0.42	2.36	0.81	0.20	1.12	0.38	0.85	1.66	1.16	1.16
DMB22%	A	4837	1.65	79.69	0.36	99.35	0.00	0.00	0.00	0.00	0.00	0.00	18.59	99.35	18.72	81.28
	B	4770	1.62	77.42	0.35	99.35	0.00	0.00	0.00	0.00	0.00	0.00	18.07	99.35	18.18	81.82
	C	5195	1.38	71.49	0.32	99.35	0.00	0.00	0.00	0.00	0.00	0.00	16.68	99.35	16.79	83.21
	AVG	**4934**	**1.55**	**76.20**	**0.34**	**99.35**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**17.78**	**99.35**	**17.90**	**82.10**
	STDDEV	228.50	0.15	4.23	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.99	0.00	0.99	0.99

*from May 7 - July 24 (78 days)

	P Uptake	Unacc (DN)
Avg	**17.85**	**82.15**
Max	21.92	85.38
Min	14.62	78.08

Amount NO_3-N applied in Batch 6-8= 99.4 g in 2002
Assume 50% of biomass established by start of Batch 6 (May 7)
Therefore, 50% of uptake for the remainder of the growing season
Growing season - March 15-Sept 15 =180 days
52 growing days elapsed before May 7, leaving 128 days in growing season
From May 7-July 24th - 78 days of growth
During the batches, the plants were exposed to nitrate 52 days
Assume constant uptake during these 78 days of growth
Assume 85% biomass accumulated by July 24 (by day 130 of growing season)

APPENDIX 3-D

Final Wetland Substrate Carbon and Nitrogen Levels

Table D.1. Carbon and nitrogen levels in the wetland substrate (Rhizome layer - 0-5 cm depth)

Layer 1 0-5 cm (Rhizomes)

Treatment	Rep	MC %	C(wet) %	N(wet) %	C(dry) %	N(dry) %	N (mg/kg)
SS	**A**	9.95	8.02	0.39	8.91	0.44	4386.12
	B	9.95	16.96	0.77	18.84	0.85	8515.71
	C	9.95	21.70	1.04	24.09	1.15	11505.83
	Avg				**17.28**	**0.81**	**8135.89**
	Stdev				**7.71**	**0.36**	**3575.02**
SSB11%	**A**	9.95	23.95	1.35	26.60	1.50	14968.35
	B	9.95	13.94	0.89	15.48	0.99	9938.81
	C	9.95	14.80	0.90	16.44	1.00	10011.55
	Avg				**19.50**	**1.16**	**11639.57**
	Stdev				**6.16**	**0.29**	**2883.04**
SSB16%	**A**	9.95	32.46	1.79	36.04	1.99	19905.61
	B						
	C						
	Avg				**36.04**	**1.99**	**19905.61**
	Stdev						
DM	**A**	9.95	35.38	1.59	35.38	1.59	15855.00
	B	9.95	19.45	0.83	21.60	0.83	8339.30
	C	9.95	17.56	1.21	19.49	1.21	12147.00
	Avg				**25.49**	**1.21**	**12113.77**
	Stdev				**8.63**	**0.38**	**3757.96**
DMB18%	**A**	9.95	27.80	1.76	30.87	1.95	19500.28
	B	9.95	28.28	1.72	31.41	1.91	19121.60
	C	9.95	20.69	1.35	22.97	1.49	14946.14
	Avg				**28.42**	**1.79**	**17856.01**
	Stdev				**4.72**	**0.25**	**2527.12**
DMB22%	**A**	9.95	31.87	2.06	35.39	2.29	22880.62
	B						
	C						
	Avg				**35.39**	**2.29**	**22880.62**
	Stdev						

***Note: No rhizomes for collection in the control tanks**

Table D.2. Carbon and nitrogen levels in the wetland substrate (Layer 2 - 5-15 cm depth)

Layer 2 - 5-15 cm

Treatment	Rep	MC %	C(wet) %	N(wet) %	C(dry) %	N(dry) %	N (mg/kg)
Control	**A**	1.68	1.86	0.12	1.89	0.12	1235.25
	B	2.00	1.40	0.10	1.43	0.11	1065.31
	C	2.00	1.52	0.12	1.55	0.12	1205.61
	Avg				**1.62**	**0.12**	**1168.72**
	Stdev				**0.24**	**0.01**	**90.78**
SS	**A**	2.03	1.97	0.12	2.01	0.12	1240.18
	B	1.78	1.93	0.12	1.96	0.12	1231.01
	C	1.86	1.81	0.12	1.84	0.12	1206.54
	Avg				**1.94**	**0.12**	**1225.91**
	Stdev				**0.09**	**0.00**	**17.39**
SSB11%	**A**	8.06	3.34	0.27	3.63	0.30	2973.03
	B	1.87	3.86	0.35	3.93	0.36	3556.30
	C	1.85	2.46	0.23	2.51	0.23	2330.31
	Avg				**3.36**	**0.30**	**2953.21**
	Stdev				**0.75**	**0.06**	**613.24**
SSB16%	**A**	1.95	5.30	0.44	5.40	0.44	4437.23
	B	1.94	4.39	0.41	4.47	0.42	4183.36
	C	2.39	7.13	0.55	7.31	0.57	5660.49
	Avg				**5.73**	**0.48**	**4760.36**
	Stdev				**1.45**	**0.08**	**789.80**
DM	**A**	3.04	5.53	0.39	5.53	0.39	3886.10
	B	2.59	5.67	0.41	5.67	0.41	4060.00
	C	2.80	5.16	0.37	5.16	0.37	3714.00
	Avg				**5.46**	**0.39**	**3886.70**
	Stdev				**0.26**	**0.02**	**173.00**
DMB18%	**A**	3.39	6.79	0.56	7.03	0.58	5760.79
	B	3.24	8.07	0.69	8.34	0.71	7089.81
	C	3.53	6.90	0.62	7.15	0.64	6441.07
	Avg				**7.51**	**0.64**	**6430.56**
	Stdev				**0.72**	**0.07**	**664.57**
DMB22%	**A**	3.91	10.62	0.95	11.05	0.99	9855.03
	B	4.50	9.77	0.84	10.23	0.88	8782.93
	C	3.71	8.13	0.68	8.44	0.70	7027.52
	Avg				**9.91**	**0.86**	**8555.16**
	Stdev				**1.33**	**0.14**	**1427.45**

Table D.3. Carbon and nitrogen levels in the wetland substrate (Layer 3 - 15-25 cm depth)

Layer 3 15-25 cm

Treatment	Rep	MC %	C(wet) %	N(wet) %	C(dry) %	N(dry) %	N (mg/kg)
Control	**A**	1.92	1.74	0.12	1.77	0.12	1223.59
	B	1.95	1.40	0.10	1.43	0.10	1015.91
	C	1.96	1.34	0.10	1.37	0.10	1031.31
	Avg				**1.52**	**0.11**	**1090.27**
	Stdev				**0.22**	**0.01**	**115.72**
SS	**A**	1.95	1.66	0.11	1.69	0.11	1077.61
	B	2.11	1.66	0.11	1.70	0.11	1076.51
	C	2.13	1.48	0.10	1.52	0.10	1043.02
	Avg				**1.64**	**0.11**	**1065.71**
	Stdev				**0.10**	**0.00**	**19.67**
SSB11%	**A**	2.02	2.57	0.22	2.62	0.22	2197.49
	B	1.96	3.45	0.32	3.52	0.33	3284.17
	C	1.93	2.59	0.24	2.65	0.25	2484.25
	Avg				**2.93**	**0.27**	**2655.30**
	Stdev				**0.51**	**0.06**	**563.17**
SSB16%	**A**	1.86	4.82	0.39	4.91	0.40	3958.22
	B	2.14	5.02	0.47	5.13	0.48	4791.64
	C	1.82	3.98	0.35	4.06	0.35	3548.28
	Avg				**4.70**	**0.41**	**4099.38**
	Stdev				**0.57**	**0.06**	**633.59**
DM	**A**	2.86	5.30	0.38	5.30	0.38	3758.80
	B	2.72	5.17	0.37	5.17	0.37	3687.40
	C	2.97	5.19	0.37	5.19	0.37	3673.20
	Avg				**5.22**	**0.37**	**3706.47**
	Stdev				**0.07**	**0.00**	**45.87**
DMB18%	**A**	3.43	7.00	0.62	7.25	0.64	6443.93
	B	3.48	7.32	0.62	7.59	0.65	6467.68
	C	3.54	7.28	0.66	7.55	0.68	6837.13
	Avg				**7.46**	**0.66**	**6582.91**
	Stdev				**0.19**	**0.02**	**220.48**
DMB22%	**A**	6.01	8.29	0.78	8.82	0.83	8348.23
	B	3.64	9.38	0.85	9.73	0.89	8868.00
	C	4.06	7.88	0.68	8.21	0.71	7056.60
	Avg				**8.92**	**0.81**	**8090.94**
	Stdev				**0.77**	**0.09**	**932.70**

Table D.4. Carbon and nitrogen levels in the wetland substrate (Layer 4 - 25-40 cm depth)

Layer 4 - 25-40 cm

Treatment	Rep	MC %	C(wet) %	N(wet) %	C(dry) %	N(dry) %	N (mg/kg)
Control	**A**	2.01	1.84	0.12	1.88	0.12	1244.31
	B	2.10	1.33	0.10	1.36	0.10	1004.49
	C	1.93	1.26	0.10	1.29	0.10	1010.40
	Avg				**1.51**	**0.11**	**1086.40**
	Stdev				**0.32**	**0.01**	**136.78**
SS	**A**	2.32	1.67	0.10	1.71	0.11	1065.93
	B	1.94	1.41	0.10	1.44	0.10	1032.12
	C	2.16	1.16	0.09	1.19	0.09	883.69
	Avg				**1.44**	**0.10**	**993.91**
	Stdev				**0.26**	**0.01**	**96.94**
SSB11%	**A**	1.86	3.91	0.35	3.98	0.36	3597.62
	B	1.81	3.68	0.34	3.75	0.35	3490.17
	C	1.95	2.08	0.18	2.12	0.18	1825.29
	Avg				**3.28**	**0.30**	**2971.03**
	Stdev				**1.02**	**0.10**	**993.69**
SSB16%	**A**	1.87	4.34	0.35	4.42	0.35	3549.17
	B	2.08	4.51	0.38	4.61	0.39	3884.40
	C	1.73	2.50	0.22	2.55	0.22	2210.03
	Avg				**3.86**	**0.32**	**3214.53**
	Stdev				**1.14**	**0.09**	**885.92**
DM	**A**	2.87	5.01	0.36	5.01	0.36	3579.40
	B	2.88	4.90	0.35	4.90	0.35	3533.80
	C	2.93	4.92	0.36	4.92	0.36	3578.60
	Avg				**4.94**	**0.36**	**3563.93**
	Stdev				**0.06**	**0.00**	**26.10**
DMB18%	**A**	3.14	7.77	0.71	8.02	0.73	7291.76
	B	3.15	7.69	0.71	7.94	0.73	7341.46
	C	3.61	7.03	0.62	7.29	0.65	6454.40
	Avg				**7.75**	**0.70**	**7029.21**
	Stdev				**0.40**	**0.05**	**498.41**
DMB22%	**A**	3.90	8.82	0.74	9.18	0.78	7751.61
	B	4.61	7.82	0.71	8.19	0.75	7478.77
	C	3.52	8.23	0.74	8.53	0.77	7687.71
	Avg				**8.63**	**0.76**	**7639.36**
	Stdev				**0.50**	**0.01**	**142.70**

Table D.5. Average carbon and nitrogen levels in the wetland substrate at the beginning (2000) and at the end of the study (2002 – Layers 2-4)

Treatment		2000 C %	2000 N (mg/kg)	2002 C %	2002 N (mg/kg)
Control	**Average**	2.38	1525.72	1.55	1115.13
	Stdev	0.34	213.32	0.23	108.18
SS	**Average**	2.21	1463.03	1.67	1095.18
	Stdev	0.28	164.51	0.26	114.46
SSB11%	**Average**	4.40	3866.82	3.19	2859.85
	Stdev	0.70	618.41	0.71	666.15
SSB16%	**Average**	5.98	4620.63	4.76	4024.76
	Stdev	0.60	320.48	1.26	950.63
DM	**Average**	5.40	3848.10	5.21	3828.09
	Stdev	n/a	110.63	0.26	169.26
DMB18%	**Average**	7.97	7754.62	7.57	6680.89
	Stdev	0.28	345.16	0.45	507.22
DMB22%	**Average**	9.84	9394.22	9.15	8095.16
	Stdev	0.28	845.30	0.99	943.00

APPENDIX 3-E

Estimates of Kinetic Coefficients for NO_3^--N Removal used in Calculating Wetland Area Requirements

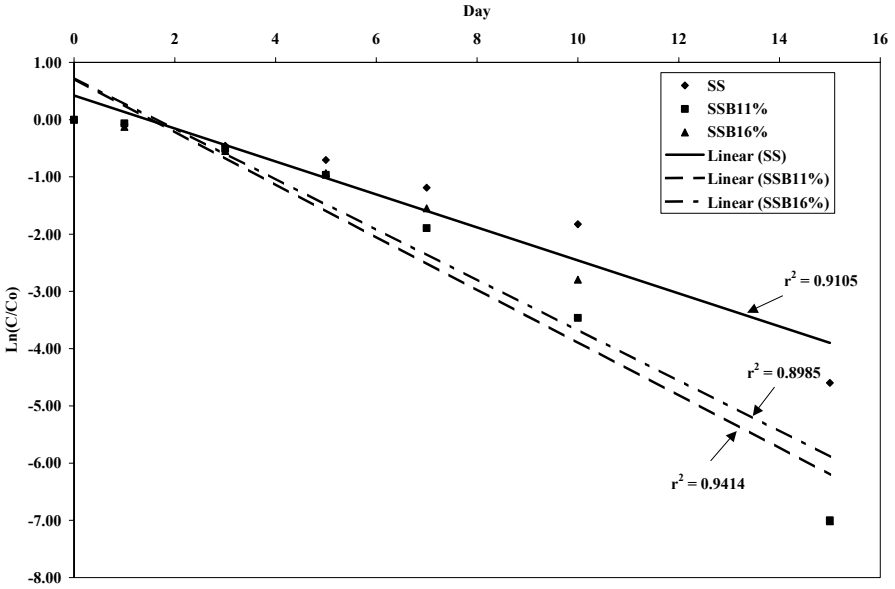


Figure E.1. Fit of the site soil based wetlands nitrate data (from Batch 6 - Spring) to a first order kinetic model (Includes days 0-15).

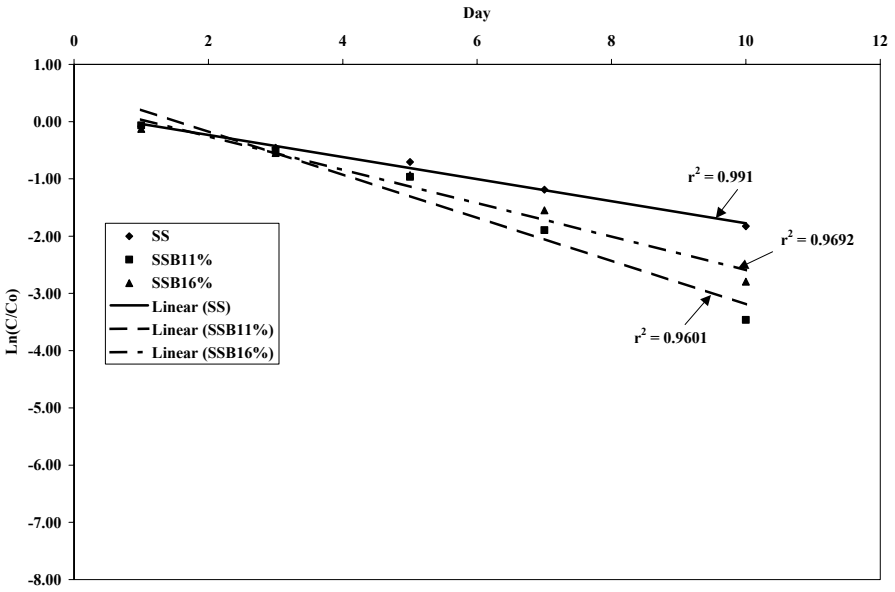


Figure E.2. Fit of the site soil based wetlands nitrate data (from Batch 6 - Spring) to a first order kinetic model (Reduced to days 1-10 to improve r^2 values). Values for k_{NO3} from this data can be found in Table E.1a.

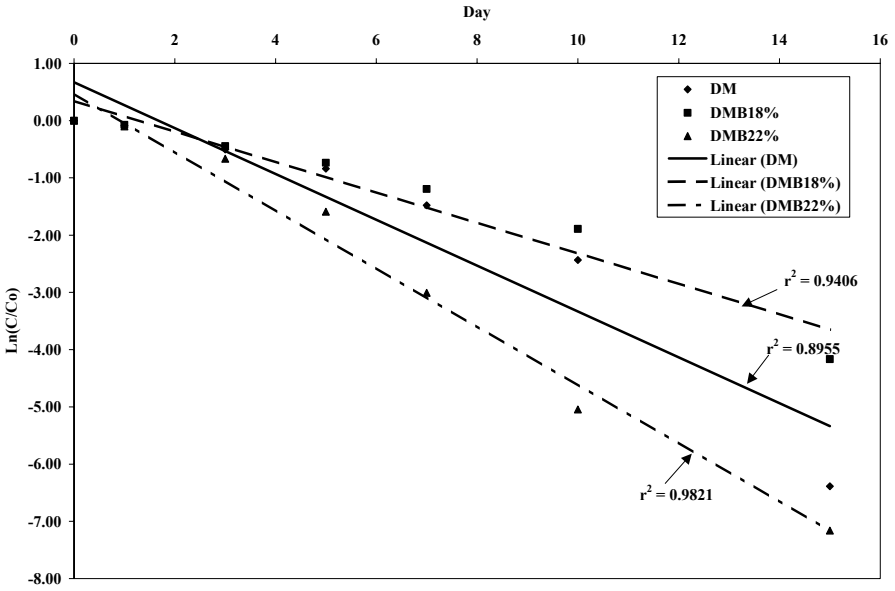


Figure E.3. Fit of the dredged material based wetlands nitrate data (from Batch 6 - Spring) to a first order kinetic model (Includes days 0-15).

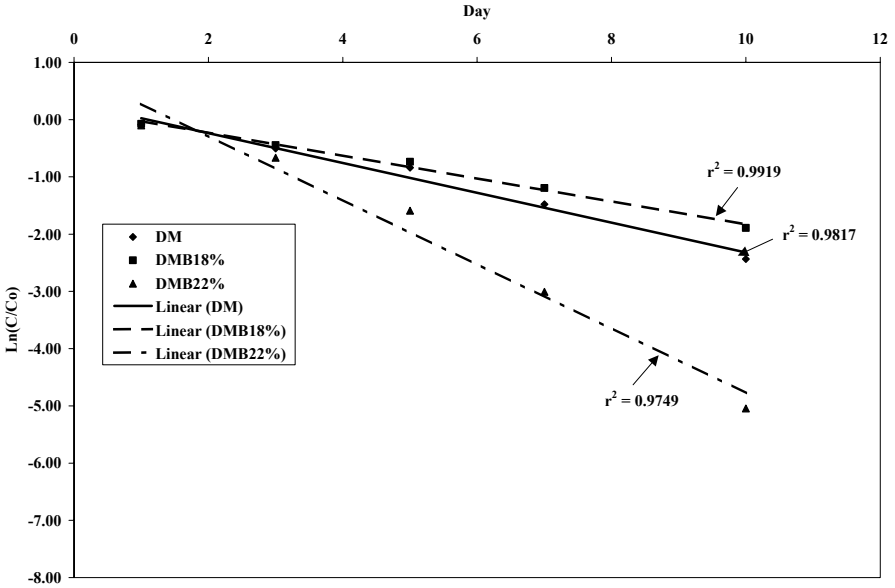


Figure E.4. Fit of the dredged material based wetlands nitrate data (from Batch 6 - Spring) to a first order kinetic model (Reduced to days 1-10 to increase r^2 values). Values for k_{NO3} from this data can be found in Table E.1a.

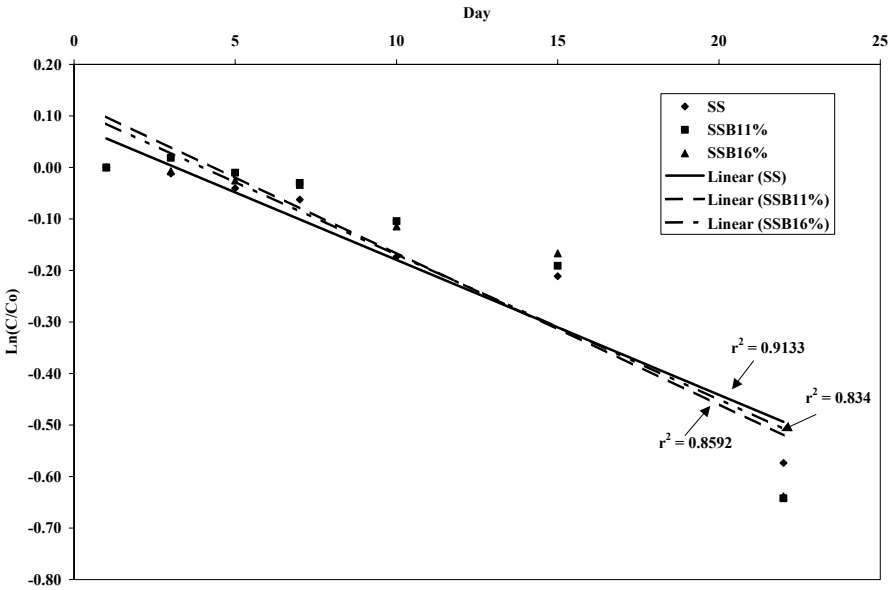


Figure E.5. Fit of the site soil based wetlands nitrate data (from Batch 5 - Winter) to a first order kinetic model (Includes days 1-22).

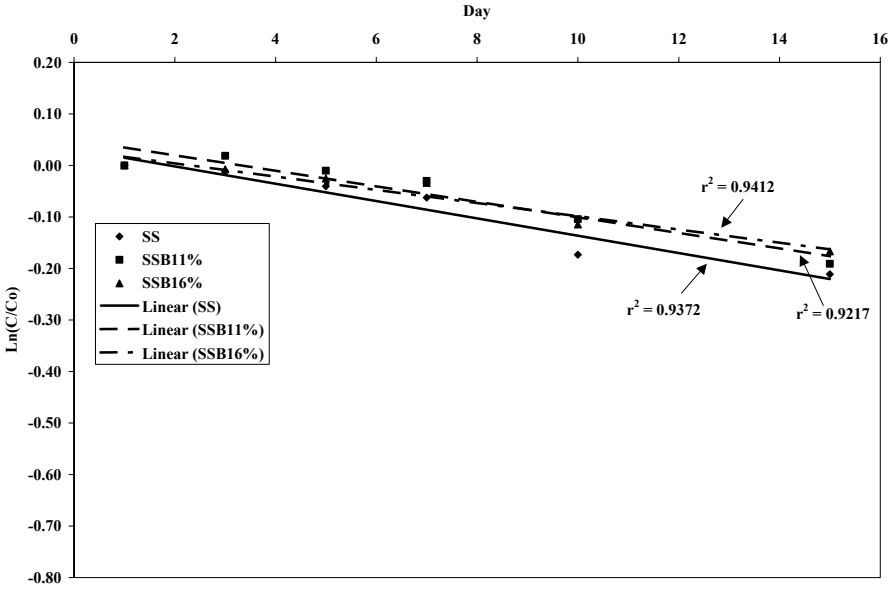


Figure E.6. Fit of the site soil based wetlands nitrate data (from Batch 5 - Winter) to a first order kinetic model (Reduced to days 1-15 to increase r^2 values). Values for k_{NO3} from this data can be found in Table E.1b.

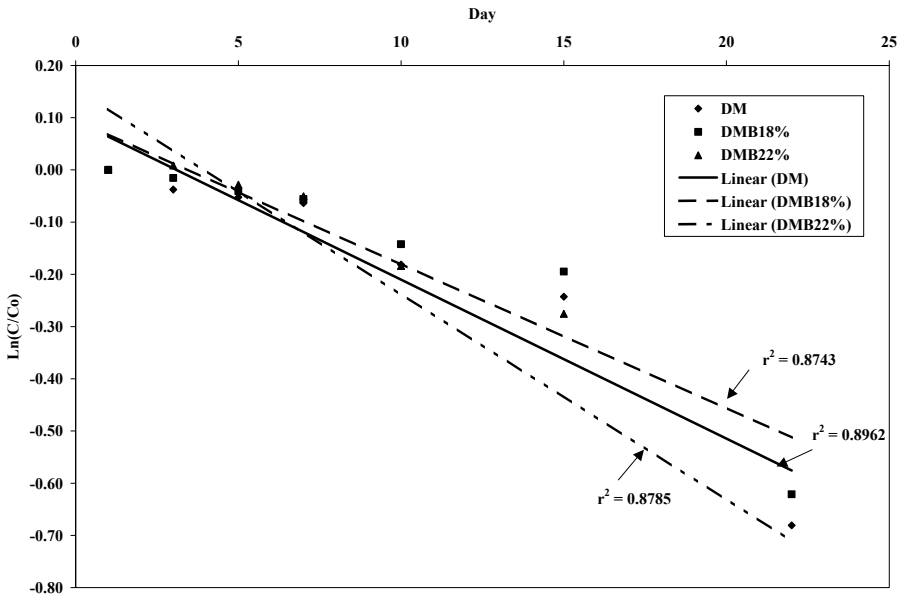


Figure E.7. Fit of the dredged material based wetlands nitrate data (from Batch 5 - Winter) to a first order kinetic model (Includes days 1-22).

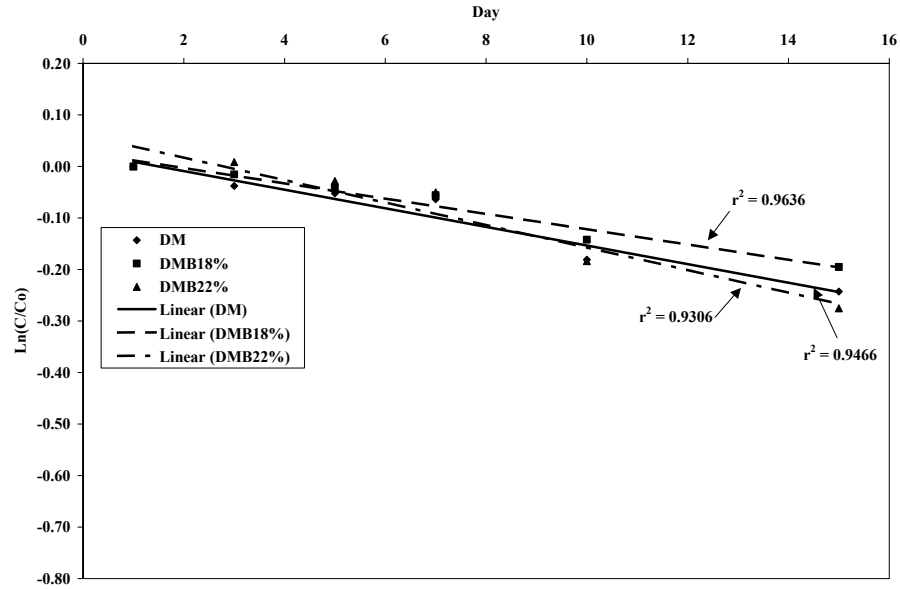


Figure E.8. Fit of the dredged material based wetlands nitrate data (from Batch 5 - Winter) to a first order kinetic model (Reduced to days 1-15 to increase r^2 values). Values for k_{NO3} from this data can be found in Table E.1b.

Table E.1. Values used to calculate k_{NO3} used in wetland area determination

a) Batch 6 - Spring				
Treatment	**Co**	**Ce**	**t**	**k_{NO3}**
	mg/L NO_3-N	**mg/L NO_3-N**	**days**	**day^{-1}**
SS	29.4	5.1	9	0.19
SSB11%	30.2	1	9	0.38
SSB16%	28.6	2	9	0.30
DM	29.1	2.8	9	0.26
DMB18%	29.8	4.8	9	0.20
DMB22%	28.6	0.2	9	0.55

b) Batch 5 - Winter				
Treatment	**Co**	**Ce**	**t**	**k_{NO3}**
	mg/L NO_3-N	**mg/L NO_3-N**	**days**	**day^{-1}**
SS	36.4	29.5	14	0.015
SSB11%	36	29.5	14	0.014
SSB16%	36	30.5	14	0.012
DM	36.8	28.9	14	0.017
DMB18%	34.4	28.3	14	0.014
DMB22%	35.7	27.1	14	0.020