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EFFECTS OF DRAINAGE AND WATER TABLE CONTROL ON GROUNDWATER AND SURFACE WATER QUALITY

Part II - Experimental Results and Simulation Models

by

G. M. Chescheir[1], R. W. Skaggs[1], J. W. Gilliam[2], M. A. Brevé[1], C. L. Munster[1], R. O. Evans[1], R. B. Leidy[3] and J. E. Parsons[1]

Department of Biological and Agricultural Engineering[1]
Department of Soil Science[2]
Department of Toxicology[3]
North Carolina State University
Raleigh, NC 27695-7625

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ABSTRACT

A 13.8 ha field with subsurface drain tubing was instrumented to determine the effects of water table management on losses of fertilizer nutrients and pesticides in the North Carolina lower Coastal Plain. The field was divided into eight 1.7 ha plots. Water table management treatments were drainage (D), controlled drainage (CD), and subirrigation (SI). CD increased corn and soybean yields by 11% and SI increased corn yields by 21%. Wheat yields were not affected by CD and SI. CD reduced total nitrogen (N) losses via drainage outflows by as much as 48% and SI reduced total N losses via drainage by as much as 66%. Nitrate nitrogen (NO_3-N) concentrations at depths less than 1.2 m peaked at 5 to 15 ppm about 30 days after fertilization of corn. NO_3-N concentrations were typically less than 1.0 ppm at depths greater than 2 m due to denitrification. Concentrations of metolachlor in soil and drainage water decreased with time after application. The amounts of aldicarb lost through the subsurface drains and by surface runoff for all three management modes were extremely small (less than 0.07% of applied).

DRAINMOD-N was developed to simulate a simplified version of the nitrogen cycle using the water balance calculations of the standard *DRAINMOD* model. *DRAINMOD-N* simulation results compared well with those of *VS2DNT*, a more complex, two-dimensional model. *DRAINMOD-N* simulations were compared to observed results of the field study. Comparisons indicated that simulated water table depths were within 8-13 cm of the observed data for conventional drainage, controlled drainage and subirrigation. Differences between simulated and observed annual subsurface drainage amounts were within 0.9-6.6 cm for all cases. Predicted annual surface runoff was within 0.5-8.9 cm of the observed value. *DRAINMOD-N* consistently underestimated NO_3-N concentrations in the soil solution. However, simulated and observed nitrate-nitrogen losses in subsurface drainage for the 14-month observation period were within 1.5 kg/ha of each other for all six experimental plots. Except for one case, the predicted total losses (subsurface plus surface) were within 2.4 kg/ha for the observation period. Both predicted and observed results showed that controlled drainage and subirrigation reduced total nitrogen losses. *DRAINMOD-N* can be used to guide design and management decisions for satisfying both productivity and environmental objectives and assessing the costs and benefits of alternative choices to each set of objectives.

The USGS computer model, VS2DT, was modified to simulate pesticide transport in fields with subsurface drains under conventional drainage, controlled drainage and subirrigation conditions. These modifications were validated by comparing measured and simulated values for drainage and subirrigation volumes, water table elevations and water quality data. The modified VS2DT model accurately predicted surface and subsurface flow rates as well as water table response to rainfall events. Model predictions were in excellent agreement with observations for chemical transport in the saturated and unsaturated soil

profile as well as concentrations in the tile outflow. However, small concentrations (<15 ppb) of aldicarb were detected in the field much deeper than simulated plume limits. These indications of preferential flow transport observed in the field were not predicted by the model. The modified VS2DT model is a useful tool for assessing the effects of water table management on the transport of chemicals in fields with subsurface drainage.

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SUMMARY AND CONCLUSIONS

This research project was initiated to study the effects of water table management on movement of nutrients and pesticides in the soil, groundwater and surface runoff. Field experiments were conducted to measure and evaluate the effects of conventional drainage, controlled drainage, and subirrigation on hydrologic and water quality variables related to movement and fate of fertilizer nutrients, sediment and pesticides. Selected models (*DRAINMOD-N* and VS2DT) for predicting the movement of pesticides and fertilizer nutrients to shallow groundwater and surface water were modified and further developed to improve their reliability. The modified models were evaluated using data collected in the field experiments.

Field experiments were conducted on the Tidewater Experiment Station near Plymouth, NC. Drain tubes for a water management system were installed in 1985 on a 13.8 ha field at spacings of 22.9 m and at depths of 0.8 to 1.1 m below the surface. Another set of plastic drains was installed in 1990 and 1991 at deeper depths ranging from 1.2 to 1.4 m below ground surface to improve the operation of the drainage system. The new drains were located midway between the old tubes resulting in a new drain spacing of 11.4 m. Valves were installed on the old drain lines allowing the system to operate with either a 22.9 m or a 11.4 m spacing. Sumps and collector drains were installed to create eight separate experimental plots. The sumps were instrumented to precisely control the outlet for drainage, controlled drainage and subirrigation, and to accurately measure and record drainage, irrigation, and surface runoff rates. Soil and water samples were collected for analyses of nitrogen, phosphorus, sediment, and selected pesticides. The field was planted to a three-crop-in-two-year rotation of corn, wheat and soybean.

Both controlled drainage and subirrigation reduced the subsurface drainage volumes for each year and each growing season of the experiment when compared to conventional drainage. Yearly reductions of subsurface drainage ranged from 5% to 16% for controlled drainage and from 23% to 37% for subirrigation; however, the fields were not in controlled drainage or subirrigation for long periods during the winters. Reductions of subsurface drainage volumes during the growing seasons varied greatly ranging from 10% to 84% for controlled drainage and from 30% to 92% for subirrigation. This variation was due to patterns of rainfall relative to time of control. While controlled drainage and subirrigation decreased the subsurface drainage, they increased surface runoff; consequently, controlled drainage reduced the annual total drainage volume (subsurface drainage plus surface runoff) by 0% to 9% and subirrigation did not significantly reduce annual total drainage volume.

Both controlled drainage and subirrigation reduced the nitrogen (N) loss from the fields for each year and each growing season of the experiment when compared to conventional drainage. Yearly reductions of nitrogen losses ranged from 15% to 18% for controlled drainage and from 47% to 66% for subirrigation. The reductions in annual N losses reported here do not reflect the potential reductions that could be achieved if the fields were in controlled drainage during the winter months. All plots for this experiment were in conventional drainage during most winters to allow drain tube installation and measurement of free drainage rates. During the one winter growing season that controlled drainage was used, controlled drainage reduced N losses by 48% when compared to conventional drainage. Nitrate concentrations in the soil and water profile declined with depth. No nitrate was detected in water samples collected from depths of 1.8 m or deeper.

Concentrations of the pesticide metolachlor decreased with time after application. Average soil concentrations of metolachlor in 1992 decreased from 1.6 ppm on the day of application to 0.3 ppm 112 days after application. Average soil concentrations of metolachlor in 1993 decreased from 8.1 ppm to 1.2 ppm over the same length of time. Metolachlor was not detected in subsurface drainage water or in soil water longer than 4 weeks after application for both 1992 and 1993.

Aldicarb dissipated from the soil by 61 days after application. Most of the aldicarb detected in the soil was found at depths between 0.00 to 0.15 m. Aldicarb was detected in the soil at a maximum depth of 0.46 m. Conventional drainage had the highest percentage of aldicarb lost from tile outflow (0.02% of applied), followed by controlled drainage (0.01% of applied), and then subirrigation (0.001% of applied). More aldicarb was lost by surface runoff in the subirrigation mode (0.06% of applied) than in the controlled drainage (0.04% of applied) or conventional drainage (0.02% of applied) modes. The amounts of aldicarb lost through the subsurface drains and by surface runoff for all three management modes were extremely small.

Controlled drainage significantly increased corn yields compared to free drainage. Subirrigation significantly increased corn yields compared to both controlled and free drainage treatments. Controlled drainage significantly increased soybean yields compared to free drainage, but there was no significant difference in soybean yields between subirrigation and either controlled or free drainage. Wheat yields were not significantly affected by the water management treatments.

DRAINMOD-N was developed to simulate a simplified version of the nitrogen cycle. As the name implies, *DRAINMOD-N* is based on the water balance calculations of the standard *DRAINMOD* model. It uses modifications to determine average daily soil water fluxes and water contents. The solute transport component is based on an explicit solution to the advective-dispersive-reactive equation. Functional relationships are used to quantify the controlling processes of rainfall deposition, fertilizer dissolution, net mineralization, denitrification, plant uptake, and runoff and drainage losses.

DRAINMOD-N was compared with *VS2DNT*, a more complex, two-dimensional model. Water table depths, total subsurface drainage rates, and total surface runoff rates predicted by *DRAINMOD* were within 7-15 cm, 0.7-2.0 cm, and 0.2-0.5 cm, respectively, of those predicted by *VS2DNT* for a 250-day simulation at Plymouth, NC. Daily NO_3-N concentrations predicted by *DRAINMOD-N* and *VS2DNT* were in disagreement, unless a lag between the concentration profiles is taken into account. However, *DRAINMOD-N* predictions for total nitrate-nitrogen loss in drainage water were within 1.0-2.9 kg ha^{-1} of those predicted by *VS2DNT*. On the average, total drainage loss predictions by *DRAINMOD-N* were within 21% of those simulated by *VS2DNT*. Denitrification, plant uptake and net mineralization *DRAINMOD-N* predictions were within 8%, 15% and 26% of those simulated by *VS2DNT*.

A sensitivity analysis of *DRAINMOD-N* indicated that predicted NO_3-N loss via subsurface drainage is most sensitive to the rate coefficients of denitrification and mineralization. Predicted NO_3-N loss in surface runoff is most sensitive to NO_3-N content in rainfall.

DRAINMOD-N simulations were compared to observed results of the field study from November 1991 to December 1992. Crops grown during this period were wheat followed by soybean. Comparisons indicated that simulated water table depths were within 8-13 cm of the observed data for conventional drainage, controlled drainage and subirrigation. Differences between simulated and observed subsurface drainage volumes were within 0.9-6.6 cm for all cases. Predicted surface runoff volumes were within 0.5-8.9 cm of observed values.

DRAINMOD-N consistently underestimated NO_3-N concentrations in the soil solution. However, simulated nitrate-nitrogen losses for the 14-month observation period were within 1.5 kg/ha of those observed for subsurface drainage for all six experimental plots. Except for one case, the predicted total losses (subsurface plus surface) were within 2.4 kg/ha of those observed during the 14 month period. Both predicted and observed results showed that controlled drainage and subirrigation reduced total nitrogen losses.

DRAINMOD-N was used to study long-term effects of drainage system design and management on two poorly drained eastern North Carolina soils. Hydrologic results indicate that increasing the drain spacing, decreasing the drain depth, and/or improving the surface drainage reduces subsurface drainage while it increases surface runoff. Results also show that the use of controlled drainage reduces subsurface drainage and increases runoff. Results also indicate that increasing the drain spacing or decreasing the drain depth reduces nitrate-nitrogen (NO_3-N) drainage losses and net mineralization, while increasing denitrification and runoff losses. Controlled drainage causes a predicted reduction in drainage losses and an increase in denitrification and runoff losses.

The ideal drainage design and management combination is one that will optimize profits and minimize environmental impacts. Results from economic analyses indicate that the maximum profit from a corn crop on Tomotley soil would be obtained with a conventional drainage system with a 20-m drain spacing, 1.25-m drain depth, and 2.5-cm depressional storage. In the case of the Portsmouth soil, a conventional drainage system with a 2.5-cm depressional storage, 40-m spacing, and 1.25-m drain depth would maximize profit from a corn crop.

Simulated results indicate that NO_3-N losses to the environment could be substantially reduced by reducing the drainage intensity below the level required for maximum profits from grain sales. That is, if the environmental objective is of equal or greater importance than profits from the agricultural crops, the drainage systems can be designed and managed to reduce NO_3-N losses while still providing an acceptable profit from the crop.

The simulation results have demonstrated the applicability of *DRAINMOD-N* for quantifying effects of drainage design and management combinations on profits from agricultural crops and on losses of NO_3-N to the environment for a specific crop, soil and climatic conditions. Thus the model can be used to guide design and management decisions for satisfying both productivity and environmental objectives and assessing the costs and benefits of alternative choices to each set of objectives.

The USGS computer model, VS2DT, was modified to simulate pesticide transport in fields with subsurface drains under conventional drainage, controlled drainage and subirrigation conditions. These modifications were validated by comparing measured and simulated values for drainage and subirrigation volumes, water table elevations and water quality data. The modified VS2DT model accurately predicted surface and subsurface flow rates as well as water table response to rainfall events. The model also provided excellent simulations of chemical transport in the saturated and unsaturated soil profile as well as concentrations in the tile outflow. However, small concentrations of aldicarb were detected in the field much deeper than simulated plume limits. Preferential flow transport, which was measured in the field, was not predicted by the model. The modified VS2DT model is an extremely useful tool in assessing the effects of water table management on the transport of chemicals in fields with subsurface drainage.

RECOMMENDATIONS

This project has produced a large and comprehensive database of field observations that has been used to study the hydrology and water quality resulting from various water table management systems. Data collected in the field support the past observations that the water table can be managed through controlled drainage and subirrigation to substantially reduce the efflux of nitrogen from high water table agricultural fields without reducing productivity. In all cases observed, controlled drainage and subirrigation reduced the amount of nitrate nitrogen and total nitrogen flowing from the field when compared to conventional drainage. Controlled drainage and subirrigation increased crop yield in some cases and did not affect crop yield in other cases. We recommend that the practices of controlled drainage and subirrigation be continued and expanded in the Coastal Plain of North Carolina and other high water table areas.

DRAINMOD-N was developed to simulate the movement and transformations of nitrogen in agricultural fields using water table management practices. *DRAINMOD-N* simulation results compared well to those of a more complex model and to the observations made in the field. *DRAINMOD-N* predictions could be improved to more accurately characterize hydraulic head losses near the drain and the transitions that occur during drainage and subirrigation processes. Additional work is needed to improve our understanding of these processes and to develop new algorithims for subsurface drainage, controlled drainage, and subirrigation. Research to make these modifications is recommended.

DRAINMOD-N should be tested on this site for an extended period of time that would include several corn-wheat-soybean rotations. This would allow evaluation of the model under a wider range of eastern North Carolina weather conditions. The model should also be tested in other locations with different soils, crops and climatological conditions. Modifications to the model are needed to improve methods used to predict and to handle freezing, thawing, and snowmelt processes. Research to make these modifications and to conduct expanded and extended field tests of *DRAINMOD-N* is recommended.

The model was used to determine optimum designs of water table management systems that satisfy both productivity and environmental objectives. We recommend that *DRAINMOD-N* be used, with appropriate field verification, to study the interaction between fertilization (amounts and timing) and water table management. Results of this study can then be used to develop user-oriented design guideleines for poorly drained soils in eastern North Carolina. This will ensure that these lands will remain agriculturally productive with minimal environmental impact.

The USGS computer model, *VS2DT*, was modified to simulate pesticide transport in agricultural fields using water table management practices. When compared to field observations, the modified model accurately predicted the hydrology of the system and the transport of aldicarb in the saturated and unsaturated profile and in the drain tube. The modified VS2DT model can be used to assess the effects of water table management on the transport of aldicarb in high water table fields and to test simpler models that may be developed for that purpose.

INTRODUCTION

Protection of the nation's ground and surface waters is of vital importance. Over the past 25 years, attention has been focused on point source pollution of surface and groundwater systems. More recently, concern has increased about the effects of non-point sources on both groundwater and surface water quality. Agricultural cropland is considered a major contributor of nonpoint source pollutants to surface and groundwater.

The development and use of water management, fertility, and pesticide practices to reduce nonpoint source pollution of surface waters in eastern North Carolina is a high priority for government officials. The primary pollutants of concern are pesticides, fertilizer nutrients (N and P), and sediment. Generally, the goal of management practices used to control surface runoff and nonpoint source pollution of surface waters is to increase retention of water on the land and increase infiltration. In some cases, these practices may have a detrimental effect on the quality of groundwater. For example, installation of subsurface drains in poorly drained North Carolina soils will reduce surface runoff, sediment, and P loadings to surface waters (Deal et al., 1986), but will increase nitrates in the shallow groundwater and nitrate outflows in the subsurface drainage water (Gambrell et al., 1975a). It is important to understand the linkage between surface water management and groundwater impacts.

The primary concern about nonpoint source groundwater pollution involves pesticides and fertilizer nutrients, mostly nitrates. Holden (1986) and Ritter (1986) reported detection of widely used herbicides such as alachlor, atrazine, metolachlor, and cyanazine in the groundwater in several states. Other pesticides of concern include fumigants such as DCP and DBCP (Cohen et al., 1984) and aldicarb (a carbonate insecticide) which has been found in groundwater in New York, Florida, and several other states.

This project addresses the effects of agricultural water management practices on pollutant movement from poorly drained lands to shallow groundwater and to surface water via both surface and subsurface runoff. These are important soils from both agricultural and environmental perspectives. Over 25 percent (110 million acres) of the total cropland in the United States requires improved drainage for agricultural production. In North Carolina 2.2 million acres or about 40 percent of our cropland is on soils that are poorly drained under natural conditions and require drainage improvements. Most of these lands are in the Coastal Plains and Tidewater regions of Atlantic Coastal states, where they are close to environmentally sensitive waters. Effects of water management, fertility, and pesticide practices on pollutant loading from these lands are magnified because of the short time required for the outflow water to appear in the receiving waters.

Previous research (Gilliam et al., 1978; Gambrell et al., 1975b; Skaggs and Gilliam, 1981; Gilliam and Skaggs, 1986) has focused on determining the effects of various water management practices on the rate and quality of runoff from the poorly drained soils. Field studies (Gilliam et al., 1979; Gilliam and Skaggs, 1986; and Skaggs and Gilliam, 1981) have shown that nitrate loss to the environment can be greatly reduced by the use of controlled drainage during certain periods of the year. The effectiveness of this practice depends on the intensity of management. Because of the potential environmental benefits of controlled drainage, it has been accepted as a Best Management Practice by the regulatory agencies in North Carolina. Structures to achieve control have been cost-shared by the State of North Carolina in nutrient sensitive watersheds for the past three years. Farmers have also readily accepted controlled drainage because it conserves water and increases yields.

Control structures have been placed in ditches draining over 250,000 acres in North Carolina. Based on results of field experiments on several soils, it is estimated that nitrate nitrogen outflows from the controlled areas have been reduced by nearly two million pounds annually. This practice has expanded to other areas along the Atlantic Coast with new programs to cost share structures for water quality purposes in adjacent states. Frequent inquiries from both regulatory and agricultural agency personnel in other Atlantic Coast states indicate that interest in this practice is widespread. A closely related water management practice involves pumping water into the controlled outlet to raise the water table in the field. This practice, called subirrigation, provides both irrigation and drainage in one system and is also being rapidly accepted by farmers in the coastal area. Protasiewicz et al. (1989) reported that subirrigation decreased nitrogen loading, but increased losses of both phosphorus and atrazine from clay soils in Michigan for one year, 1987. Both controlled drainage and subirrigation are growing in popularity as farmers learn of their advantages; thus they have the potential for dramatic increases in use over the next few years.

Methods for estimating nutrient losses as related to drainage system design and management have been developed (Deal et al. 1986). However, these methods are based on field experimental data and can be used with confidence for only a few soils. They cannot be used to determine the best way to manage controlled drainage systems to minimize nutrient loading to receiving waters, nor can the effects of increased or decreased use of fertilizer or changes in the timing of fertilizer application be predicted. Pollutant loading from agricultural lands is clearly affected by cultural practices such as crop rotation and tillage methods, as well as water management. The effects of these factors cannot be evaluated with present methods. Furthermore, we are not able to predict the effects of alternative water management and cultural practices on sediment and pesticide losses from flat agricultural lands with high water tables.

USDA Agricultural Research Service Researchers have developed the models CREAMS (Knisel et al., 1983) and GLEAMS (Leonard et al., 1987) for predicting the effects of cultural practices such as reduced tillage and contour farming on the movement of sediment, pesticides, and fertilizer nutrients from agricultural lands. However, both models were developed for upland conditions and are not directly applicable to poorly drained soils. They do not consider subsurface drainage and water table control processes, which are dominant in soils with high water tables. The water management model, DRAINMOD (Skaggs, 1978) was developed to quantify the hydrology of high water table soils and has been combined with CREAMS for application to poorly drained soils (Parsons et al., 1989; Wright et al. 1992).

The CREAMS and GLEAMS models do not treat subsurface drainage processes and are therefore not appropriate for predicting losses and fate of mobil solutes such as nitrates and some pesticides. Two approaches were followed to develop models to quantify losses of these solutes. DRAINMOD was extended to simulate the movement and fate of nitrogen in poorly drained soils. The resulting model, DRAINMOD-N was tested using experimental data from this study. Another approach involved modification of the USGS model, VS2DT, to simulate the movement and fate of the pesticide Aldicarb. Thus, this research project involved the collection and analysis of field data, the development and testing of simulation models, DRAINMOD-N and VS2DT and the application of the models to examine effects of various combinations of water management, fertility and pesticide practices.

The objectives of the research project were to:

1. Conduct field experiments to measure and evaluate the effects of drainage, controlled drainage, and subirrigation on the following hydrologic and water quality variables:
    a. Movement and fate of fertilizer nutrients and sediment in surface runoff, shallow groundwater and subsurface drainage waters.
    b. Loss of pesticides in surface and subsurface drainage waters and their movement into shallow groundwaters,
2. Test the reliability of selected models for predicting the movement of pesticides and fertilizer nutrients to shallow groundwater and the losses of these pollutants via surface and subsurface drainage waters.
3. Modify and further develop these existing models to improve their reliability.

Work on this project has proceeded in two phases. The project was first funded by WRRI under the name of "Prediction of Pollutant Movement from Poorly Drained Soils". This first project became part of a larger project "Effects of drainage and water table control on groundwater and surface water quality" funded by the USGS Matching Grants Program in 1991. During the early part of the study, the effectivness of the original drainage system was found to be reduced due to a slowly permeable layer located in the soil profile at approximately the same depth as the drain tubes. New drain tubing was installed at deeper depths in 1991 to improve drainage and allow realistic comparisons between water management treatments.

This is the second in a series of two reports on this project. The first report describes the research site prior to the installation of the new drains, the installation and design of the data collection system, initial modelling of the site hydrology and pollutant movement, and preliminary results from the field site. This report describes the research site after the installation of the new drainage system and presents field results for comparing the hydrology and water quality of different water management treatments. This report also discusses the development, verification and application of the VS2DT model and the DRAINMOD-N model.

FIELD EXPERIMENTS: DESCRIPTIONS AND RESULTS

SITE DESCRIPTION

A 13.8 hectare agricultural field has been instrumented to study the movement of nutrients and pesticides in the soil, groundwater and surface runoff. The site is located on the Tidewater Research Station, near Plymouth, in the North Carolina Lower Coastal Plain approximately 200 km east of Raleigh. The field, which was cleared for agriculture in 1975, is nearly flat. The research site is bounded on all four sides by drainage ditches approximately 2.0 m deep. Plastic drainage tubes, 101 mm in diameter, were installed in 1985 at a spacing of 22.9 m on center, and a depth of 0.8 to 1.1 m below the surface (Figure 1). The effectiveness of these drains was limited by low hydraulic conductivity of soil at the depth of the drains. A new set of plastic drains was installed in 1990 and 1991 at deeper depths to improve the operation of the drainage system.

A detailed description of the drainage and data collection system before the installation of the new drain lines is given in the first report on this project (Munster et al., 1994). A description of the new drainage system is given below along with

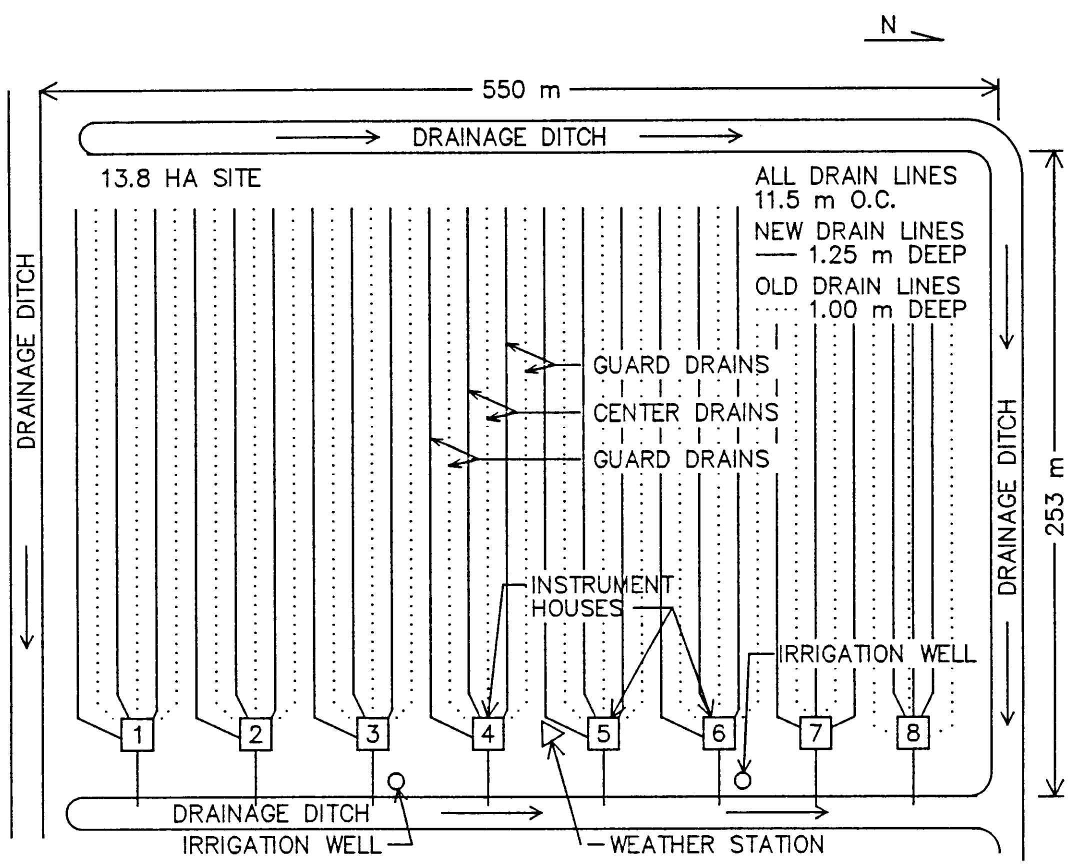

Figure 1. Experimental layout of water table management study in Plymouth, N.C.

a brief summary of the data collection system. For details about the research site and the data collection system refer to the first report (Munster et al., 1994).

The site is divided into eight, 1.7 hectare, experimental plots (Figure 2). These plots are delineated by the area drained by six adjacent subsurface drains (three old drains and three new drains). The new drains were installed in 1990 at plots 7 and 8, and in 1991 at plots 1 through 6. These drains were installed at depths ranging from 1.2 to 1.4 m below ground surface. Details for drain depths for both the new and old drain lines are given in Appendix 1. The new drains are located midway between the old tubes resulting in a new drain spacing of 11.4 m (Figure 1).

Valves were installed on the old drain lines in plots 1 through 6 allowing the system to operate with either a 22.9 m or a 11.4 m spacing; therfore, either 3 or 6 drain lines could drain to each house (1 center line and 2 guard lines or 2 center lines and 4 guard lines). Due to the limited space at the north end of the field, only 5 drain lines drained to each house on plots 7 and 8 (1 center line and 4 guard lines). No valves were installed on the drains on these plots; therefore, the drain spacing on these plots was always 11.4 m.

The soil on the research site is classified as Portsmouth sandy loam (Typic Umbraquult; fine-loamy, siliceous, thermic). It is a very poorly drained soil that formed in loamy fluvial and marine sediments. The Ap horizon is a black fine sandy loam 0.3 m thick with an organic content in the 3 to 5% range. Various layers of fine sandy loam extend down to a sandy clay loam located at 0.5 to 0.9 m. The sandy clay loam is underlain by a horizon comprised of alternating thin layers of sand or loamy sand and silt. Depending on location in the field, this horizon is underlain at 1.0 to 1.2 m by grey sand. Coarse sand intermixed with pockets of sandy clay loam is found from 1.2 to 2.4 m. A tight marine clay deposit, approximately 6.1 m thick restricts vertical seepage from the profile at 2.4 m.

Each experimental plot has an underground vault and instrument house. Each underground vault intercepts the drainage outflow from the six adjacent subsurface drains as well as the surface runoff from two field catch basins. Each vault contains four cylindrical PVC outlet tanks that are 0.61 m in diameter. The center and guard tanks are 1.8 m in height and the two surface runoff tanks are 0.9 m in height. These four holding tanks intercept water from the field as follows: the center tank receives water from the two middle subsurface drains, each surface runoff tank receives water from the one of the surface runoff collectors, and the guard tank receives water from the four outside subsurface drains (guard drains). All four holding tanks are equipped with sump pumps and control floats that automatically pump water from the holding tanks to the drainage ditch outlet (Figure 3).

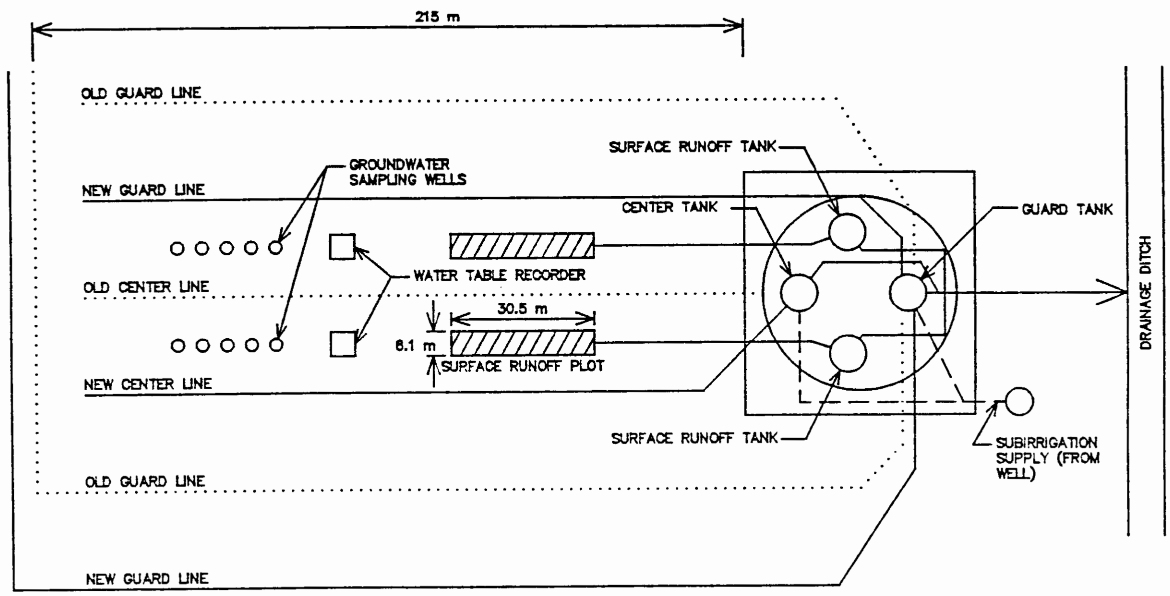

Figure 2. Layout of experimental plot.

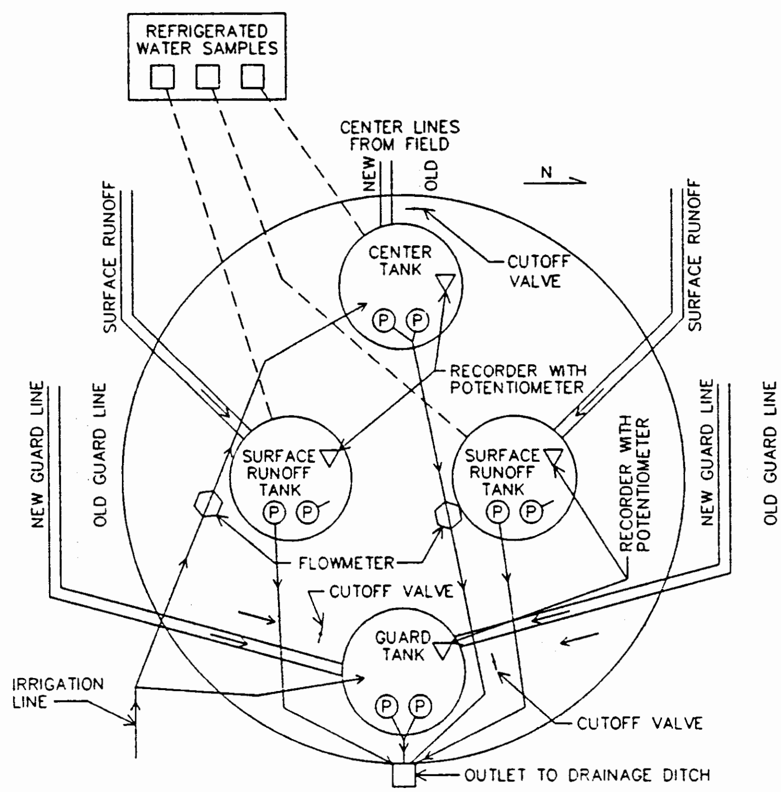

Figure 3. Layout of facilities for controlling drainage outlets, and measuring and sampling runoff and drainage water.

Drainage and runoff rates and volumes are measured in two ways. 1. The water level in each holding tank is continuously measured with a potentiometer mounted on a Stevens water level recorder. The output is recorded directly by the computer which determines flow rate by calculating the change of volume (water elevation times tank area) with time in the tank during an inflow cycle. The rates are stored and integrated to determine cumulative flow volumes, which are also stored as part of the data file. 2. Flowrates are measured directly by a Signet Industrial Paddlewheel Flowmeter installed in the outlet line from each of the drainage outlet tanks. The computers record the flowrate and the time of pumping at 10 sec intervals. Flowmeters and cumulative flow volumes are processed by the computers and available in graphical form for on-site monitoring.

The function of the guard drains is to prevent water table management treatments in one plot from influencing soil water conditions in adjacent plots. The two outside drains on each side of the center drains function to hydraulically isolate the area drained by the center drains from the influence of adjacent experimental plots.

Three water table management treatments: conventional drainage, controlled drainage and subirrigation can be implemented using the subsurface drains. In conventional drainage, the pumps are set so that the water level in the holding tanks is always below the drain tubes in the field. In controlled drainage, pump controls are set to remove water when the water level in the holding tanks exceeds a set point or control elevation, which is higher than the drain. The pumps come on when the water level exceeds the set point and go off when the tank water level falls to the set point. No water is pumped in to maintain the control water level elevation in controlled drainage. This emulates field conditions where a weir in a drainage ditch serves to block drainage until the water level in the ditch rises to the weir elevation. In subirrigation, the water level in the holding tank is maintained at a set point above the field drain outlet. Irrigation water from a shallow irrigation wells is pumped in to replace water lost from the outlet tanks via subirrigation; when rainfall occurs, drainage water is pumped out of the tanks to maintain the subirrigation set point. Set points changed time depending on water table managemnt strategy. The exact elevations and timing of the set points for this study are presented later.

Drainage outflow and subirrigation data are collected and processed by personal computers located in climate controlled rooms in equipment houses 2 and 5. The computer in house 2 collects data from plots 1, 2 and 3 while the computer in house 5 collects data from plots 4, 5, 6, 7,and 8. Water surface elevations in the outlet tanks, flow rates and weather data are processed by the computers, which can be accessed by telephone from our lab in Raleigh to evaluate experimental conditions and to download data.

Each equipment house has a refrigerator to preserve samples. Each refrigerator contains three large sample containers (carboys), one for subsurface drainage and two for surface runoff samples. Flexible 12 mm diameter tubing is connected to the discharge pipes from the subsurface drainage tank and the surface runoff tank. This flexible tubing passes through the wall of the refrigerators and discharges into the sample containers. Every time the drainage tank pump or the surface runoff tank pump operate, a 0.5% portion of the discharge flows into the refrigerated sample containers. The flow proportional samples are taken to the soil science water quality laboratory for analysis at least weekly and more frequently for rainfall events after fertilization.

Each experimental plot has two 100 mm diameter water table wells equipped with automated water level monitoring equipment. One well is located midway between the two control drains and the other well is located midway between the old control drain and the new guard drain. Both wells are equipped with a float, weight, and pulley system connected to a potentiometer and an Omni Data Pod mounted on a Stevens Recorder platform. Thus water table depth is continuously recorded at two points in each plot. A deep irrigation well, 91 m deep, and two shallow irrigation wells, 23 m deep, are located on the eastern edge of the field.

Surface runoff is collected from two in-field surface runoff plots approximately 6.1 m (4 crop rows) wide by 30.5 m long (Figure 2). The north plots were graded at 0.6% to 0.8% slope and the south plots were left with their natural slope which is approximately flat. The plots are surrounded by 30 cm tall berms to isolate them from the rest of the field. Gutter collectors made of PVC were installed at the end of each plot to collect runoff and route it through underground PVC pipe to the vaults. The soil surface within 30 cm of the collectors is stabilized by a porous plastic sheet.

A series of five to six wells, referred to as a well nest, are installed in lines parallel to the drain tubes. Wells in each nest are spaced approximately 0.45 m horizontally and are at depths of 0.6 m, 0.9 m, 1.2 m, 1.8 m, 2.4 m, and 3.0 m, or 3.7 m. They are constructed of 50.8 mm diameter polyvinyl chloride (PVC) well casing, with a slotted screen for the bottom 150 mm. Each well in the nest is screened in a distinct soil layer. The number, location, and depth of the wells are designed to provide detailed information on the movement of fertilizer nutrients in the flow domain. The wells are installed with granular filter pack around the screen and a bentonite clay seal around the well casing.

The research site is equiped with a complete Campbell CR-10 weather station as well as two additional recording rain gages. Weather parameters measured at the research site are rainfall, air and soil temperature, wind speed and direction, and solar radiation.

PROCEDURES

Climatological Data. Rainfall data were collected from 3 automatic and 1 manual raingages. Multiple raingages allowed comparisons between recorded rainfall amounts to document proper functioning of the raingages and detect consistency in the rainfall data set.

Potential evapotranspiration was calculated using the air temperature, solar radiation, and wind speed data collected by the Campbell weather station. Calculations were made for the following methods: Thornthwaite, Jensen-Haise, Turc, Penman-Monteith grass reference, and Penman-Monteith alfalfa reference. The reader is refered to Jensen et al., (1990) for details of these methods.

Cropping and Fertilization. The study site was planted to a three-crop-in-two-year rotation - corn, year 1; wheat, year 1-2; soybeans, year 2. This cropping sequence is common on approximately one million hectares in eastern North Carolina.

Prior to beginning the study, one replication (Plots 1, 2 and 3) received 900 kg/ha of triple super phosphate (0-48-0). A long history of phosphorus fertilization has resulted in high phosphorus indexes on many agricultural fields. Since this site had been in agricultural production for only 10 years, the one time application of triple super phosphate was applied to establish a phosphorus index typical of fields with a longer cropping history.

Corn, the first crop in the rotation, was typically planted between April 10-15 and harvested around mid September. Pre-plant tillage operations were performed as needed and typically included: one or two passes with a disk harrow, one or two passes with a chisel, then bedding to form 90 cm rows. Potassium was applied pre-plant at the rate of 170 kg/ha. Nitrogen and phosphorus were applied at planting at the rates of 65 kg/ha P, and 35 kg/ha N. Sidedress applications of N were applied in split applications; the first approximately one week after planting and the second at the knee high stage (6 weeks after planting) to achieve a total N application of 225 kg/ha. Fertilizer applications are summarized in Table 1. The timing and rate of pesticide applications are discussed later.

Prior to planting wheat, the corn stubble was disked once and dolimitic lime applied at rates established by soil test reports. The field was disked again in early November followed by one or two passes with a chisel. Fertilizer was applied pre-plant at the rates of 16 kg N, 80 kg P and 80 kg K per hectare. Traditionally, wheat is planted flat (drilled) in 17-18 cm rows; but, to accommodate surface runoff collection, the field was bedded to form 90 cm beds. Wheat was then drilled on the beds in 17 cm

Table 1. Cropping sequence and fertilization rates and timing for the period 1990 to 1994.

Crop	Date	Fertilizer Analysis	Rate	N	P_2O_5	K_2O
			kg/ha			
	4-03-89	0-48-0	896	0	430.1	0
	12-06-89	lime	2643	-	-	-
Wheat	12-06-89	10-20-20	365	38.8	77.6	77.6
	2-22-90	30-0-0	158	47.5	-	-
	3-26-90	30-0-0	79	23.7	-	-
	total			110.0	77.6	77.6
Soybean	1990	-	-	-	-	-
Corn	4-10-91	4-0-38	448	17.9	-	170.2
	4-17-91	10-34-0	198	19.8	67.3	-
	4-18-91	30-0-0	268	80.4	-	-
	5-22-91	30-0-0	343	105.9	-	-
	total			224.0	67.3	170.2
	11-15-91	lime	1833	-	-	-
Wheat	11-15-91	5-25-25	326	16.3	81.5	81.5
	2-21-92	30-0-0	487	146.1	-	-
	total			162.4	81.5	81.5
Soybean	1992	-	-	-	-	-
Corn	4-21-93	0-25-25	300	-	75.0	75.0
	4-29-93	10-34-0	50	5.0	17.0	-
	5-04-93	30-0-0	268	80.4	-	-
	6-09-93	30-0-0	219	65.7	-	-
	6-30-93	30-0-0	174	52.1	-	-
	total			203.2	92.0	75.0
	11-08-93	lime	2013	-	-	-
Wheat	11-12-93	30-0-0	69	20.8	-	-
	3-22-94	30-0-0	271	81.4*	-	-
	total			102.2	-	-
Soybean	1994	-	-	-	-	-

*Nitrogen side dress fertilizer applied to plots 2,4,7 and 8 only.

rows. One side dress application of nitrogen was applied in February or early March at the rate of 100 kg/ha. Wheat was harvested early to mid June.

Soybeans were planted (no-till drill) in the wheat stubble immediately following wheat harvest. No-till soybeans would normally be planted flat, but to accommodate surface runoff collection, soybeans were planted on the 90 cm beds in 17 cm rows. Soybeans received no fertilization or nitrogen sidedress. Soybeans were typically harvested in mid November. The soybean stubble was left in tact and the field was fallow from soybean harvest until corn was planted the following April. This cropping sequence was completed twice (two harvest of each crop) during the period reported herein.

The cultural practices just discussed represent typical procedures, although some exceptions are noteworthy. Soybeans were planted on beds in 50 cm rows in 1990 to be compatible with a one time application of aldicarb. Corn harvest in 1993 was extremely low due to drought conditions. In anticipation of significant N carryover resulting from poor 1993 yields, only half the 1994 wheat crop (plots 2,4,7 and 8) received N fertilizer at the rates previously discussed. No nitrogen was applied to the other four plots in 1994.

Crop yield was determined for each water management plot from two subplots located at the midpoint between drains (i.e., 6 m on either side of the experimental drain). Corn subplots were typically 2 rows wide (1.8 m) by 23 m long. Soybean and wheat subplots were approximately 4 m wide by 23 m long. Harvest area varied slightly from year to year and crop to crop depending on planting arrangement. Yields reported herein are based on scaling the exact harvest area which ranged from 0.0042 to 0.0094 hectares.

Water Management. The following general water management strategy was implemented from 1991 to September of 1993. Plots 3 and 4 were managed in conventional drainage, plots 2 and 5 were managed in controlled drainage, and plots 1 and 6 were managed in subirrigation. Plot 7 and 8 began operation in June 1991 and were managed in subirrigation for the 1991 corn season, the 1991-92 wheat season, and the 1992 soybean season. Plot 7 was in controlled drainage for the 1993 corn season, and plot 8 was in conventional drainage for the 1993 corn season. The exact dates and water elevations of the various water management strategies are summarized in Figures 4 - 6.

Very low drainage volumes (less than 3 cm) occurred during the corn growing season of 1993. We hypothesized that low drainage rates coupled with low crops yields resulted in low nutrient losses from the field. This meant that relatively high amounts of nutrients remain in the field at the end of the 1993 corn season. In response to this condition, an aggressive management plan to reduce nutrient outflow was implemented on half of the experimental plots. This management plan involved raising the level of controlled drainage to 30 cm below the soil surface on September 14 1993 and keeping controlled drainage at that level throughout the winter. The winter wheat crop was planted on November 15 with no adjustments to the water control practices. The management plan for the 1993-94 winter wheat crop was free drainage for plots 1, 2, 3, and 8, and controlled drainage for

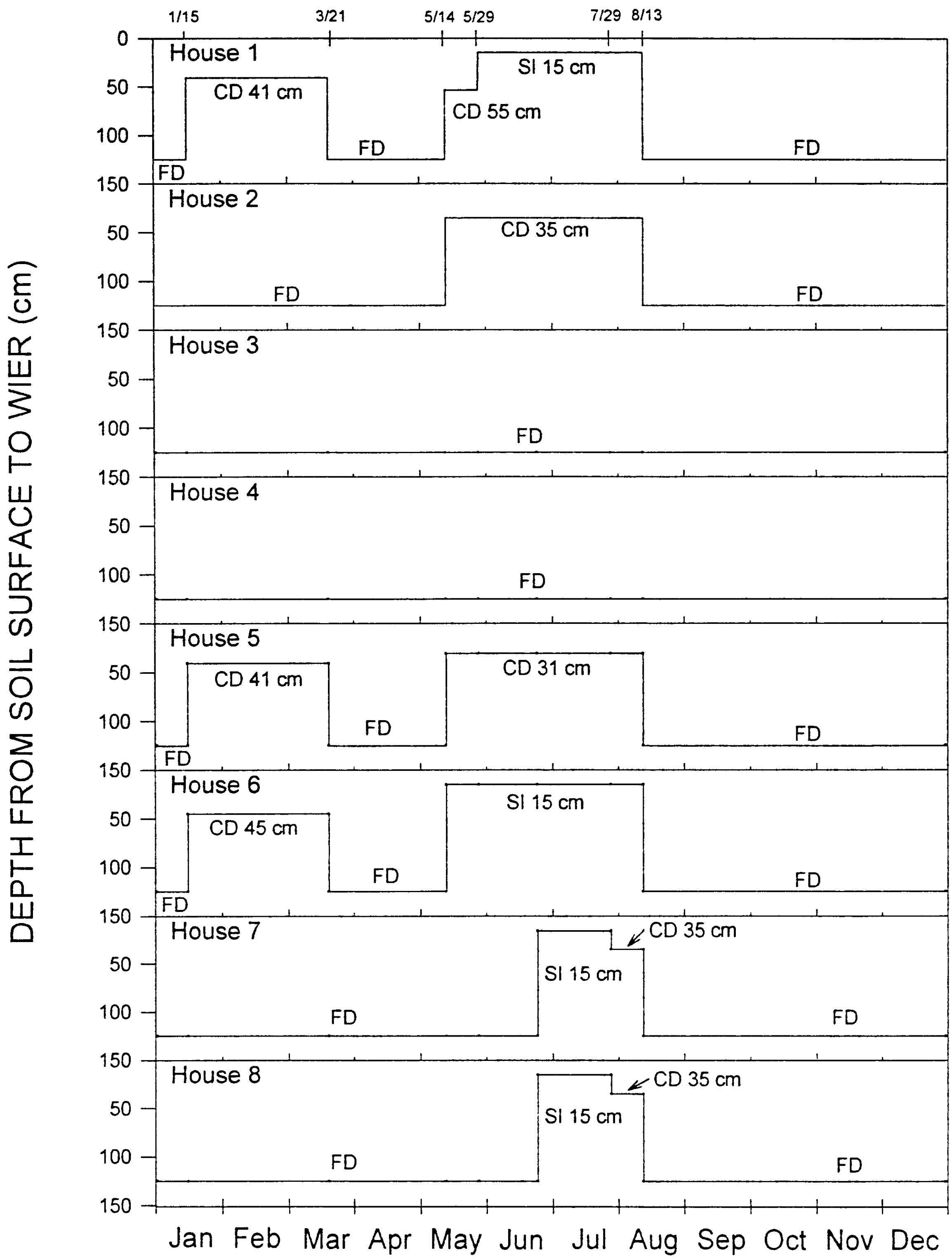

Figure 4. Experimental water management set up for 1991.

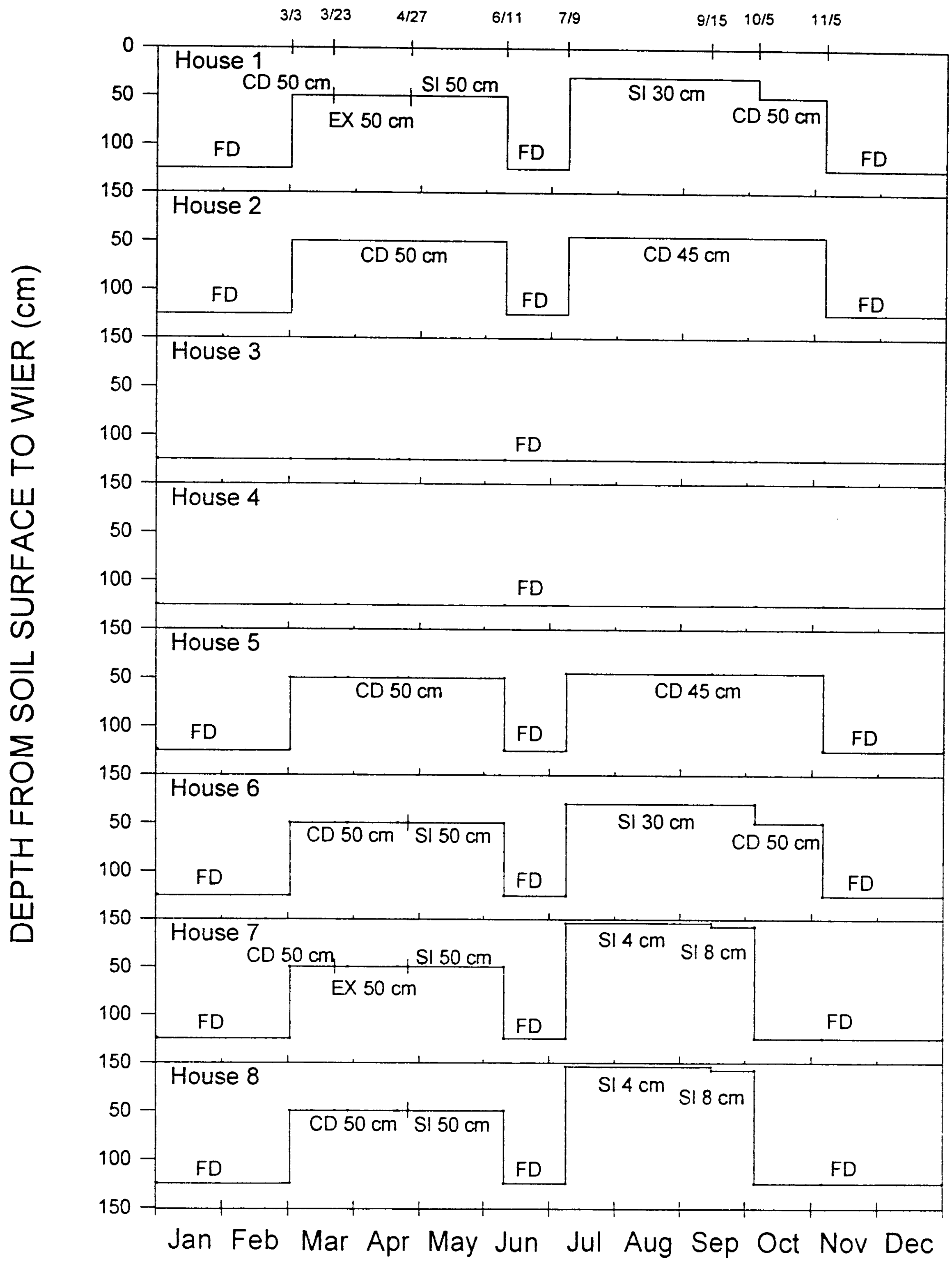

Figure 5. Experimental water management set up for 1992.

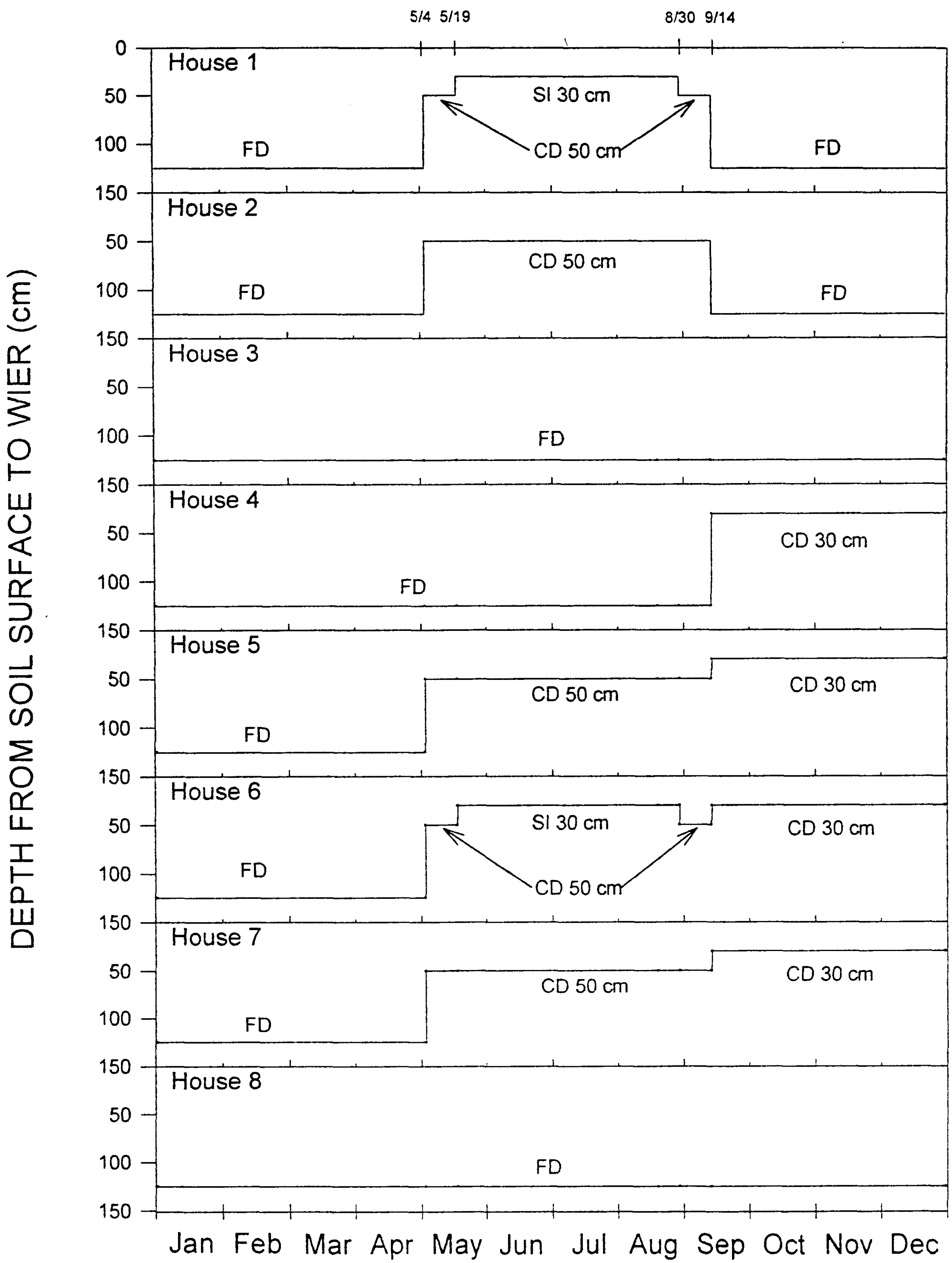

Figure 6. Experimental water management set up for 1993.

plots 4, 5, 6, and 7. Plots 6 and 7 were put into subirrigation at a level of 15 cm below ground surface on May 5, 1994.

<u>Pesticide Application, Sampling, and Analysis - Metolachlor</u>. The pesticide portion of the project was designed to study the most important herbicides and insecticides used in the production of corn and soybeans on the blackland soils. We concentrated efforts on metolachlor [2-chloro-<u>N</u>-(2-ethyl-6-methylphenyl)-<u>N</u>-(2-methoxy-1-methylethyl)acetamide], a herbicide used on both corn and soybeans in the blackland area, and on aldicarb (2-methyl-2-(methylthio)propionaldehyde *O*-methylcarbamoyloxime) a systemic insecticide, acaricide and nematicide for use in agriculture and silviculture. Aldicarb is not normally used on these soils, but was chosen because it is among the more mobile pesticides that could be used.

On June 27, 1990, soybeans were drilled into wheat stubble on plots 1 through 6; and metolachlor as the Dual 8E formulation (EPA Reg. No. 100-597) was applied preemergence at a rate of 2.8 kg of active ingredient per ha (kg ai/ha). Glyphosate [isopropylamine salt of <u>N</u>-(phosphonomethyl)glycine] was applied with the metolachlor at a rate of 1.12 kg ai/ha to control emerged weeds in the wheat stubble. Metolachlor was not applied to plots 7 and 8 in order to provide untreated water and soil for quality control analyses.

Corn was planted on April 16, 1991, by conventional tillage methods, and a herbicide formulation containing metolachlor and atrazine [6-chloro-<u>N</u>-ethyl(1-methylethyl)-1,3,5-triazine-2,4-diamine], with the product name of Bicep, was applied as a preemergence spray to plots 1 through 6 on April 18, 1991. Rates of application were 2.8 and 2.2 kg ai/ha of metolachlor and atrazine, respectively. Plots 7 and 8 received a preemergence application of alachlor [2-chloro-<u>N</u>-(2,6-diethylphenyl)-<u>N</u>-(methoxymethyl)acetamide] at a rate of 4.5 kg ai/ha. Plots 7 and 8 were, therefore, set aside for sampling as control for plots 1 through 6.

In 1992, Soybeans were planted over wheat and plots 1 through 7 were treated with metolachlor (Dual 8E) using a tractor-mounted Hi-Boy Sprayer at an application rate of 3.4 kg a.i./ha. Plot 8 was treated with alachlor and was used as an untreated control. To verify that the correct amount of metolachlor was applied to the plots, 16 filter papers (934AH, 11 cm diam.) were placed in a linear arrangement ca.1.O M apart. Analyses of these papers confirmed the application rate.

In 1993, corn was planted on April 29 and 30. Two rates of metolachlor, 3.4 and 6.8 kg a.i./ha were applied to three (plots 1, 2, and 3) and four (plots 4, 5, 6, and 7) plots, respectively, and experimental plots 1 - 7 received atrazine at a concentration of 1.7 kg a.i./ha. Plot 8 was treated with alachlor and was used as an untreated control. Sampling protocols were identical to 1992 tests. Filter papers were placed on all plots and confirmed the proper application rates of both herbicides.

Concentrations of metolachlor were determined in soil samples collected in the field plots, and water samples collected from sampling wells and from the center drainage and surface runoff tanks. Soil and water samples were analyzed using gas chromatography. Details of sampling and analysis procedures are given in the first report (Munster et al. 1994).

Pesticide Application, Sampling, and Analysis - Aldicarb. Aldicarb was applied to a no-till soybean crop on experimental plots 1, 2, and 3 at the time of planting (June 27, 1990). The granular aldicarb was incorporated into the soil, 25 mm deep, in 0.48 m rows at a formulated rate of 6.1 kg/ha (0.92 kg/ha active ingredient). Over a six month period, nine sampling rounds were conducted starting on the day aldicarb was applied to the field. A total of 106 soil samples and 545 water samples were obtained. Included in the 545 water samples were 60 replicate samples that were used for split sample analysis by an independent laboratory. Since aldicarb had never been applied to the research site, no background sampling was performed.

Water samples for aldicarb analysis were obtained from the well nests, the drain outflow, the surface runoff collectors, the outlet ditch and from two irrigation wells on the site. The well nest piezometers were purged and sampled using polyethylene bailers as described in Munster (1992).

Soil samples were obtained in 0.15 m increments in the unsaturated zone to the depth of the water table using an 83 mm diameter bucket auger (Kirkland 1989). Soil samples from four random locations were sampled and composited within each experimental plot. A 1000 g subsample for each increment was taken from the composite samples. All soil samples were refrigerated until the aldicarb extraction procedure as described by Hudson (1990) was performed. The soil water extract was then frozen until the analysis was performed.

Aldicarb concentrations were determined by a high pressure liquid chromatography (HPLC) system with on-line post-column derivatization/fluorescence (Hudson 1989). This HPLC system is capable of simultaneously measuring the amount of aldicarb and its breakdown products, sulfoxide and sulfone in a sample. All aldicarb concentrations reported are the sum of aldicarb, sulfoxide and sulfone concentrations.

Soil and Water Sampling and Nutrient Analysis Procedures. Water quality samples were collected from the refrigerated carboys receiving drainage water at least once a week or more frequently if drain flow rates were high. Surface runoff samples were collected from the refrigerated carboys as soon as possible after a runoff event, usually within two days. Shallow ground water and soil samples were collected every two weeks or one day after a significant rainfall event (greater than 1.3 cm), whichever occurred first. All soil, well water, surface and subsurface drainage water samples were stored in freezers on-site, transported in coolers to the laboratory in Raleigh and stored at 4°C until analysis.

Soil samples were collected to quantify nitrate-nitrogen movement in the vadose zone. A 1.9-cm dia, 30-cm long probe was used to take 15 cm samples at 0-15 cm, 15-30 cm, 45-60 cm and 75-90 cm or 90-105 cm depths. Samples were taken at three locations (32, 62, and 92 m from the equipment houses, Figure 1) within a 0.3-0.9 m strip along the side of the center drain line. Soil samples were composited in plastic bags and stored in refrigerators. Soil nitrate-nitrogen was extracted using a 1M KCL solution. The extracted solution and water samples were analyzed for nitrate-nitrogen using the bacteroid method (Lowe and Hamilton, 1967).

Well and subsurface drainage samples were filtered through Whatman no. 42 filter paper which gave a clear filtrate on which NO_3-N, NH_4-N, PO_4-P, and Cl were determined. The procedure of Lowe and Hamilton (1967) was used for nitrate. Ammonium was determined using the procedure of Smith (1980). Orthophosphate was determined by the Murphy and Riley (1962) method. Chloride was analyzed using a chloride titrator. Total Kjeldahl nitrogen (TKN) was determined by digestion of an aliquot using H_2SO_4, K_2SO_4, and $CuSO_4$ at 350^0 C for 6 hours after the solution cleared. Total phosphorus was analyzed using the persulfate digestion method in "Standard Methods for the Examination of Water and Wastewater" followed by analysis using the procedure of Murphy and Riley.

Surface runoff samples were centrifuged at 10,000 rpm, after which NO_3-N, NH_4-N, PO_4-P, and Cl were analyzed using the procedures described above. An aliquot of stirred whole sample was taken for digestion by the Kjeldahl procedure. After digestion, the sample was brought to a volume of 100 ml and an aliquot taken for determination of total P using the same colorimetric procedure as PO_4-P. Ammonium was distilled from another aliquot, collected in boric acid and titrated to obtain total Kjeldahl nitrogen in the runoff sample. Total suspended solids were obtained using the procedure from "Standard Methods".

RESULTS AND DISCUSSION

Hydrology. Water management affected subsurface drainage volumes, surface runoff volumes and water table elevation. Conventional drainage resulted in the highest subsurface drainage volumes and the lowest water table elevations when compared to controlled drainage and subirrigation (Tables 2 and 3) . Since the head in the drain was managed at the lowest level in conventional drainage, subsurface drainage occurred for longest periods of time. For example, drainage water was flowing from the drains in the conventional drainage plot (plot 4) for nearly the entire year in 1992 with the exception of a 45 day period in April and May (Figure 7). In contrast, drainage water flow was stopped for much of the time that plots 5 and 6 were in controlled drainage and subirrigation (Figures 8 and 9). No drain flow occurred from plots 5 and 6 between Mar 3 and Jun 1,

Table 2. Yearly cumulative rainfall, subsurface drainage, surface runoff, and irrigation volumes under various water table management practices.

1991	Rainfall	Subsurface Drainage	Surface Runoff	Irrigation
	(cm)	(cm)	(cm)	(cm)
SI* & CD*	128	19.9	ND	6.4
CD	128	31.4	ND	0.0
FD*	128	33.8	ND	0.0
1992	Rainfall	Subsurface Drainage	Surface Runoff	Irrigation
	(cm)	(cm)	(cm)	(cm)
SI & CD	115	28.8	19.1	6.5
CD	115	33.4	10.8	0.0
FD	115	39.9	8.7	0.0
1993 **	Rainfall	Subsurface Drainage	Surface Runoff	Irrigation
	(cm)	(cm)	(cm)	(cm)
SI & CD	72	22.5	10.4	8.4
CD	72	27.9	6.9	0.0
FD	72	29.3	4.9	0.0

* SI & CD in the table represents subirrigation and controlled drainage. CD in the table represents controlled drainage. Conventional drainage is represented by FD in the table.

** Data for 1993 are only from January 1 to September 14. The water management strategies were changed on September 14 (see Figure 6

ND - Not determined

Table 3. Cumulative rainfall, subsurface drainage, surface runoff, and irrigation volumes under various water table management practices for different growing seasons.

1991 Corn	Rainfall	Subsurface Drainage	Surface Runoff	Irrigation
	(cm)	(cm)	(cm)	(cm)
SI* & CD*	59.5	5.7	ND	6.4
CD	59.5	10.2	ND	0.0
FD*	59.5	12.6	ND	0.0
1991-92 Wheat	Rainfall	Subsurface Drainage	Surface Runoff	Irrigation
	(cm)	(cm)	(cm)	(cm)
SI & CD	49.2	7.7	0.0	2.8
CD	49.2	9.9	0.0	0.0
FD	49.2	11.0	0.0	0.0
1992 Soybean	Rainfall	Subsurface Drainage	Surface Runoff	Irrigation
	(cm)	(cm)	(cm)	(cm)
SI & CD	51.5	7.6	19.1	3.6
CD	51.5	10.6	10.8	0.0
FD	51.5	19.6	8.7	0.0
1993 Corn	Rainfall	Subsurface Drainage	Surface Runoff	Irrigation
	(cm)	(cm)	(cm)	(cm)
SI & CD	20.1	0.2	0.0	8.4
CD	20.1	0.4	0.0	0.0
FD	20.1	2.4	0.0	0.0
1993-94 Wheat	Rainfall	Subsurface Drainage	Surface Runoff	Irrigation
	(cm)	(cm)	(cm)	(cm)
SI & CD	75.8	7.6	13.1	4.7
CD	75.8	15.3	9.9	0.0
FD	75.8	24.7	6.8	0.0

* SI & CD in the table represents subirrigation and controlled drainage. CD in the table represents controlled drainage. Conventional drainage is represented by FD in the table.

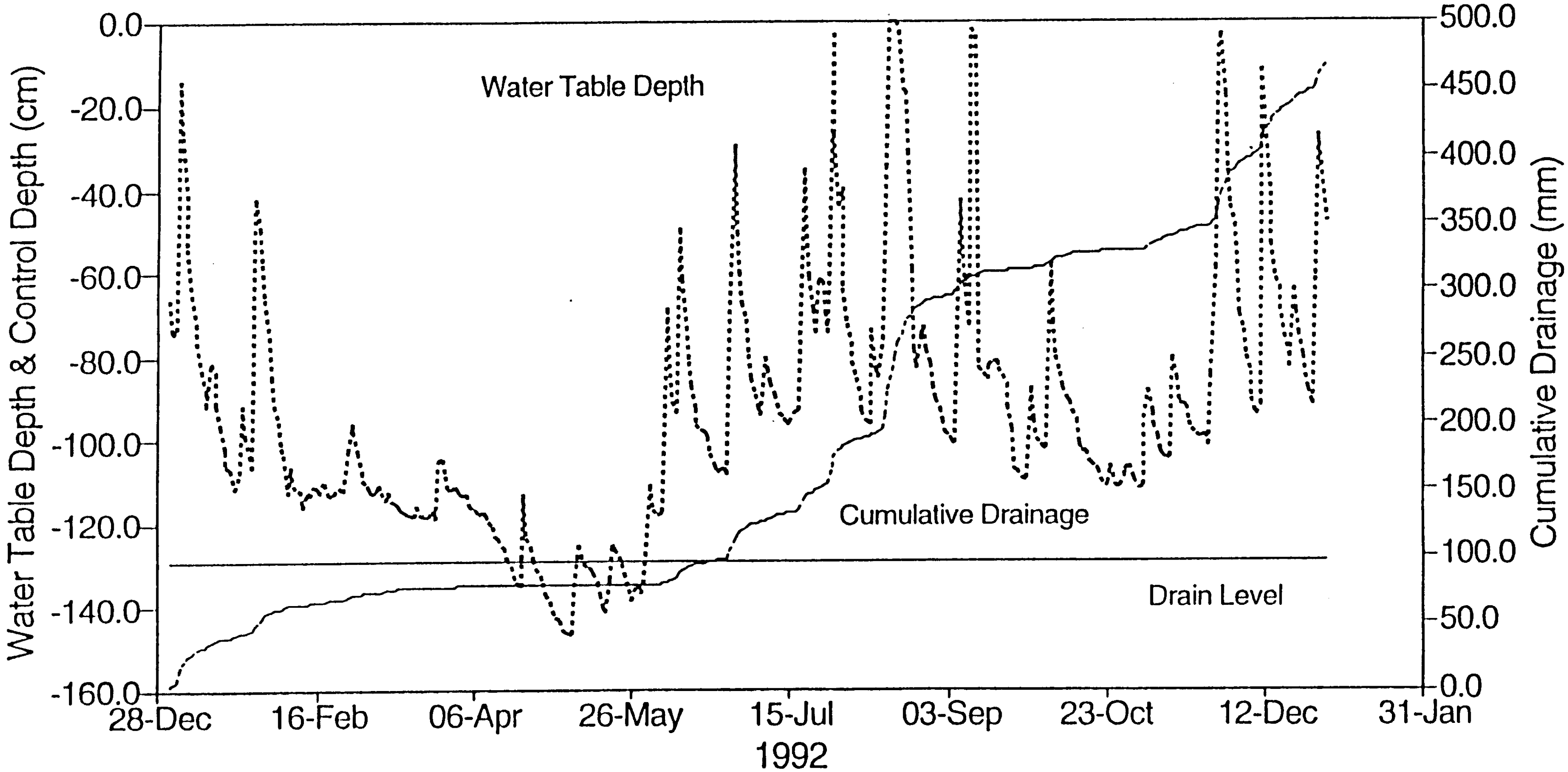

Figure 7. Cumulative subsurface drainage, water table elevation, and water level control for conventional drainage (plot 4) during 1992.

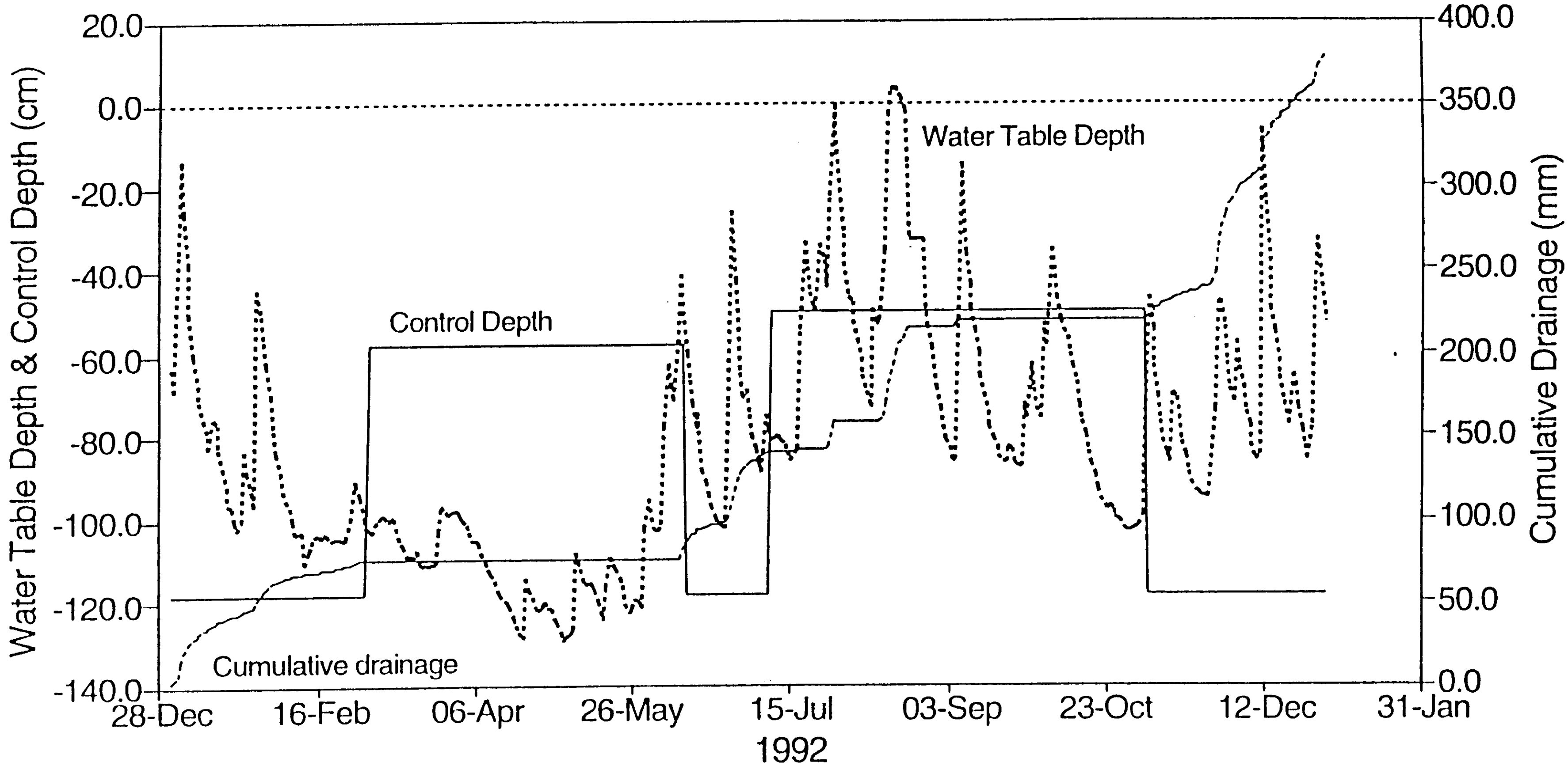

Figure 8. Cumulative subsurface drainage, water table elevation, and water level control for controlled drainage (plot 5) during 1992.

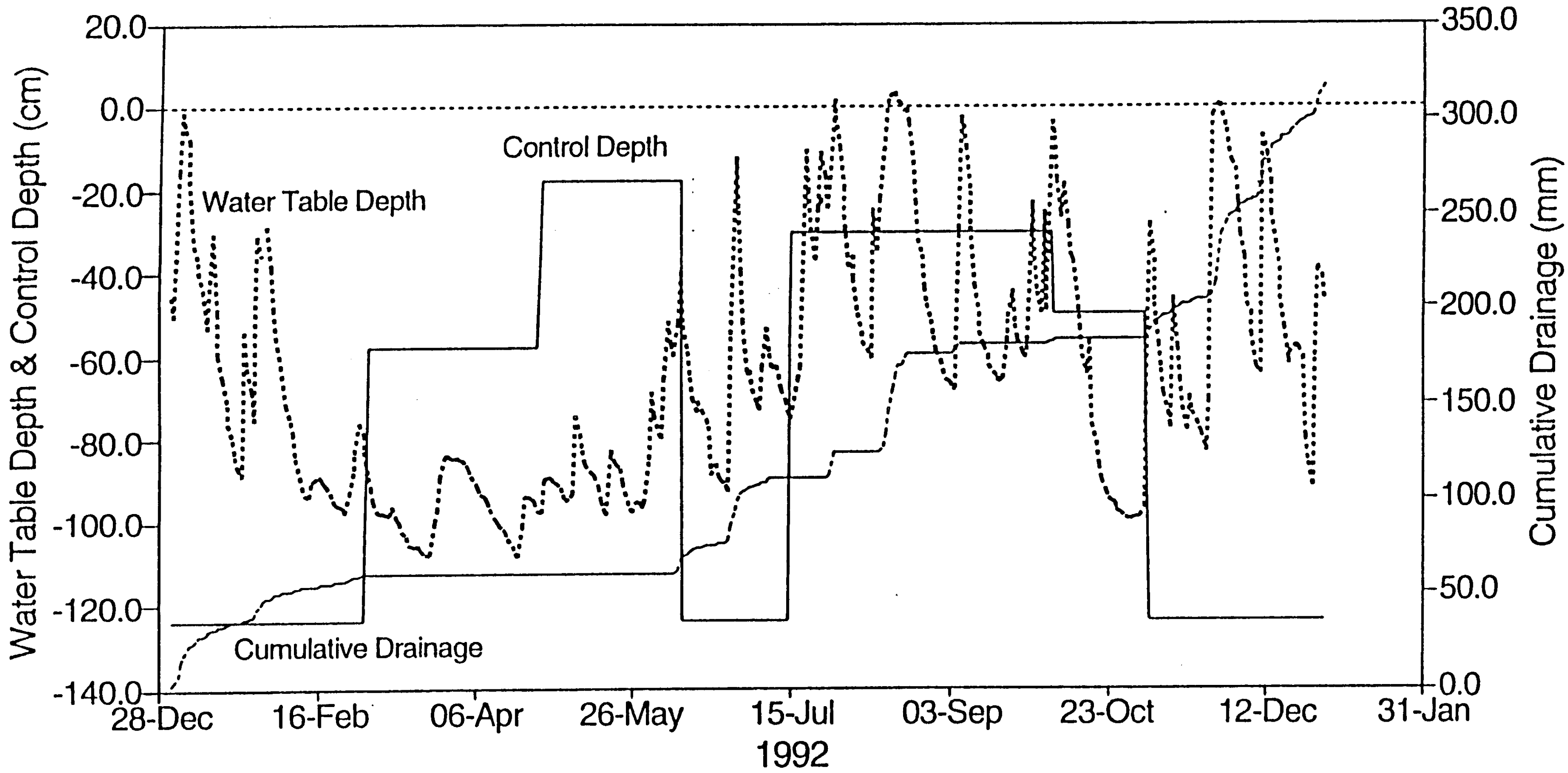

Figure 9. Cumulative subsurface drainage, water table elevation, and water level control for subirrigation (plot 6) during 1992.

and drain flow only occurred for 10 days for the time between Jul 9 and Nov 5.

Controlled drainage reduced the subsurface drainage volumes for each year and each growing season of the experiment. Yearly reductions of subsurface drainage ranged from 5% to 16% (Table 2); however, the fields were not in controlled drainage for long periods during the winters (Figures 7-9). Reductions of subsurface drainage volumes during the growing seasons varied greatly ranging from 10% to 84% (Table 3). This variation was due to patterns of rainfall relative to time of control. For example, only a 10% reduction occurred during the 1991-92 wheat season since controlled drainage was used for only the last half of the season when there were small amounts of rainfall to be drained and the water table was near or below the elevation of the drains (Figures 7-9). A 54% reduction occurred during the 1992 soybean growing season since controlled drainage was used for most of the period and and higher rainfall amounts caused the water table to fluctuate above and below the control elevation (Figures 7-9). The 84% reduction occurred during the 1993 corn season when controlled drainage began just after a wet spring and before a very dry summer. The very dry summer of 1993 resulted in very low water tables and total drained volumes less than 3 cm for all treatments.

Reductions of subsurface drainage volumes for subirrigation were greater than the reductions observed for controlled drainage. This was due to the higher weir levels used for subirrigation. Yearly reductions of subsurface drainage by subirrigation ranged from 23% to 37% (Table 2). Reductions of subsurface drainage volumes during the growing seasons varied greatly ranging from 30 to 92 % (Table 3). As for controlled drainage, the greatest reduction occurred during the very dry 1993 corn growing season and the lowest reduction occurred during the 1992 soybean season when subirrigation was used for only part of the season.

Higher subsurface drainage rates observed in conventional drainage resulted in lower water table elevations when compared to controlled drainage (Figure 10). The water table elevations during subirrgation were higher than for controlled drainage since water was being pumped into the drain lines. Higher water table elevations will likely increase evapotranspiration; however, higher water table elevations will also increase surface runoff. The surface runoff volumes for 1992 were: 8.7 cm for conventional drainage, 10.8 cm for controlled drainage, and 19.1 cm for subirrigation (Table 2). Surface runoff volumes for 1993 were: 4.9 cm for conventional drainage, 6.9 cm for controlled drainage, and 10.4 cm for subirrigation.

Controlled drainage reduced the total drainage volume (subsurface drainage plus surface runoff) by 9% for 1992 and did not reduce total drainage for 1993. The observation of no reduction for 1993 even though a 84% reduction was observed for the 1993 corn season was not surprising since the very dry conditions during

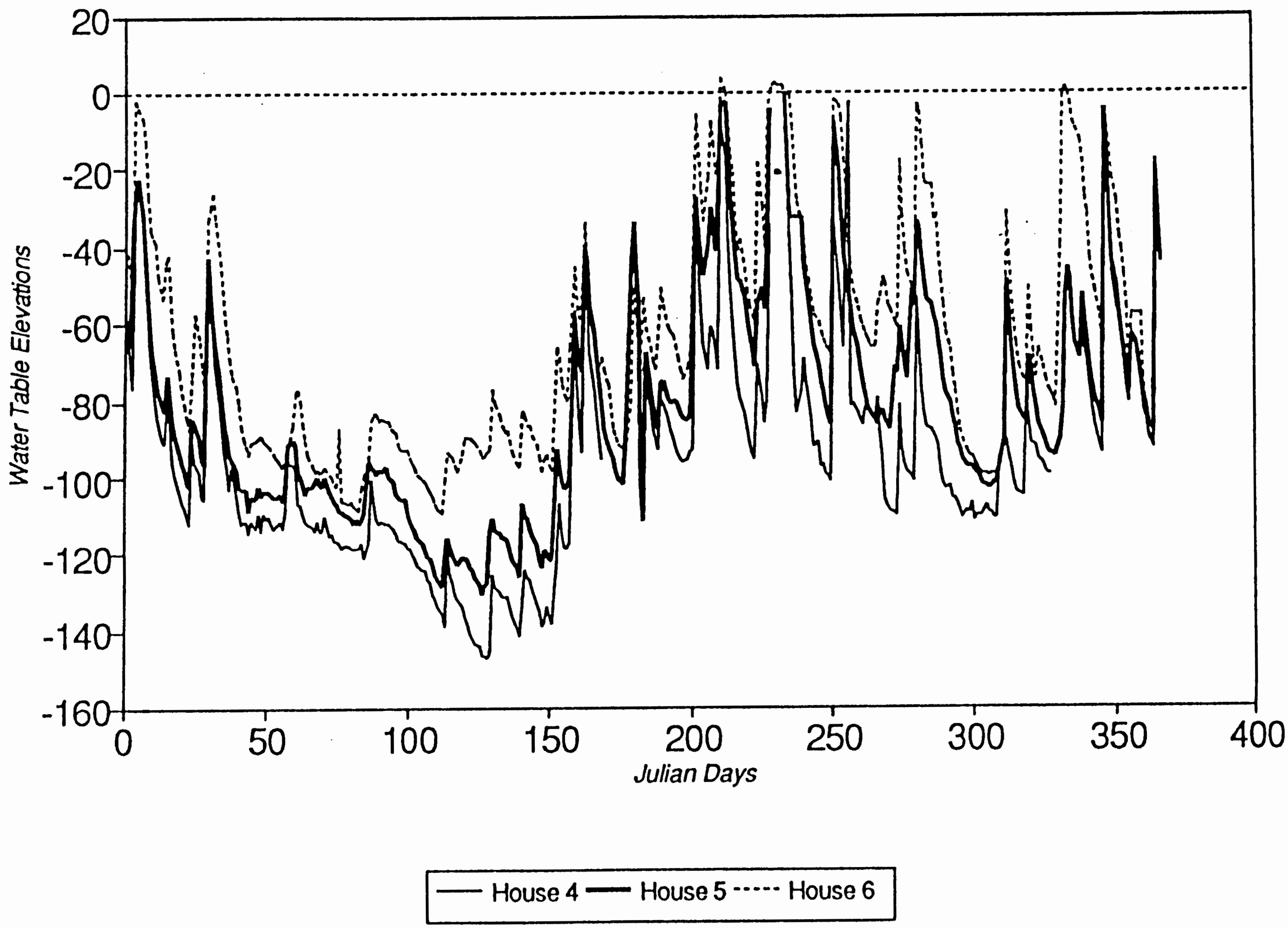

Figure 10. Water table elevations for conventional drainage (house 4), controlled drainage (house 5), and subirrigation (house 6) during 1992.

the controlled drainage period resulted in extremely low drainage volumes. Note also that the 1993 data in Table 2 were only for the first 9.5 months of the year. The experimental design for water management changed for the last 2.5 months of 1993.

Subirrigation did not significantly change the total drainage volume for 1992 or 1993 when compared to free drainage. Total drainage volume for 1992 was more than that of controlled drainage due to the addition of irrigation water to the system. While more irrigation water was added to the subirrigation plots in 1993, the very dry conditions during the corn growing season caused nearly all of the added water to be removed by ET.

<u>Crop Yields</u>. Corn, soybean and wheat yields are summarized by water management treatment in Table 4 for the period 1990 to 1994. Controlled drainage significantly increased corn yields at the 5 percent level of significance (LSD = 475 kg/ha) compared to free drainage in both 1991 and 1993. Subirrigation significantly increased corn yields compared to both controlled and free drainage treatments. Yields were significantly lower in 1993, a dry year, than in 1991 on all three water management treatments (LSD = 387 kg/ha).

Controlled drainage significantly increased soybean yields (LSD = 162 kg/ha) compared to free drainage, but there was no significant difference between subirrigation and either controlled or free drainage. Wheat yields were not significantly

Table 4 Corn, wheat, and soybean yield as influenced by water table management[+].

Crop	Year	Free Drainage	Controlled Drainage	Subirrigation
		kg/ha		
Corn	1991	6513.5	6908.7	7426.0
	1993	3728.7	4512.7	5019.2
	Mean[#]	5121.1 a	5710.6 b	6222.6 c
Wheat	1990	2815.0	2860.7	2539.2
	1992	4934.2	4898.9	5172.5
	1994[*]	4268.9	3185.3	3324.8
	Mean[#]	4244.5 a	3805.8 a	3894.7 a
Soybean	1990	2563.7	3087.9	2906.4
	1992	2859.4	3022.3	2923.2
	Mean[#]	2760.8 a	3044.2 b	2917.6 ab

[*]Only one replication of each treatment received nitrogen fertilizer. Fertilized plot yields were approximately 2 times higher than unfertilized plots.
[+]Values are means of two replications with 2 subplot samples measured for each replication.
[#]Means followed by the same letter are not significantly different

affected at the 5 percent level (LSD = 864) by the water management treatments although free drainage average yields were approximately 10 percent higher than either controlled drainage or subirrigation. Mean yields in 1990 and 1994 were significantly lower than in 1992. Mean yields reported for 1994 include both fertilized and unfertilized treatments.

Nitrogen in Subsurface Drainage Water. Nitrogen analyzed in the subsurface drainage water included nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), and total Kjeldahl nitrogen (TKN). Total nitrogen concentration in the drainage water was obtained by summing NO_3-N and TKN. Organic N was obtained by difference between TKN and NH_4-N. Yearly average (2 replications) cumulative nitrogen losses through subsurface drainage under various water management practices during 1991, 1992 and 1993 are shown in Table 5. Due to the change of water management practices after September of 1993, the amount of cumulative nitrogen loss shown in Table 5 for 1993 included only the loss from January of 1993 to September of 1993.

The data in Table 5 show the range of values for the various forms of N lost during free drainage (no water management) over a three year period. The total annual loss of N through subsurface drainage ranged from 10 to 34 kg/ha. The larger value occurred during 1991 when corn was the crop and the year had near average rainfall. The lower value occurred during 1992 when wheat was in the field during the winter and spring and soybeans followed wheat. The spring provided near ideal growing conditions for wheat with adequate but not excessive rainfall and a very high yield was obtained (Table 4). Because of this high yield, over 100 kg/ha of N was harvested in the grain. This left little N to be lost to drainage water. Since no fertilizer N was applied to the soybean crop which followed, the 10 kg N/ha loss recorded during 1992 probably represents a minimum for a cropped field in this region. It can be observed from the data in Table 5 that NO_3-N is the major form of N lost in subsurface drainage water. There are small and rather consistent losses of NH_4-N and organic N but the loss of these forms is small compared to loss of NO_3-N.

The objective in this project was not to determine the annual effect of water management on nitrogen losses to drainage water, but to develop methods for predicting the cumulative effects of water management, fertility practices, etc on N loss. Thus the water was not managed throughout a calendar year to minimize N loss. For example, drainage control was not used in the winters of 1991-92 or 1992-93 because we were either installing new drain lines or obtaining more accurate data on flow rates from each of the plots during free drainage. We know from our many years of previous data that the winter is the most important time for drainage control to minimize N losses to drainage water. Therefore the annual N losses shown in Table 5 do not accurately reflect the potential reduction in N losses which can be achieved by either controlled drainage alone or controlled drainage plus

Table 5. Yearly cumulative nitrogen loss through subsurface drainage under various water table management practices. * SI & CD in the table represents subirrigation and controlled drainage. CD in the table represents controlled drainage. Conventional drainage is represented by FD in the table.

1991					
	Total N	NO_3^-	NH_4^+	TKN	Organic N
	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)
SI* & CD*	16.2	13.8	0.4	2.4	2.0
CD	28.0	24.7	0.2	3.3	3.1
FD*	34.3	31.1	0.1	3.2	3.0
1992					
	Total N	NO_3^-	NH_4^+	TKN	Organic N
	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)
SI & CD	5.8	2.7	0.8	3.1	2.3
CD	9.2	6.7	0.6	2.5	1.9
FD	10.9	8.3	0.4	2.7	2.2
1993					
	Total N	NO_3^-	NH_4^+	TKN	Organic N
	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)
SI & CD	5.1	2.4	0.7	2.7	2.0
CD	12.7	10.1	0.6	2.6	2.0
FD	14.9	12.3	0.3	2.6	2.2

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subirrigation. This effect can best be determined by looking at selected time periods (less than a year but for several months) when all water management treatments were being imposed in the experiment.

The most interesting and important period showing effects of water management on N losses in subsurface drainage occurred during the winter and spring of 1993-94. This period followed a dry summer when corn yields were considerably below normal (Table 4). Because of the low corn yields during 1993, the amount of N harvested in the crop was also below normal. This low harvest of

Table 6. Effect of drainage control and fertilizer N on losses of NO_3-N in subsurface drainage during wheat growing season of 1993-94 (From 9/14/93 to 6/18/94).

	TREATMENT			
	Free Drainage		Controlled Drainage	
	N Added⁺	No N Added⁺	N Added⁺	No N Added⁺
N lost (kg/ha)	47.3(C)*	33.6(F) 54.4(SI)	36.3(F)	27.8(C) 5.8(SI)

Averages

Free drainage	- 45.1	Controlled Drainage	- 23.3
Fertilizer N	- 41.8	No sidedness N	30.4

⁺ All plots received 21 kg N/ ha at planting (11/12/93)and plots indicated by N added received 81 kg N as a sidedness application (3/22/94).

* Letters refer to water management treatment on plot during the previous corn crop. F is free drainage, C is controlled drainage and SI is subirrigation and controlled drainage.

N by the crop meant that more N was potentially available for loss through the drainage system during the winter. This worst case situation with regard to N loss offered a best case situation with regard to use of water and fertility management to minimize N losses. Because of this opportunity, we changed our management strategy for the field during the wheat growing season of 1993-94. The treatments consisted of free and controlled drainage and N and no N fertilizer added as a spring sidedress application with two replications of each treatment. We had measurement problems with drainage water on two treatments but the results obtained on the six remaining plots were extremely valuable for understanding the interaction of fertilizer and water management on N losses to the environment.

The data in Table 6 show that the average reduction in NO_3-N lost for controlled drainage across all fertility treatments during the wheat growing season was 23.3 kg/ha or a 48% reduction over free drainage. The average reduction for no sidedress N application was 11.4 kg N/ha for a 28% reduction compared to plots receiving N sidedress. There were not sufficient plots to sort out the interaction between water and N sidedress application. However, it is apparent that controlled drainage was much more effective in reducing N loss in the drainage water than not applying N fertilizer. Also, there was a tremendous difference between the two treatments in effects on wheat yield. Controlled drainage had no measurable effect on wheat yields compared to free drainage, but the plots receiving no sidedress N yielded 56% less than fertilized plots. Thus controlled drainage was more effective in reducing N loss and is a much more attractive management option for the producer. Because of the large reduction in yield on the plots not receiving sidedress N, this would be a management option only when the primary consideration was reduction of entry of N into surface water with potential profit from the crop being relatively unimportant.

The water management treatment imposed during the previous corn crop also had an apparent effect on N lost during the wheat crop. In both the controlled drainage and uncontrolled drainage treatments during the wheat crop, the plot which lost the most N was the one which had been in free drainage during the previous corn crop. The plots which lost the least N during the wheat season were those that had been in subirrigation and controlled drainage for the previous corn crop. It is believed that this difference is a result of the differences in amount of N harvested in the corn crop, the effect of water management on the amount of N mineralized and the level of N management. The average N harvested in the corn crop in the free drainage, controlled drainage and subirrigation-controlled drainage plots were 61, 73 and 75 kg N per ha, respectively. Thus the free drainage plots contained more residual N for leaching during the growth of the following crop.

The water management treatments were also imposed during the growing seasons of 1991-93. These periods are not the most important for controlling loss of N to surface waters because losses during the growing season are generally small compared to the winter. However the total average losses during the growing seasons from the corn crop in 1991 through the corn crop in 1993 was 18.3, 12.6 and 6.3 kg NO_3-N per ha for the free drainage, controlled drainage and subirrigation treatments, respectively. Thus the reduction for controlled drainage during this period was 31% while subirrigation reduced the losses by 66%.

<u>Nitrogen in groundwater</u>. The presence of excessive nitrate (> 10mg/L of NO_3-N) in groundwater is a problem in most of the world where grain crops are grown. We obviously have nitrate moving to shallow groundwater in our experimental field because it moves into surface waters via the subsurface drainage system. One of the objectives of our research program has been to determine the effect of water management on concentration of mineral N (usually NO_3-N) at various depths in the soil profile. This concentration is influenced by several factors including fertilization, mineralization and denitrification. The amount of fertilizer N added is known, and one M.S. thesis (Kimmelshue, 1992) has been completed on the effect of water management on mineralization and another M.S. thesis (Kliewer, 1994) on the effect of water management on denitrification. These studies are very valuable for prediction of the concentrations of NO_3-N in shallow groundwater. The abstracts of these studies are included in Appendix 2 of this report.

Although NO_3-N certainly moves into the shallow groundwater at this site, there is essentially no nitrate which moves to deeper ground water. Figures 11-13 show NO_3-N concentration in the soil before and after fertilization of the corn crop in 1993. These data show that regardless of the water management treatment, nitrate concentrations decrease with depth in the soil profile. Figures 14-16 show NO_3-N concentrations in shallow groundwater wells during the 1991 corn growing season. These data show that concentrations are variable above the 1.2 m depth but all nitrate has been lost from the percolating water by the time it reaches the 1.8 m depth. All previous information and the data in Kliewer's thesis indicate that the reduction in concentration is a result of denitrification. Because of the reduced conditions present in the groundwater below a depth of 1-2 m, there is essentially no possibility of nitrate contamination of deeper groundwater below naturally poorly drained soils similar to those on this experimental field.

<u>Metolachlor in the groundwater and drainage water</u>. Soil samples collected from the field and water samples collected from shallow groundwater wells and from surface and subsurface drainage water were analyzed from 1990 to 1993. The results for the first two years of the study are reported in the first report of this series. The results for 1992 and 1993 are reported below.

Soil samples were collected prior to spraying and at 0, 7, 14, 28, 56 and 112 days after application in 1992. Initial samples were collected at two depths, 0 to 15.2 and 15.2 to 30.5 cm by taking 20, 2.5 cm diam. cores. The average background of metolachlor was 0.07 ppm. For the remaining sampling data only the 0 to 15.2 cm. depth were analyzed. Average soil concentrations at 0, 7, 14, 28, 56 and 112 days after application were 1.56, 1.43, 1.42, 0.74, 0.48 and 0.30 ppm, respectively at a low detectable level of 0.01 ppm. Six surface water samples were to be collected 24 to 30 h after rainfalls of 2.5 cm or greater. The 1992 season was particularly dry and only 4 collections were made, 21, 30, 46 and 50 days after application. Residue levels of metolachlor in the first two sampling periods ranged from <0.01 to 0.27 ppb. All of the third and fourth samples had residues less than the low detectable level of 0.01 ppb.

Residues of metolachlor were detected in most tile drainage samples from the first three weekly samplings after applications and averaged 0.11, 0.06 and 0.01 ppb, respectively. There was neither field irrigation nor significant rainfall during this time period.

Well water samples were taken every 14 days after application or within two days following a significant rainfall. The first two samples from well depths of 61 to 579 cm generally found metolachlor at concentrations ranging from 0.01 to 0.12 ppb. No residue level > 0.01 ppb was found in any subsequent sampling.

Soils collected prior to application in 1993 contained average residue levels of atrazine of 0.43 and 0.29 ppm at soil depths of 0 to 15.2 and 15.2 to 30.5 cm, respectively. Concentrations of

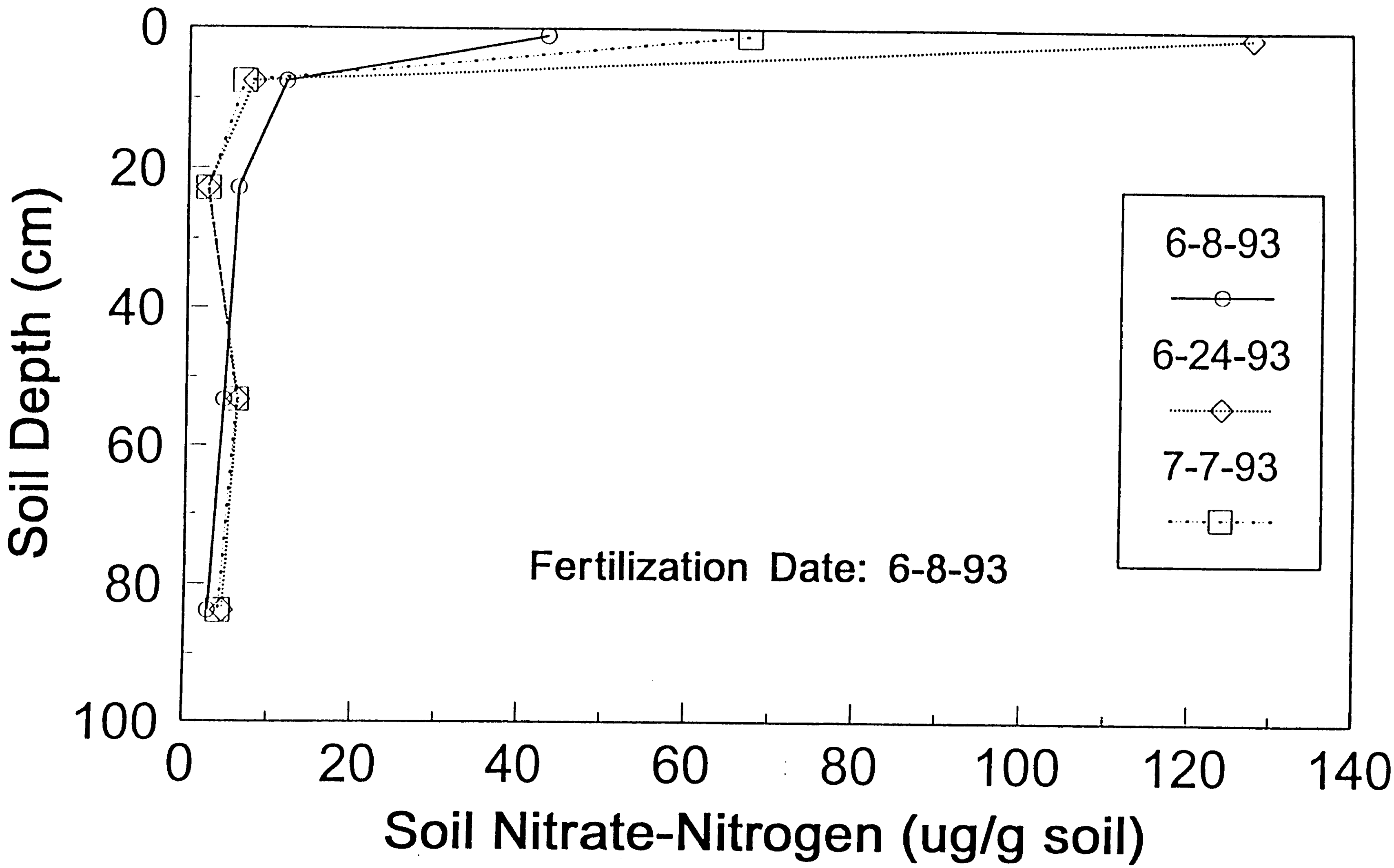

Figure 11. Nitrate distribution in the soil profile before and after fertilization of the corn crop with conventional drainage in 1993

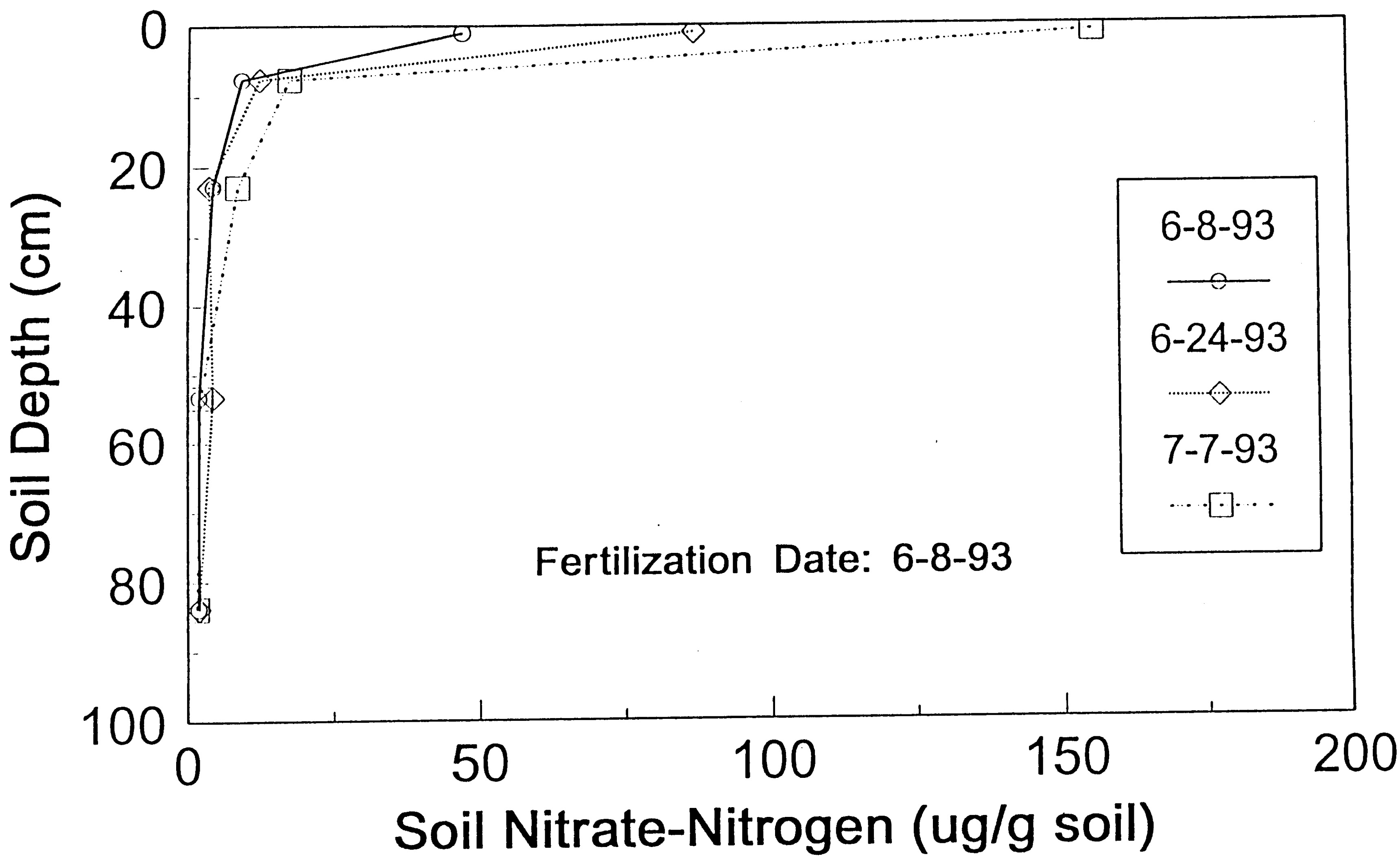

Figure 12. Nitrate distribution in the soil profile before and after fertilization of the corn crop with controlled drainage in 1993

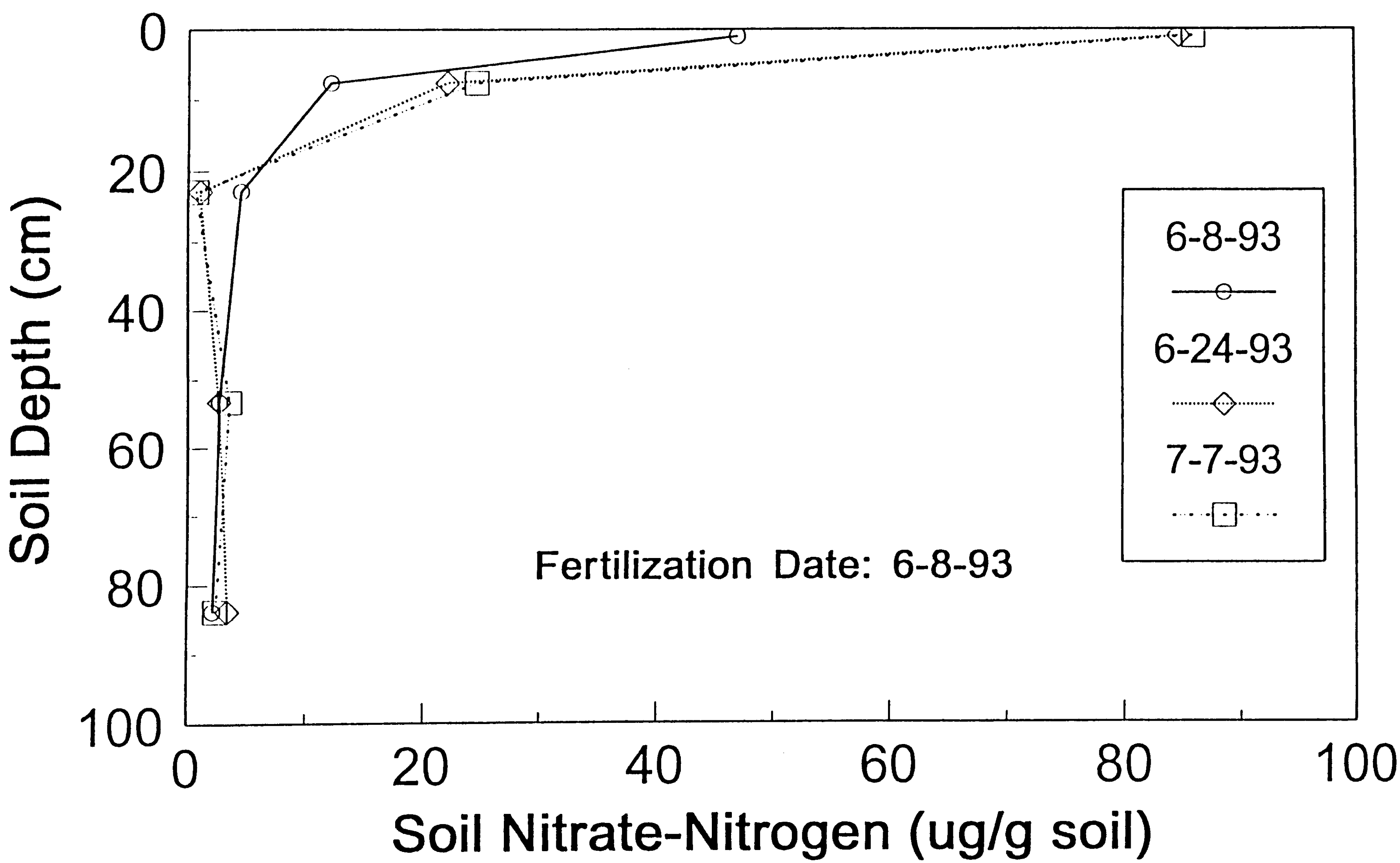

Figure 13. Nitrate distribution in the soil profile before and after fertilization of the corn crop with subirrigation in 1993

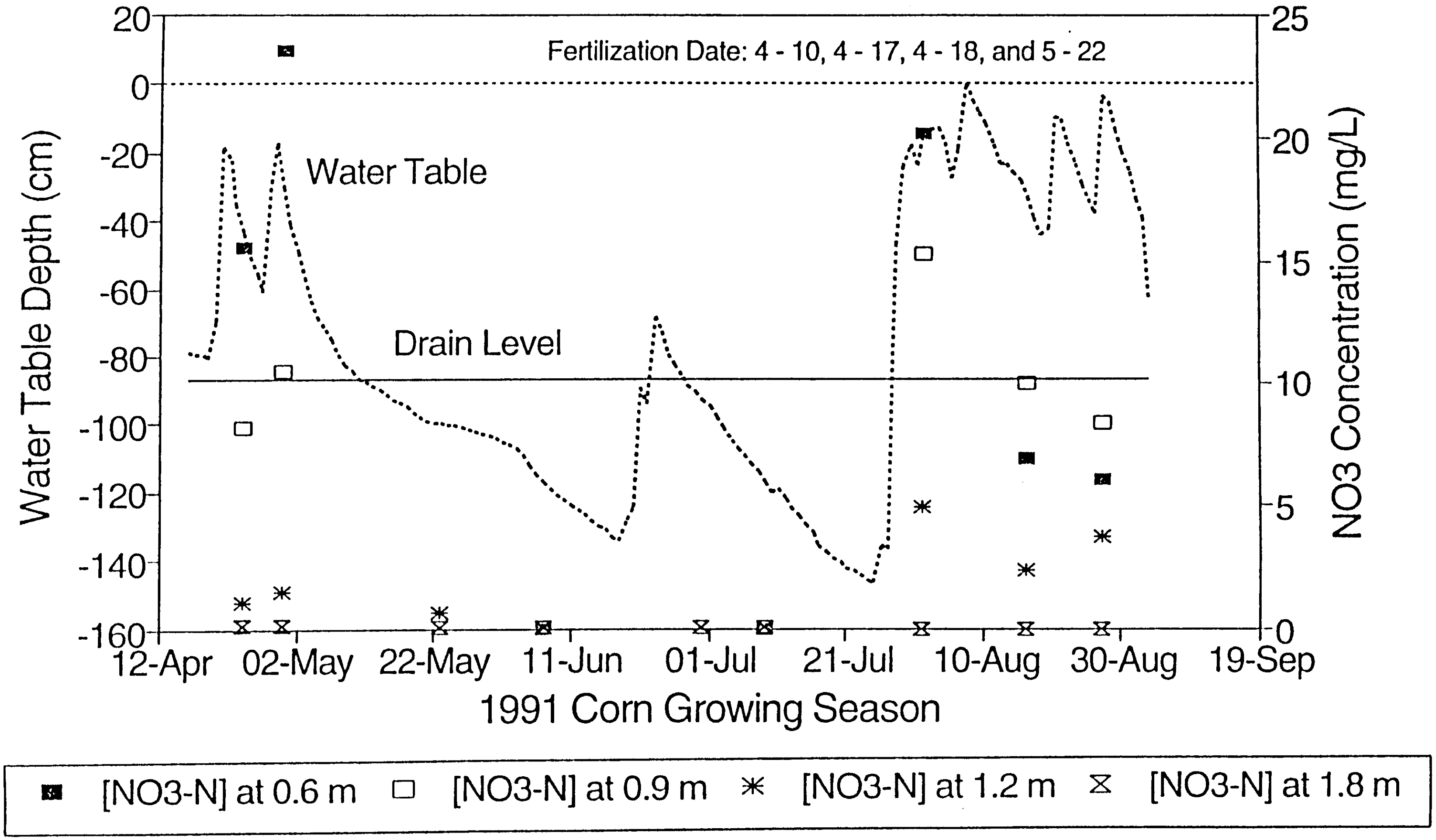

Figure 14. Nitrate concentrations in shallow groundwater wells during the 1991 corn growing season with conventional drainage

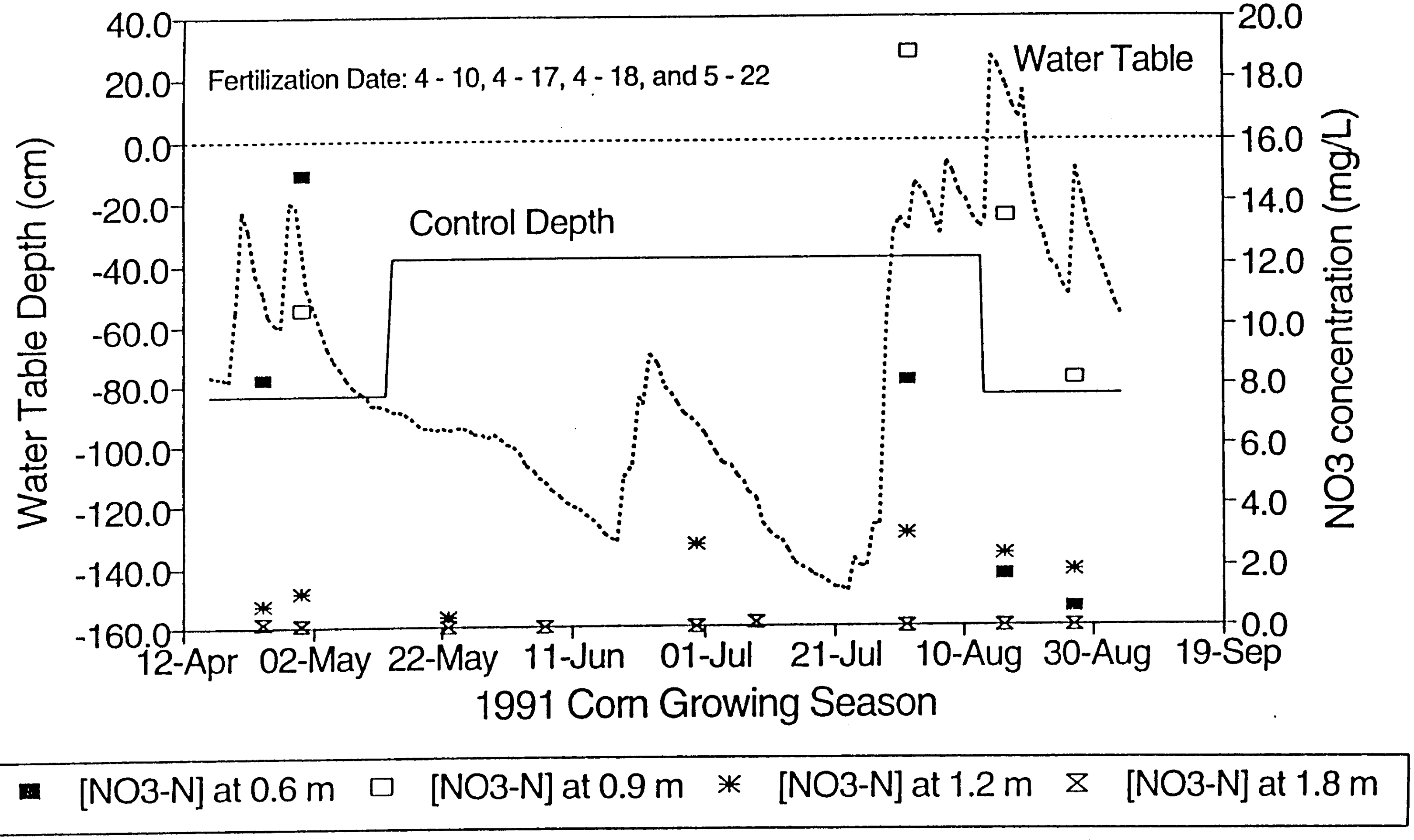

Figure 15. Nitrate concentrations in shallow groundwater wells during the 1991 corn growing season with controlled drainage

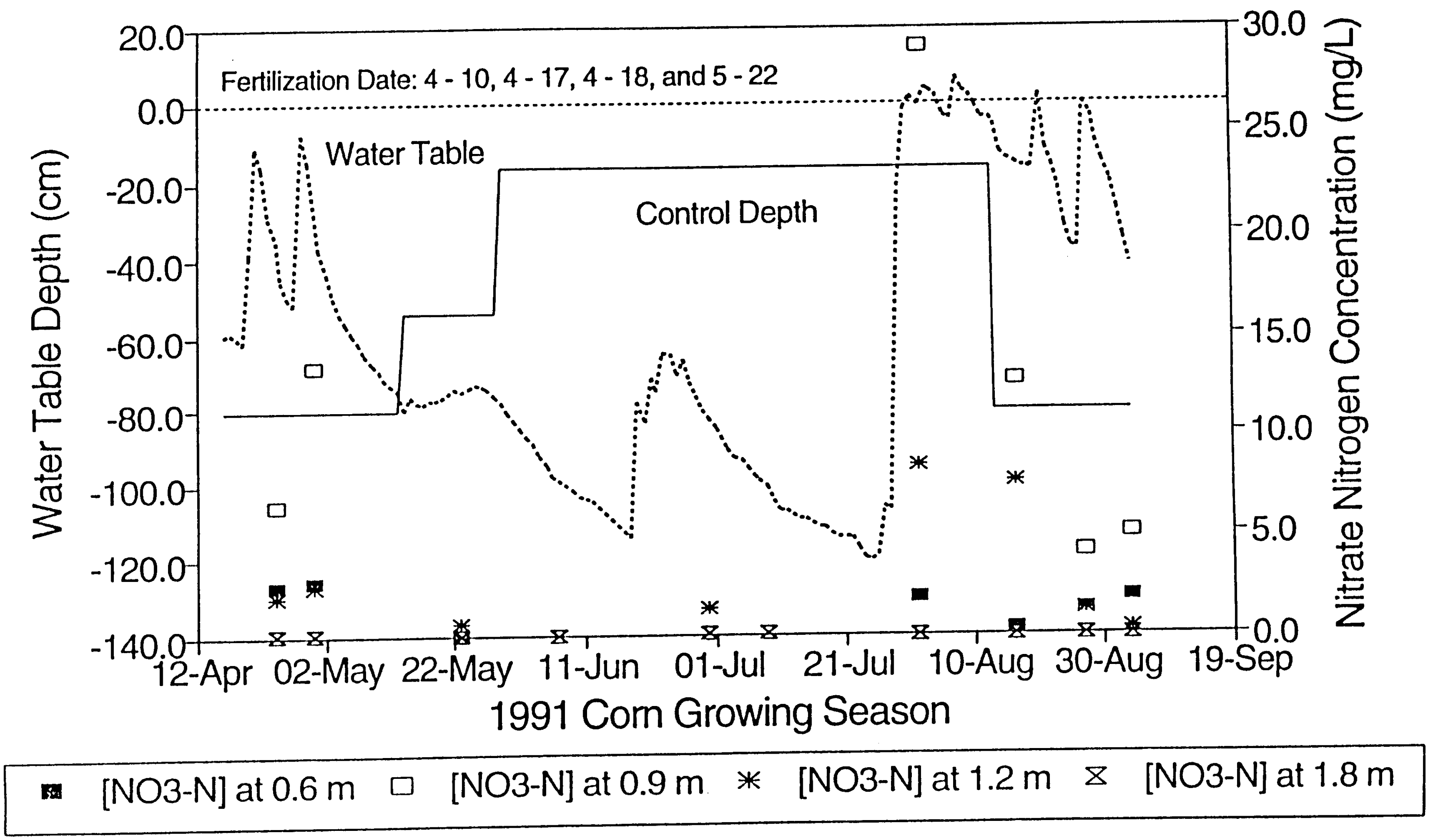

Figure 16. Nitrate concentrations in shallow groundwater wells during the 1991 corn growing season with subirrigation.

metolachlor from the same sample depths averaged 1.44 and 1.08 ppm, respectively. Average concentrations of atrazine in soils sampled at 7, 14, 28, 56 and 112 days after application were 1.21, 1.12, 1.10, 0.64 and 0.45 ppm, respectively. Plots receiving the 3.4 kg/ha a.i. rate of metolachlor averaged 8.07, 4.10, 4.59, 4.15 and 1.21 ppm at 7, 14, 28, 56, and 112 days, respectively, where residue levels from plots receiving 6.8 kg/ha a.i. were 7.94, 5.92, 4.40, 3.35 and 1.11 ppm. Although the filter paper indicated that twice as much metolachlor was applied to 4 of 7 plots, the data do not show twice the residue level. We have no good explanation for this as residue levels among replications were consistent. Due to a dry season, surface run off samples were collected only once. This sampling occurred at ca. 42 days after application when greater than 2.5 cm of rain were recorded. The atrazine and metolachlor residue levels, if present, were below the detection limit of 0.01 ppb from all plots.

Residues of atrazine and metolachlor were detected in the drainage samples from the first three weekly collections after application. Average concentration of atrazine were 0.16, 0.01 and 0.02 ppb, respectively. Samples from plots receiving metolachlor at 3.4 kg/ha a.i. averaged 0.16, 0.02 and 0.09 ppm at 1, 2 and 3 weeks after application, respectively. Average levels of metolachlor from plots receiving 6.8 kg/ha averaged 0.32, 0.31 and 0.31 ppm 1, 2 and 3 weeks after application, respectively.

Because of the dry season measurable levels of atrazine and metolachlor were found in well water only in the first three collections, 1, 2 and 4 weeks after application. Residue levels of atrazine from all well depths averaged 0.31 ppb and ranged from 0.01 to 1.09 ppb. Highest levels were found in the 122-, 183-, 244- and 305-cm deep wells. No residue level of atrazine was found above the detectable level of 0.01 ppb in the 457- and 579-cm deep wells. Concentration of metolachlor from all plots ranged from 0.01 to 1.87 ppb and averaged 0.42 ppb. Highest levels were found in the 122-, 183- and 244- cm deep wells, and although only levels of 0.01 ppb were found in the 457- and 579-cm deep wells at 1 and 4 wk. after application, measureable levels averaged 0.74 and 0.39 ppb in samples collected from these wells at 2 wks.

In general, residue levels of metolachlor, applied at 3.4 kg/ha a.i. were higher in both soil and water samples collected in 1993. It is possible that the cover crop of corn had some effect on herbicide movement compared to soybeans planted in 1992. In addition, the organic matter content difference between wheat and soybean stubble might have influenced movement into water and soil residue levels.

Aldicarb in the groundwater and drainage water. Aldicarb dissipated from the soil in all three treatments by 61 days after application. Most of the aldicarb detected in the soil was found at depths between 0.00 to 0.15 m. Aldicarb was detected in the soil at a maximum depth of 0.46 m.

In each treatment, the aldicarb concentrations in well water at the midpoint between the drains were consistently higher than in well water near the drain. For the subirrigation plot, this is due to a combination of dilution due to subirrigation water and aldicarb transport from near the drain with tile outflow when there was drainage. For the controlled drainage and conventional drainage plots, aldicarb transport in the vicinity of the drain with tile outflow is the sole cause. Aldicarb was not consistently detected in the well water samples past 61 days after application.

The conventional drainage plot produced the largest volume of drain outflow with the highest aldicarb concentrations. This combination resulted in conventional drainage having the highest percentage of aldicarb lost from tile outflow (0.02% of applied), followed by controlled drainage (0.01% of applied), and then subirrigation (0.001% of applied). However, the amount of aldicarb lost through the subsurface drains for all three management modes is extremely small. Aldicarb was not detected in the tile outflow after Julian day 225, 47 days after application.

Aldicarb concentrations in the surface runoff were similar in all three plots. However the volume of surface runoff was highest for the subirrigation plot and lowest for the conventional drainage plot. The subirrigation plot maintained the highest water table while the conventional drainage plot had the lowest water table. Therefore, the soil profile in subirrigation had the least amount of storage for infiltration and the soil profile in conventional drainage had the most storage. Accordingly, more aldicarb was lost in the subirrigation mode (0.06% of applied)than in the controlled drainage (0.04% of applied) or conventional drainage (0.02% of applied) modes. Although the amount of aldicarb lost through surface runoff was higher than tile outflow, the total percentage of aldicarb lost through surface runoff is extremely low. Aldicarb was not detected in the surface runoff after Julian day 239, 61 days after application.

Aldicarb degraded quickly in each plot. Calculations based on a mass balance for aldicarb resulted in an estimated half life of 11.5 days. The information summarized above is given in more detail in the Section 5 of this report.

DRAINMOD-N, A NITROGEN MODEL FOR ARTIFICIALLY DRAINED SOILS: DEVELOPMENT *

The movement of agricultural chemicals in soils is a major public concern because of potential contamination of surface and ground water. Pollutant outflows from shallow water table soils with improved drainage are increasingly perceived as a major contributor to the degradation of surface waters (Gilliam and Skaggs, 1986; Gilliam, 1987; Hubbard et al., 1991; Evans et al., 1992; Thomas et al., 1992). However, extensive research has shown that the water quality effects of improved drainage are complex and cannot be stated clearly (Skaggs et al., 1994). They can be positive or negative, depending on factors such as conditions prior to drainage improvements, design and management of drainage systems, cultural practices, soil type, solute type, and climate (Skaggs et al., 1994).

Computer simulation models are useful to evaluate the effects of agricultural practices on the movement and fate of nutrients and pesticides. Although many simulation models are available, only a few adequately incorporate the effects of improved drainage on pollutant transport and fate. Coupling *DRAINMOD* (Skaggs, 1978), a model that simulates the hydrology of shallow water table soils, with *CREAMS* (Knisel, 1980) or *GLEAMS* (Leonard et al., 1987), two water quality models, is a common approach used to consider the effects of artificial drainage on water quality (Skaggs et al., 1982; Parsons and Skaggs, 1988; Parsons et al., 1989; Chung et al., 1991, 1992; Saleh, 1992; Singh et al., 1992; Wright et al., 1992).

An alternative approach is developed in this paper. Algorithms to compute the movement and fate of solutes were added to *DRAINMOD*. They make use of recent modifications in *DRAINMOD* to compute soil-water fluxes (Skaggs et al., 1991) and are most applicable for mobile constituents such as nitrogen. The objective of this paper is to describe *DRAINMOD-N*, a quasi two-dimensional model that simulates the movement and fate of nitrogen in shallow water table soils with artificial drainage; model predictions are compared to those of a more complex, two-dimensional nitrogen model.

MODEL DESCRIPTION

DRAINMOD-N was developed to simulate a simplified version of the nitrogen cycle. Nitrate-nitrogen is the main N pool considered.

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* The following chapters on *DRAINMOD-N* were taken (with minor editing) from the Ph.D. dissertation by M.A. Brevé entitled "Modeling the movement and fate of nitrogen in artificially drained soils". The work was directed by R. W. Skaggs and J. E. Parsons. J. W. Gilliam assisted in developing methods to describe chemical reactions and transformations and the analysis of water quality data. G. M. Chescheir, R. O. Evans, and A. T. Mohammad assisted with collection and analysis of the field data.

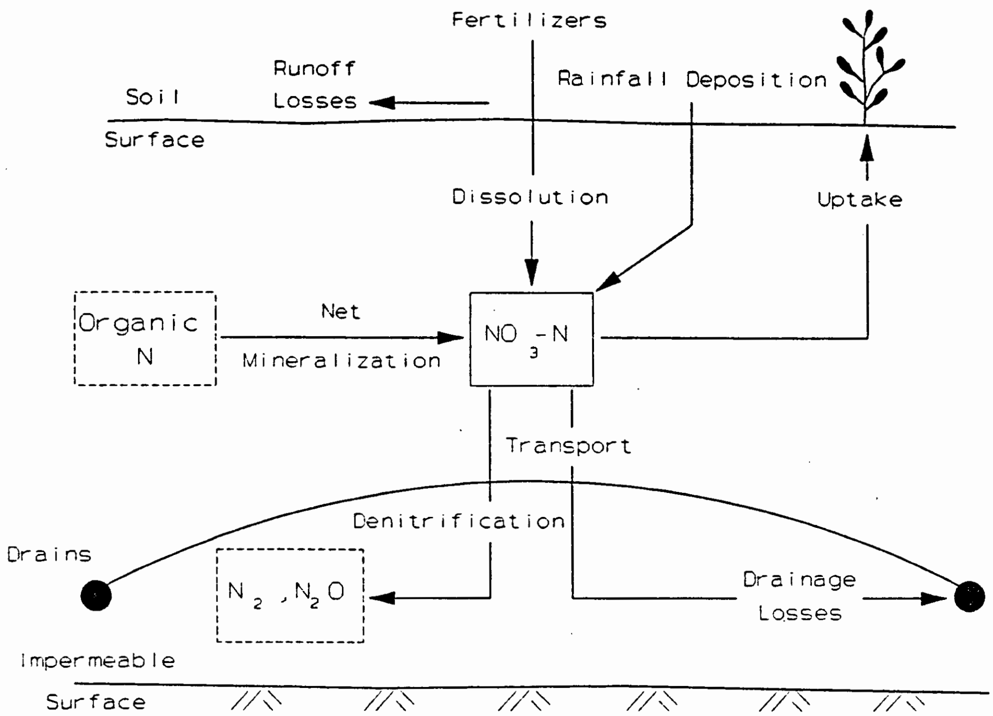


Figure 17. Nitrogen cycle considered in *DRAINMOD-N*.

The ammonium-nitrogen pool is ignored because in most soils ammonium nitrifies quickly or stays fixed to the soil; thus ammonium losses in subsurface drainage can be neglected. The controlling processes considered by the model are rainfall deposition, fertilizer dissolution, net mineralization of organic nitrogen, denitrification, plant uptake, and runoff and drainage losses (Fig. 17).

The nitrogen cycle shown in Figure 17 can be represented by the advective-dispersive-reactive (*ADR*) equation:

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial C}{\partial z}\right) - \frac{\partial(qC)}{\partial z} + \Gamma \tag{1}$$

where C is the NO_3-N concentration [M L^{-3}], θ is the volumetric water content [L^3 L^{-3}], q is the vertical water flux [L T^{-1}], D is the coefficient of hydrodynamic dispersion [L^2 T^{-1}], Γ is a source/sink term [M L^{-3} T^{-1}], used to represent additional processes (plant uptake, transformations, etc.), z is the coordinate direction along the flow path [L], and t is the time [T].

The coefficient of hydrodynamic dispersion is defined as follows:

$$D = \lambda \left|\frac{q}{\theta}\right| + \tau D^* \tag{2}$$

where λ is dispersivity [L], τ is a dimensionless tortuosity factor, and D^* is the molecular diffusion coefficient [L^2 M^{-1}] Assuming z is positive in the downward direction and water flows downward in the soil profile, Equation 1 may be approximated as follows:

$$C_i^{l+1} = \frac{C_i^l \theta_i^l}{\theta_i^{l+1}} + \frac{\theta_{i+1}^l D_{i+1}^{l+1} \left(\dfrac{C_{i+1}^l - C_i^l}{\Delta z}\right) - \theta_i^l D_i^{l+1} \left(\dfrac{C_i^l - C_{i-1}^l}{\Delta z}\right)}{\Delta z} \frac{\Delta t}{\theta_i^{l+1}} + \frac{(q_i^{l+1} C_{i-1}^l - q_{i+1}^{l+1} C_i^l) \Delta t}{\theta_i^{l+1} \Delta z} + \frac{\Gamma \Delta t}{\theta_i^{l+1}} \tag{3}$$

where l and $l+1$ indicate the previous and new time steps, respectively, i corresponds to the layer where the concentration is being estimated, and Δz and Δt are the space and time discretizations, respectively.

As the name implies, *DRAINMOD-N* is based on the water balance calculations of *DRAINMOD*. It uses modifications described by Skaggs et al. (1991) to determine average daily soil water fluxes and water contents by breaking the profile into increments and conducting a water balance for each increment. In the saturated zone, vertical fluxes are linearly decreased from Hoodghout's drainage flux at the depth of the water table to zero at the impermeable layer depth. In addition, a water content profile is generated using soil-water characteristic data, based on the assumption that hydrostatic conditions are prevalent in the profile at the end of the day. This approach for computing fluxes and water contents proved to be reliable for shallow water table soils as indicated by comparisons with numerical solutions to the Richards equation for saturated and unsaturated flow (Skaggs et al., 1991; Kandil et al., 1992; Karvonen and Skaggs, 1993). Since *DRAINMOD* fluxes may be computed at midpoint between the drains or as the average vertical flux in the zone between drains, depending on the drainage algorithm used, the predicted solute concentrations correspond to the same location.

An additional term is added to Equation 3 for the saturated zone to represent lateral mass flow. Equation 3 then becomes:

$$C_i^{l+1} = \frac{C_i^l \theta_i^l}{\theta_i^{l+1}} + \frac{\theta_{i+1}^l D_{i+1}^{l+1} \left(\dfrac{C_{i+1}^l - C_i^l}{\Delta z}\right) - \theta_i^l D_i^{l+1} \left(\dfrac{C_i^l - C_{i-1}^l}{\Delta z}\right)}{\Delta z} \frac{\Delta t}{\theta_i^{l+1}} + \frac{(q_i^{l+1} C_{i-1}^l - q_{i+1}^{l+1} C_i^l - {q_s}_i^{l+1} C_i^l) \Delta t}{\theta_i^{l+1} \Delta z} + \frac{\Gamma \Delta t}{\theta_i^{l+1}} \tag{4}$$

where q_s, the difference between the vertical fluxes entering and leaving the corresponding layer, is the lateral flux going to the drain [L T^{-1}]. Total nitrate-nitrogen losses in subsurface drainage are estimated by adding up the lateral transport from each layer in the saturated zone. An average concentration in drainage water is approximated by dividing the predicted total lateral mass transport by the predicted drainage rate.

The solution for upward flow is similar to Eq. 4, except that the product of $q_i^{l+1}C_{i-1}^{l}$ becomes $q_i^{l+1}C_i^{l}$ and $q_{i+1}^{l+1}C_i^{l}$ becomes $q_{i+1}^{l+1}C_{i+1}^{l}$. In addition, the q_s term vanishes, unless water is flowing from the drains into the soil profile as it sometimes happens for controlled drainage or subirrigation. In that case, the model assumes water flows proportionally into each layer in the saturated zone, with a corresponding concentration.

DRAINMOD-N uses functional relationships to quantify processes other than NO_3-N transport, as follows:

$$\Gamma = \Gamma_{dep} + \Gamma_{fer} + \Gamma_{mnl} - \Gamma_{rnf} - \Gamma_{upt} - \Gamma_{den} \tag{5}$$

where Γ_{dep} stands for rainfall deposition [M L^{-3} T^{-1}], Γ_{fer} for fertilizer dissolution [M L^{-3} T^{-1}], Γ_{mnl} for net mineralization [M L^{-3} T^{-1}], Γ_{rnf} for loss in surface runoff [M L^{-3} T^{-1}], Γ_{upt} for plant uptake [M L^{-3} T^{-1}], and Γ_{den} for denitrification [M L^{-3} T^{-1}].

Fertilizer dissolution is quantified by a zero-order function:

$$\begin{aligned} \Gamma_{fer} &= K_{fer}\,\frac{A_{fer}}{D_{fer}} \\ K_{fer} &= 1\ day^{-1}\quad for\ \theta \geq \theta_{fer} \\ K_{fer} &= 0\ day^{-1}\quad for\ \theta < \theta_{fer} \end{aligned} \tag{6}$$

where K_{fer} is the dissolution constant [T^{-1}], θ_{fer} is a threshold soil-water content [L^3 L^{-3}] below which fertilizer dissolution will not occur [L^3 L^{-3}], D_{fer} is the depth at which the fertilizer is incorporated [L], and A_{fer} is the amount of fertilizer present in D_{fer} [M L^{-2}]. Fertilizer dissolution is controlled by the water content (i.e., fertilizer will dissolve into the soil solution only if the water content is greater than a given value). The threshold water content, θ_{fer}, is fixed to a value equivalent to wilting point plus a fraction (0.25) of the difference between saturation and wilting point.

Net mineralization is also represented by a zero-order term:

$$\Gamma_{mnl} = K_{mnl}\, f_{mnl_\theta}\, f_{temp}\, \rho\, O_n \tag{7}$$

where K_{mnl} is the net mineralization rate coefficient [T^{-1}], $fmnl_\theta$ and $ftemp$ are dimensionless soil-water content and temperature adjustment factors, as defined ahead, ρ is the soil bulk density

[M L^{-3}], and O_n is the concentration of organic nitrogen [M M^{-1}]. Since net mineralization is the net effect of mineralization and ammonium and nitrate immobilization, the rate coefficients for net mineralization are similar to those of mineralization. Values for K_{mn1} range from 0.00003 to 0.008 d^{-1} in the literature (Davidson et al., 1978; Johnsson et al., 1987; Schepers and Mosier, 1991).

The effect of soil type on net mineralization is also reflected in the O_n term, as it represents the amount of organic nitrogen in the soil. O_n is estimated using the following expression by Davidson et al. (1978):

$$O_n = O_{n_{max}} [\exp(-\alpha z)] \tag{8}$$

where On_{max} is the maximum organic nitrogen concentration in the top layer, kept constant in the simulation, and α is an empirical constant (0.02-0.05). The choice of α is based on a best-fit relationship between observed organic nitrogen concentrations in the soil profile and Equation 8.

Denitrification is approximated by a first-order equation, as follows:

$$\begin{aligned} \Gamma_{den} &= K_{den}\, f_{den_\theta}\, f_{temp}\, \theta_i^l\, C_i^l \quad for\, \theta \geq \theta_{den} \\ \Gamma_{den} &= 0 \quad for\ \theta < \theta_{den} \end{aligned} \tag{9}$$

where K_{den} is the denitrification rate coefficient [T^{-1}], θ_{den} is a threshold water content below which denitrification will not occur [L^3 L^{-3}], and $fden_\theta$ and $ftemp$ are dimensionless soil-water content and temperature adjustment factors, as defined ahead. Values for K_{den} range from 0.004 to 1.08 d^{-1} in the literature (Davidson et al., 1978; Johnsson et al., 1987).

Plant uptake is represented by a relationship similar to that presented by Shaffer et al. (1991):

$$\Gamma_{upt} = \frac{Yld\ \%N\ \Delta ft}{Rz} \tag{10}$$

where Yld is the actual crop yield [M L^{-2}], $\%N$ is the percentage of nitrogen present in the crop yield, Rz is the effective rooting depth [L], and Δft is a fractional N-uptake demand [T^{-1}],

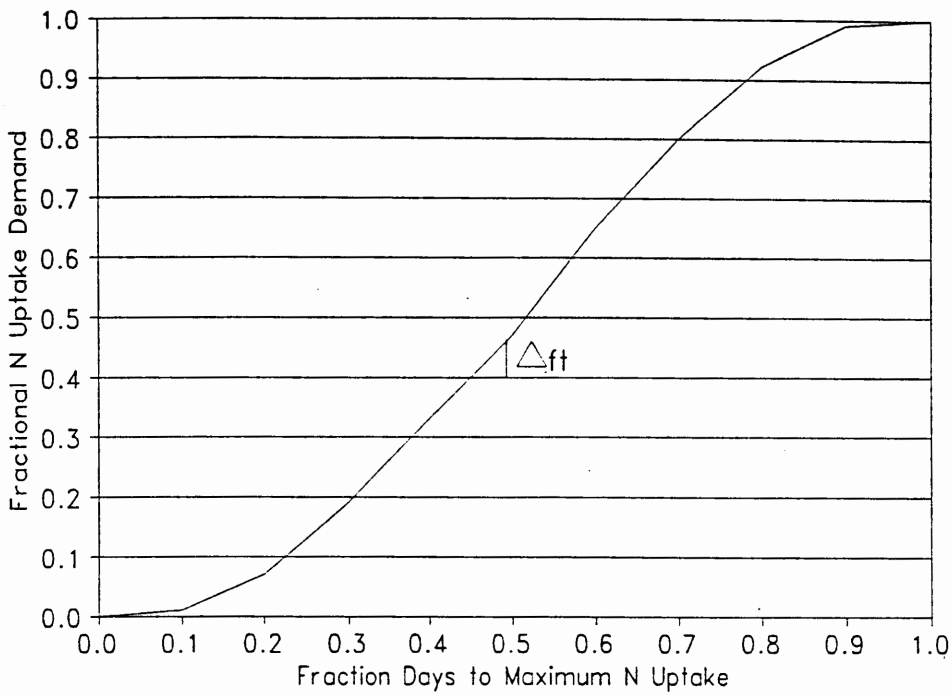


Figure 18. Nitrogen uptake demand versus growing season (Adapted from Shaffer et al., 1991).

given by an N-uptake versus growing season curve presented by Shaffer et al. (1991) and shown in Figure 18.

Runoff loss is quantified with methods similar to those used in *CREAMS* (Knisel, 1980):

$$\Gamma_{rnf} = q_{rnf}^{l+1} \frac{C_{rnf}}{\Delta z}$$

$$C_{rnf} = \frac{(C_f - C_{rain})\,[1 - \exp(-K_2 q_{rnf}^{l+1})]}{K_2 q_{rnf}^{l+1}} + C_{rain}$$

$$C_f = (C_1^l - C_{rain}) \exp(-K_1 f^{l+1}) + C_{rain}$$

$$K_1 = \frac{K_{ext_1}}{\theta_{sat}} \quad , \quad K_2 = \frac{K_{ext_2}}{\theta_{sat}} \tag{11}$$

where C_{rnf} is the mean NO_3-N concentration in runoff [M L^{-3}], q_{rnf} and f are the runoff and infiltration rates [L T^{-1}], respectively, C_{rain} and C_1 are the NO_3-N concentrations in the rain and surface layer [M L^{-3}], $Kext_1$ and $Kext_2$ are the extraction coefficients for infiltration and runoff, and θ_{sat} is the soil-water content at saturation (porosity).

Rainfall deposition to the surface layer is estimated as follows:

$$\Gamma_{dep} = \frac{f^{l+1}\, C_{rain}}{\Delta z} \tag{12}$$

where all terms are as defined previously.

In the case of legumes, *DRAINMOD-N* uses a simple method to account for nitrogen fixation. If the crop NO_3-demand is greater than the NO_3-N available in the soil, the model assumes that the difference is fixed and supplied by the legume (Knisel, 1993).

Soil water content and temperature adjustment factors are used to account for the effect of aerobic or anaerobic conditions and temperature on the different reaction rates. The functional relationships presented by Johnsson et al. (1987) for denitrification and mineralization are adopted in *DRAINMOD-N.* The soil-water content coefficient for denitrification is defined as follows:

$$f_{den_\theta} = \left[\frac{\theta - \theta_{den}}{\theta_{sat} - \theta_{den}}\right]^2 \tag{13}$$

where all terms are as defined previously.

For net mineralization, the soil-water content factor is:

$$\begin{aligned} f_{mnl_\theta} &= 0.6 + 0.4\left[\frac{\theta_{sat} - \theta}{\theta_{sat} - \theta_{high}}\right]^2 && \theta_{high} \le \theta < \theta_{sat} \\ f_{mnl_\theta} &= 1.0 && \theta_{low} \le \theta < \theta_{high} \\ f_{mnl_\theta} &= \left[\frac{\theta - \theta_{wp}}{\theta_{low} - \theta_{wp}}\right]^2 && \theta_{wp} \le \theta < \theta_{low} \end{aligned} \tag{14}$$

where $\boldsymbol{\theta}_{high}$ and $\boldsymbol{\theta}_{low}$ are threshold soil-water contents defining the optimum range for mineralization.

The temperature coefficient, for both denitrification and net mineralization, is also based on a relationship given by Johnsson et al. (1987):

$$f_{temp} = Q_{10}^{\left[\frac{T - t_b}{10}\right]} \tag{15}$$

where Q_{10} is the rate of change associated with a 10°C change in soil temperature, t_b is the base temperature at which f_{temp} is unity [°C], and T is the soil temperature [°C]. Soil temperature can be estimated based on observed soil or air temperature by fitting the following equation, similar to the one presented by Rijtema and Kroes (1991):

$$T = T_a - A_0 \exp(-\frac{z}{D_m}) \cos[\frac{2\pi}{365}(t_j - \phi) - \frac{z}{D_m}] \tag{16}$$

where T_a is the average yearly surface (or air) temperature [°C], A_0 is the amplitude of the temperature wave [°C], D_m is the wave damping depth [L], ϕ is the phase shift [T], t_j is Julian date, and the other terms are as previously defined. The value for A_0 can be computed as the difference between the highest and lowest average monthly surface or air temperatures divided by two and ϕ can be taken as 16 d. Field data has shown that common values for D_m in North Carolina are within 2 m.

Because the overall algorithm used in *DRAINMOD-N* is an explicit solution to the *ADR* equation, limitations to the time and space discretizations are necessary in some cases, especially to minimize numerical dispersion and conserve mass. *DRAINMOD-N* has an internal mechanism which adjusts the time step based on the Courant number [$Cr=q\ \Delta z/(\theta\ \Delta t)$]. When limited or no rainfall/ET occurs, a time step of 0.5 d is selected. If substantial rainfall/ET occurs, the time step is computed based on a Cr number of 1.0. A global mass balance is performed at the end of each time step. If a mass balance error criterion is not met, the time step is reduced by half. However, the smallest time step is limited to 0.025 d, to prevent run times from being excessive. In most cases, a 5-cm space discretization is sufficient to meet the numerical criteria. If the error criterion is not met for dz=5 cm and dt=0.025 d, a small mass balance error may result. When this occurs the concentrations are adjusted at the end of day to satisfy conservation of mass requirements on a daily basis. Daily outputs include NO_3-N concentrations in the soil solution, drainage water and runoff water, total nitrate-nitrogen amounts in the soil solution, and cumulative rates for rainfall deposition, fertilizer dissolution, plant uptake, net mineralization, denitrification, and drainage and runoff losses.

MODEL COMPARISON

Procedure. One method of verifying *DRAINMOD-N*, which is a quasi two-dimensional, management model, is to compare it to a more complex, two-dimensional, model. Such comparisons are especially valuable when simulating water flow and solute transport in soils with drainage systems where lateral flow is significant in the saturated zone. The United States Geological Survey (USGS) developed the 2-D, numerical model *VS2DT* to handle water flow and solute transport in variably saturated soils (Healy, 1990). The water flow model is based on a finite difference solution to the

Richards equation. A modified version, *VS2DNT*, was presented by Harmsen et al. (1991) to simulate the movement and fate of ammonium-nitrogen and nitrate-nitrogen in artificially drained soils. *VS2DNT* also uses finite differences to sequentially solve the *ADR* equation (first for NH_4-N, then for NO_3-N). The controlling processes in *VS2DNT* include mineralization (ammonification), immobilization, nitrification, adsorption, fertilizer dissolution, plant uptake, and drainage losses for NH_4-N, and immobilization, adsorption, nitrification, denitrification, fertilizer dissolution, plant uptake, and drainage losses for NO_3-N.

Simulations were conducted with *DRAINMOD-N* and *VS2DNT* for identical inputs characterizing a Lumbee sandy loam typical of eastern North Carolina. Simulations were conducted for corn production over a 250-day wet period (1989) of climatological record at Plymouth, NC. The field was assumed to have a depressional storage of 0.5 cm. A subsurface drainage system consisting of parallel, 10-cm diameter corrugated plastic drains was used in the simulations. Two drain spacings, 15 and 30 m, and two drain depths, 75 and 100 cm, were simulated. Detailed inputs of the soil properties, drainage system parameters, corn production practices, and nitrogen transport and transformation variables are listed in Table 7. The nitrogen reaction rates were assumed based on values reported in the literature (Johnsson et al., 1987; Schepers and Mosier, 1991).

Because *VS2DNT* does not consider the effect of temperature on the reaction rates, the *DRAINMOD-N* simulations were performed without adjustments for temperature. Other inputs specific to *VS2DNT* are a value of 0.07 for the immobilization rate and 100 cm for the longitudinal dispersivity. In addition, inputs to *VS2DNT* were also manipulated to simulate the fertilization and adsorption processes accordingly. Fertilizers were applied in nitrate form only and adsorption was assumed linear for NH_4 and non-occurring for NO_3.

Daily results based on the standard *DRAINMOD* for water flow and on *DRAINMOD-N* for nitrogen movement and fate were compared to those generated with *VS2DNT* using two statistical parameters: the standard (root mean square) error and average absolute deviation (mean absolute residual). These two parameters are defined as follows (Workman and Skaggs, 1989):

$$s = \sqrt{\frac{\sum (Y_{VS2} - Y_{DMOD})^2}{n}}$$

$$\alpha = \frac{\sum |Y_{VS2} - Y_{DMOD}|}{n} \tag{17}$$

Table 7 Summary of inputs to *DRAINMOD-N* and *VS2DNT* simulations.

1.	**Soil Properties:**	Lumbee Sandy Loam
	θ_{sat} ($cm^3\ cm^{-3}$)	0.34
	θ_{wp} ($cm^3\ cm^{-3}$)	0.12
	Bulk Density ($g\ cm^{-3}$)	1.1
	Organic-N in top soil ($\mu g\ g^{-1}$)	3300
	Lateral Sat. Hyd. Cond. ($m\ d^{-1}$)	0.24 (0-100 cm) 0.72 (100-170 cm)
2.	**Drainage System Parameters:**	
	Drain Depth (m)	0.75 and 1.0
	Drain Spacing (m)	15 and 30
	Depth to Impermeable Layer (m)	1.7
	Effective Drain Radius (cm)	1.5
	Surface Storage (cm)	0.5
3.	**Corn Production Parameters:**	
	Desired Planting Date	April 15
	Length of Growing Season (d)	130
	Max. Effective Root Depth (cm)	40
	N-Fertilizer Input ($kg\ ha^{-1}$)	150
	Date Fertilizer Application	April 15
	Depth Fertilizer Incorporated (cm)	10
4.	**Nitrogen Movement and Fate Parameters:**	
	Longitudinal Dispersivity (cm)	100
	Transverse Dispersivity (cm)	20
	K_{mnl} (d^{-1})	5.0E-05
	K_{den} (d^{-1})	0.25
	K_{nit} (d^{-1})	3.0
	K_{imm} (d^{-1})	0.07
	Potential Yield ($kg\ ha^{-1}$)	10000
	N Content of Plant (%)	1.55
	NO_3-N Concentration of Rain ($mg\ L^{-1}$)	0.8

where s is the standard error, α is the average absolute deviation, Y_{VS2} and Y_{DMOD} are daily values of variables predicted by *VS2DNT* and *DRAINMOD-N*, respectively, and n is the number of days in the simulation period.

Results and Discussion. Hydrologic results (rainfall, mid-point water table depth, and cumulative drainage and runoff) are shown in Figures 19-22 for the different drain depth and spacing combinations. These results show good agreement between the water table (WT) depths simulated by *DRAINMOD* and *VS2DNT* (Fig. 19-22). This is also reflected by the statistical parameters presented in Table 8.

Water table results indicate that, on the average, *DRAINMOD* predictions for any day are within 9-15 cm of those predicted by

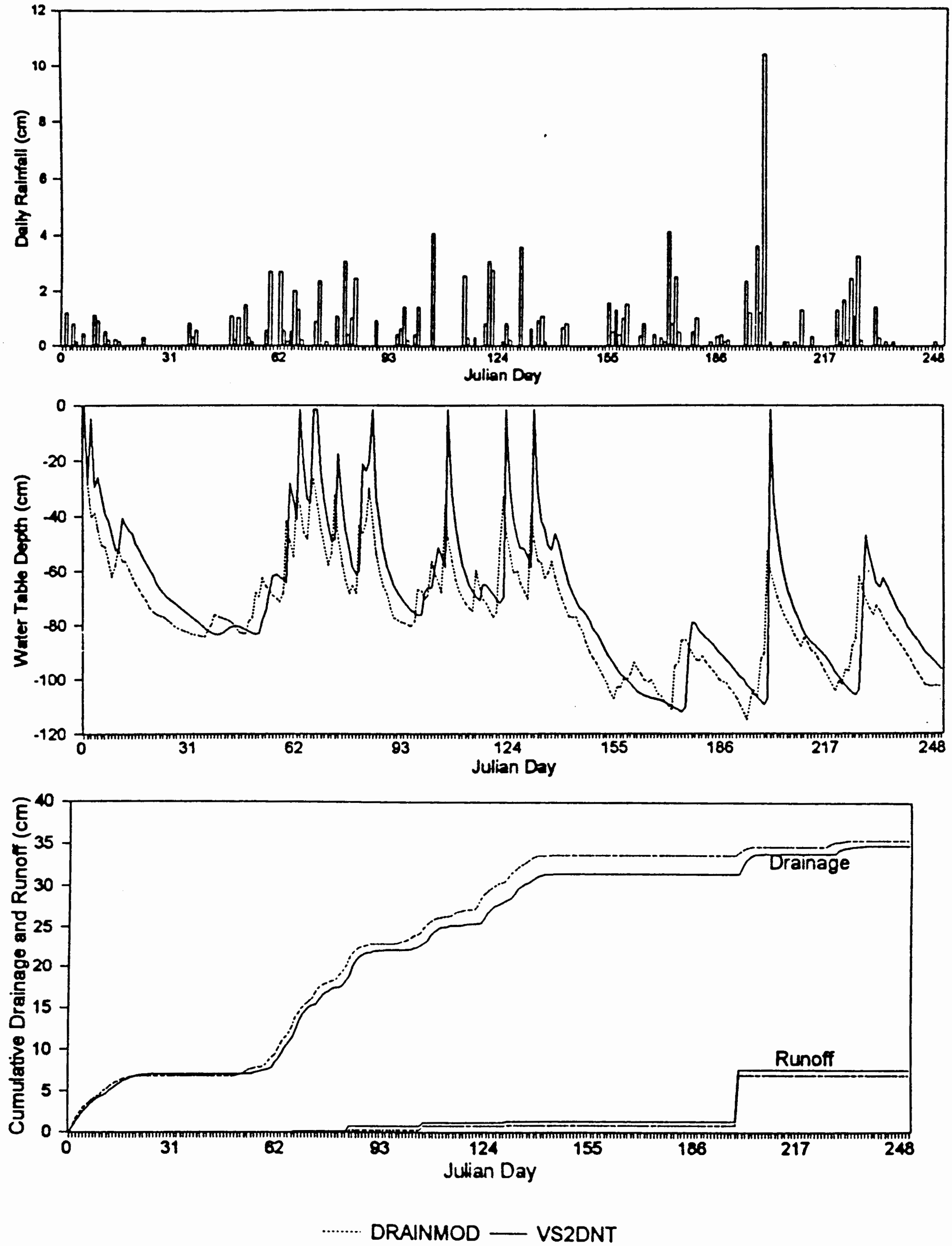


Figure 19 Water table depth and cumulative drainage and runoff simulated by *DRAINMOD* and *VS2DNT* for a 0.75-m drain depth and 15-m spacing.

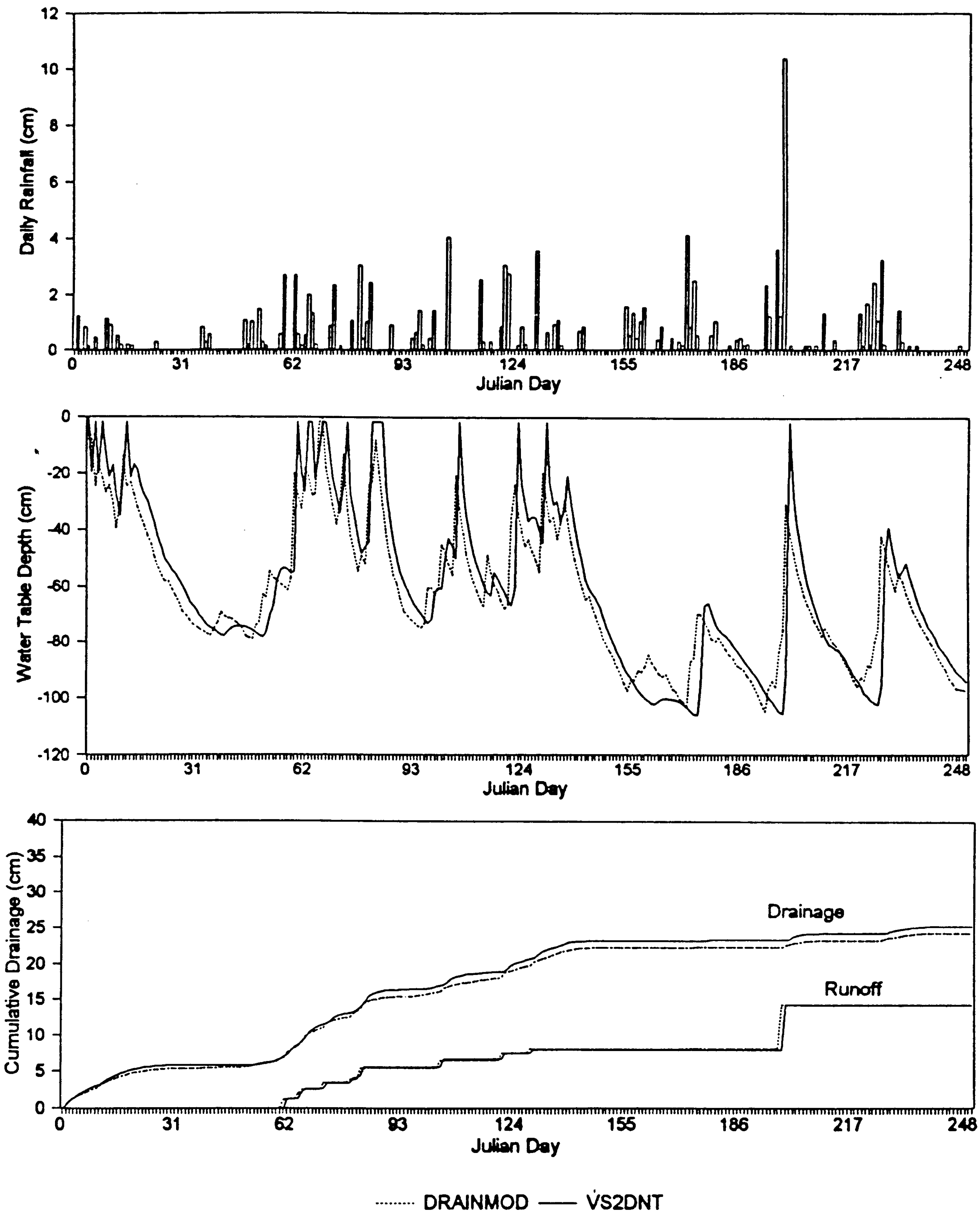


Figure 20 Water table depth and cumulative drainage and runoff simulated by *DRAINMOD* and *VS2DNT* for a 0.75-m drain depth and 30-m spacing.

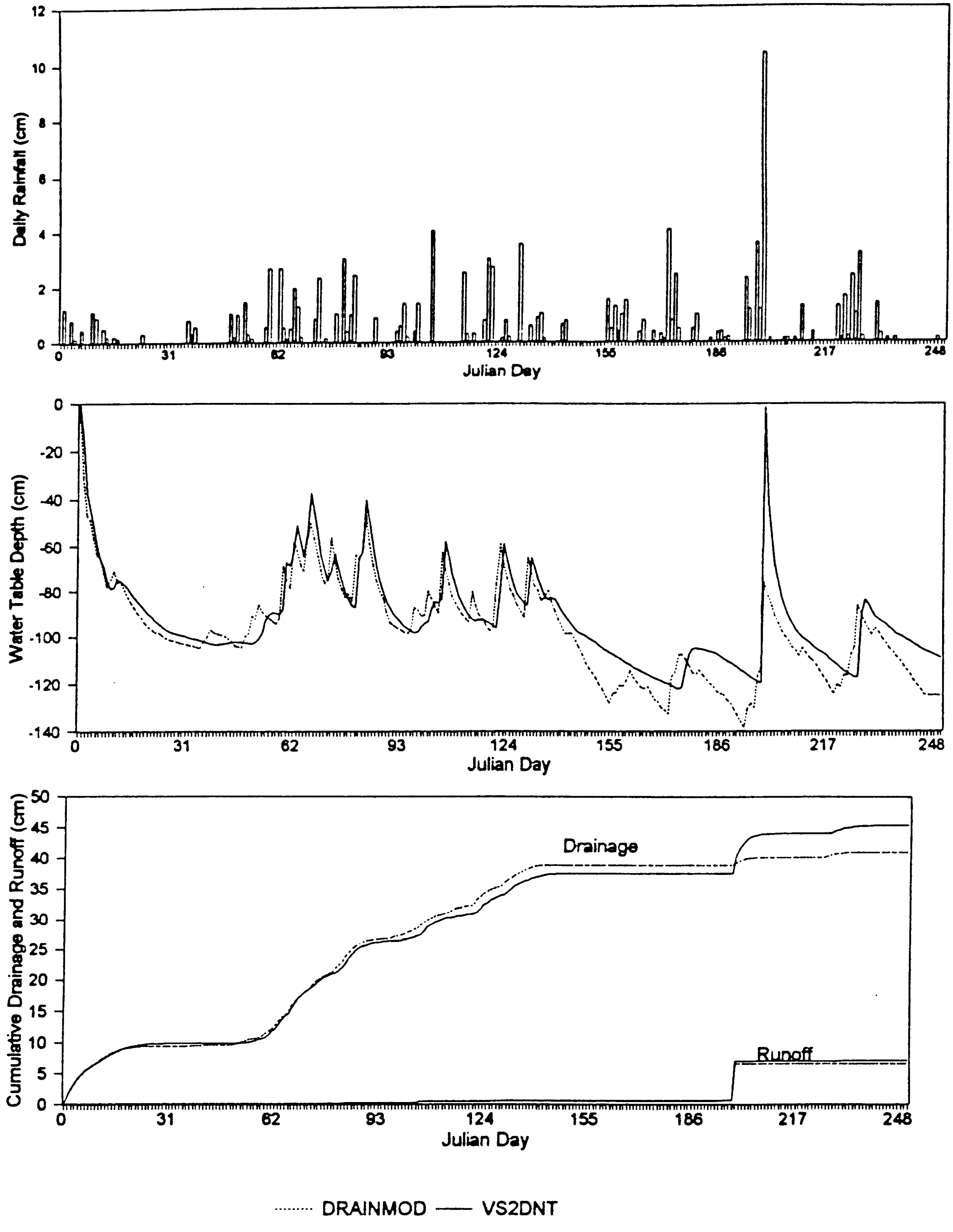


Figure 21 Water table depth and cumulative drainage and runoff simulated by *DRAINMOD* and *VS2DNT* for a 1.0-m drain depth and 15-m spacing.

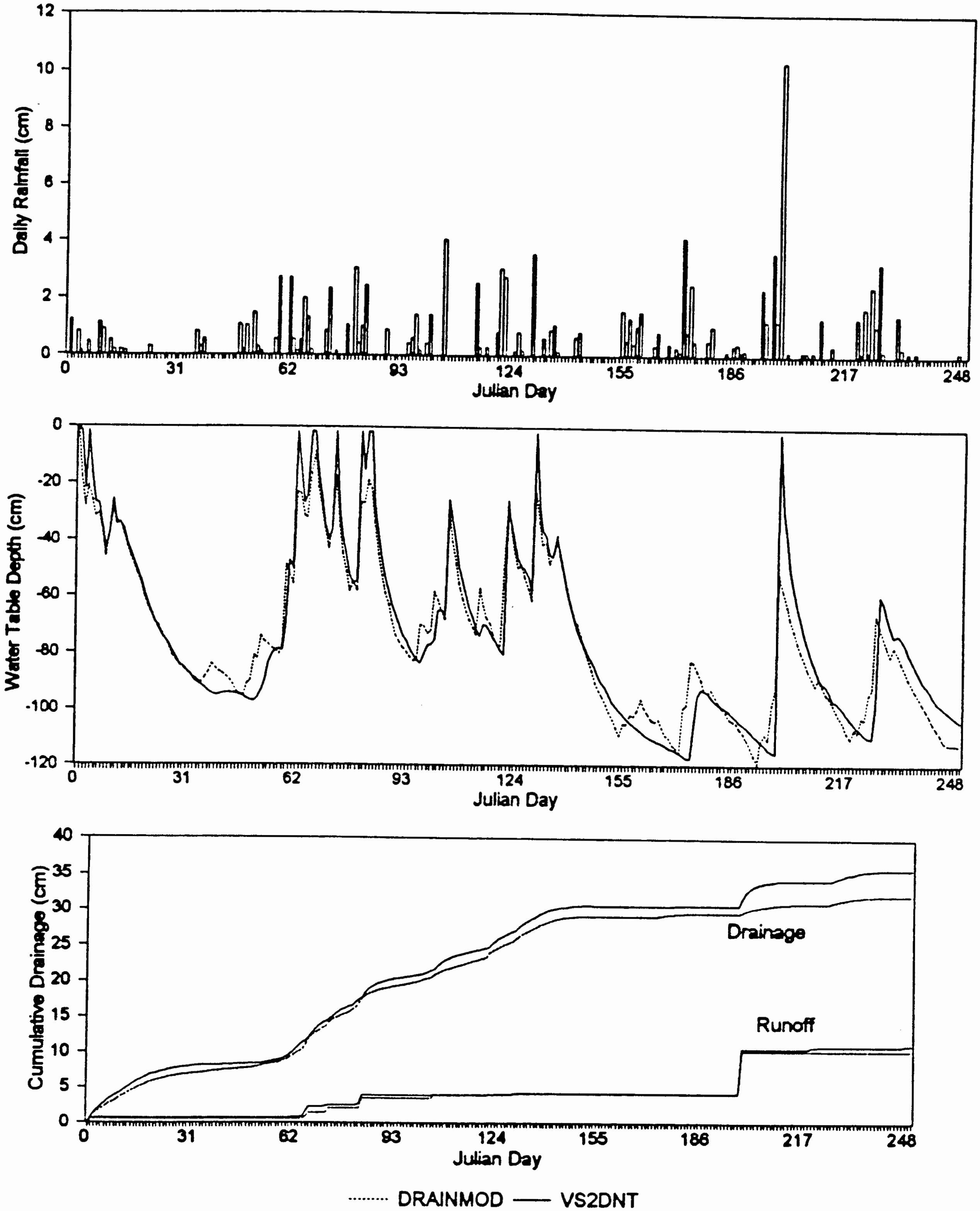


Figure 22 Water table depth and cumulative drainage and runoff simulated by *DRAINMOD* and *VS2DNT* for a 1.0-m drain depth and 30-m spacing.

Table 8. Summary of standard errors of estimate (s) and average absolute deviation (α) for hydrologic results simulated by *DRAINMOD* and *VS2DNT*.

Hydrologic Variable	15-m Spacing s (cm)	15-m Spacing α (cm)	30-m Spacing s (cm)	30-m Spacing α (cm)
<u>0.75 m Drain Depth</u>				
Daily Water Table Depth	15.2	12.1	13.1	9.8
Adjusted Daily Water Table Depth	11.6	9.5	8.2	6.4
Daily Drainage	0.2	0.1	0.1	0.1
Daily Cumulative Drainage	1.5	1.3	0.8	0.7
Daily Runoff	0.0	0.0	0.6	0.1
Daily Cumulative Runoff	0.4	0.3	0.5	0.2
<u>1.0 m Drain Depth</u>				
Daily Water Table Depth	11.5	8.8	9.5	6.5
Adjusted Daily Water Table Depth	11.1	7.0	11.7	6.5
Daily Drainage	0.2	0.1	0.1	0.1
Daily Cumulative Drainage	2.0	1.5	1.9	1.6
Daily Runoff	0.0	0.0	0.1	0.0
Daily Cumulative Runoff	0.3	0.2	0.4	0.3

VS2DNT for the 15-m spacing (Table 8). The agreement in the predictions is better for the 30-m spacing (*DRAINMOD* values are within 7-13 cm of those simulated with *VS2DNT*). WT predictions by *DRAINMOD* are within 10-15 and 7-12 cm for the 0.75 and 1.0 m drain depths, respectively. The largest differences in WT predictions between the models occurred after major rainfall events (Fig. 19-22). In these situations, *VS2DNT* predicts greater water table rises than *DRAINMOD*. Results for predicted water tables also indicate *DRAINMOD* responded faster to rainfall events, as reflected by the lagging in WT peaks observed between the two curves. These differences may be explained by the method each model uses to handle rainfall events. *VS2DNT* assumes daily rainfall is distributed linearly throughout the day while *DRAINMOD* uses hourly rainfall inputs. This may become an important limitation for *VS2DNT* when intense events occur over a relative short period of time. Differences between the models may also be attributed to the underlying assumptions of each model. *DRAINMOD* assumes that the profile is drained to equilibrium with the water table for some distance above the water table. *VS2DNT* is based on a numerical solution to the Richards' equation. Drained-to-equilibrium assumptions imply equilibrium is obtained instantaneously after a rainfall event which may not be the case in the surface layers where solutions to the Richards' equation predict the development of a wetting front, especially for low conductivity soils (Workman and Skaggs, 1989).

Except for the peak water table elevations, the differences between water table depths are primarily due to the lag between the predicted curves. The instantaneous drained-to-equilibrium assumption in *DRAINMOD* causes the predicted water table to rise and fall earlier than predicted solutions to the Richards' equation. Correcting for a one-day lag between *DRAINMOD* and *VS2DNT*, the water table depth predictions of *DRAINMOD* are, on the average, within 12 cm of those of *VS2DNT* for the 15-m spacing, and within 12 cm for the 30-m spacing. This is indicated by the statistical parameters shown in Table 8 for the adjusted daily water table depth analysis.

Results for the rates of subsurface drainage and runoff (Figures 19-22 and Table 8) show that there is also good agreement between values simulated by the two models. While Figures 19-22 show that there is a better agreement in the daily runoff results for the 30-m than for the 15-m spacing, the standard error (s) and average absolute deviation (α) values are greater for the 30-m spacing. This is attributed to the observed lagging in the water table curves which is more substantial for the 30-m spacing, as reflected by the *DRAINMOD* predictions of some runoff events one day before they are simulated by *VS2DNT* (Fig. 20 and 22). As previously stated, these differences can be explained by the rainfall inputs and the underlying assumptions of each model.

Simulated results for NO_3-N losses in drainage and concentrations in the soil profile are shown in Figures 23-30. Figures 23-26 display mid-point nitrate-nitrogen concentrations in the soil solution at three depths for all drain depth and spacing combinations. Figures 27-30 show predicted cumulative NO_3-N losses in drainage. While the concentration profiles simulated by the models display somewhat similar trends (Fig. 23-26), there is a lag between the curves. The graphical results also indicate that the lag increases with depth. The concentration lag may be partially explained by differences (in magnitude and lag) in water table depth (Fig. 19-22). Simulated results show that in general *DRAINMOD-N* tends to overestimate NO_3-N concentrations predicted by *VS2DNT*, especially in the top 60 cm. Statistical analyses indicate that the concentration differences range from 0.3 to 3.8 $\mu g\ g^{-1}$ for the 15-m spacing and from 0.1 to 2.6 $\mu g\ g^{-1}$ for the 30-m spacing (Table 9). Similarly, differences in predicted concentrations between the models range from 0.1-2.6 and 0.4-3.8 $\mu g\ g^{-1}$ for the 0.75 and 1.0 m drain depths, respectively. The differences in concentration decrease substantially if an adjustment is made to take into account the lag between the concentration profiles.

NO_3-N losses in drainage predicted by *DRAINMOD-N* and *VS2DNT* are shown in Figures 27-30 and Tables 9-10. Simulated results show that *VS2DNT* predicted a more substantial drainage loss than *DRAINMOD-N* for the rainfall events occurring between days 104-106 and 199-201 (Fig. 29-30). Statistical results listed in Table 9 indicate that *DRAINMOD-N* predictions for cumulative nitrate-nitrogen loss in drainage water are between 1.7-2.5 and 1.0-2.9

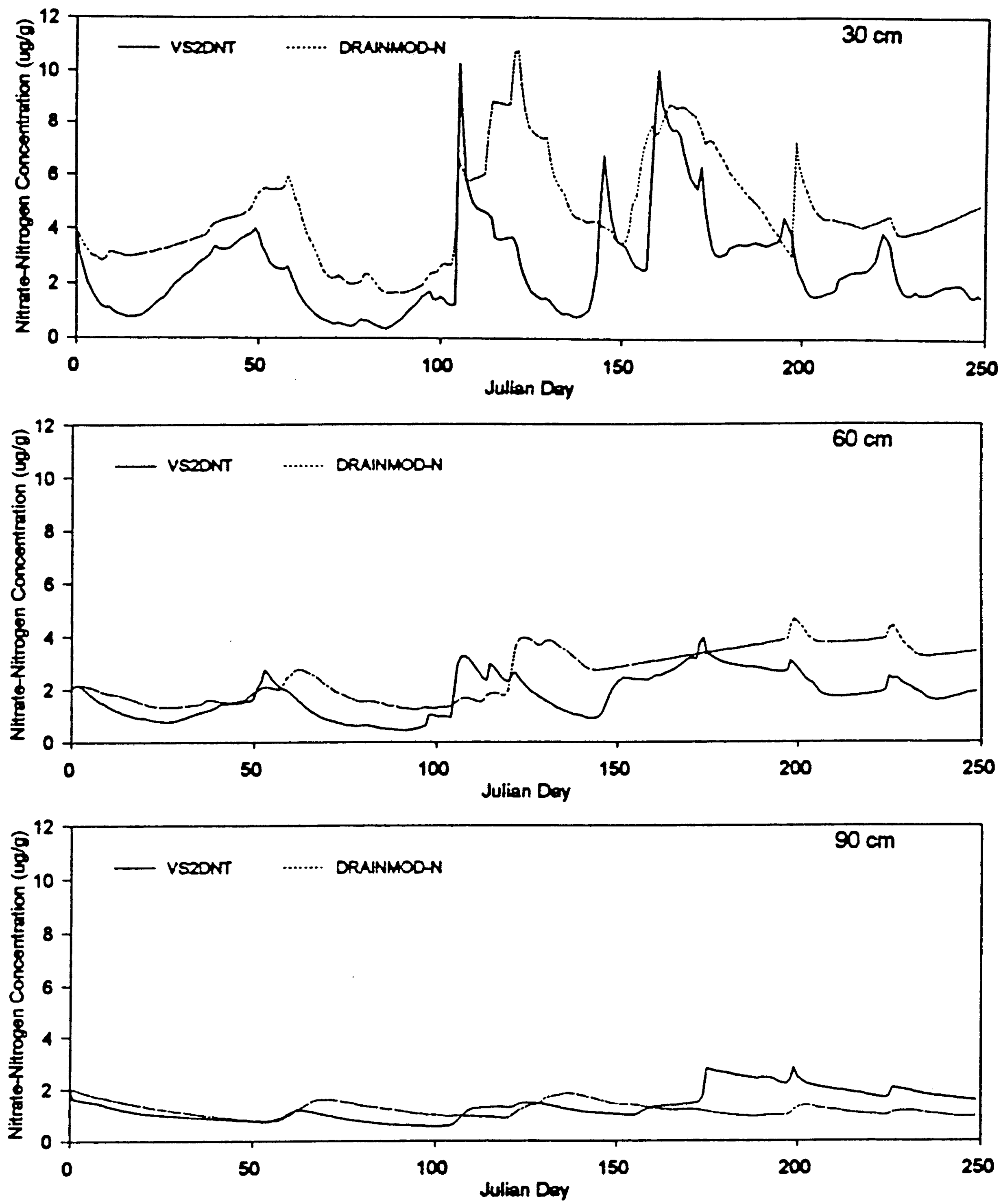


Figure 23 Simulated nitrate-nitrogen concentration in soil (µg/g) at three depths (30, 60 and 90 cm) for a 0.75-m drain depth and 15-m spacing.

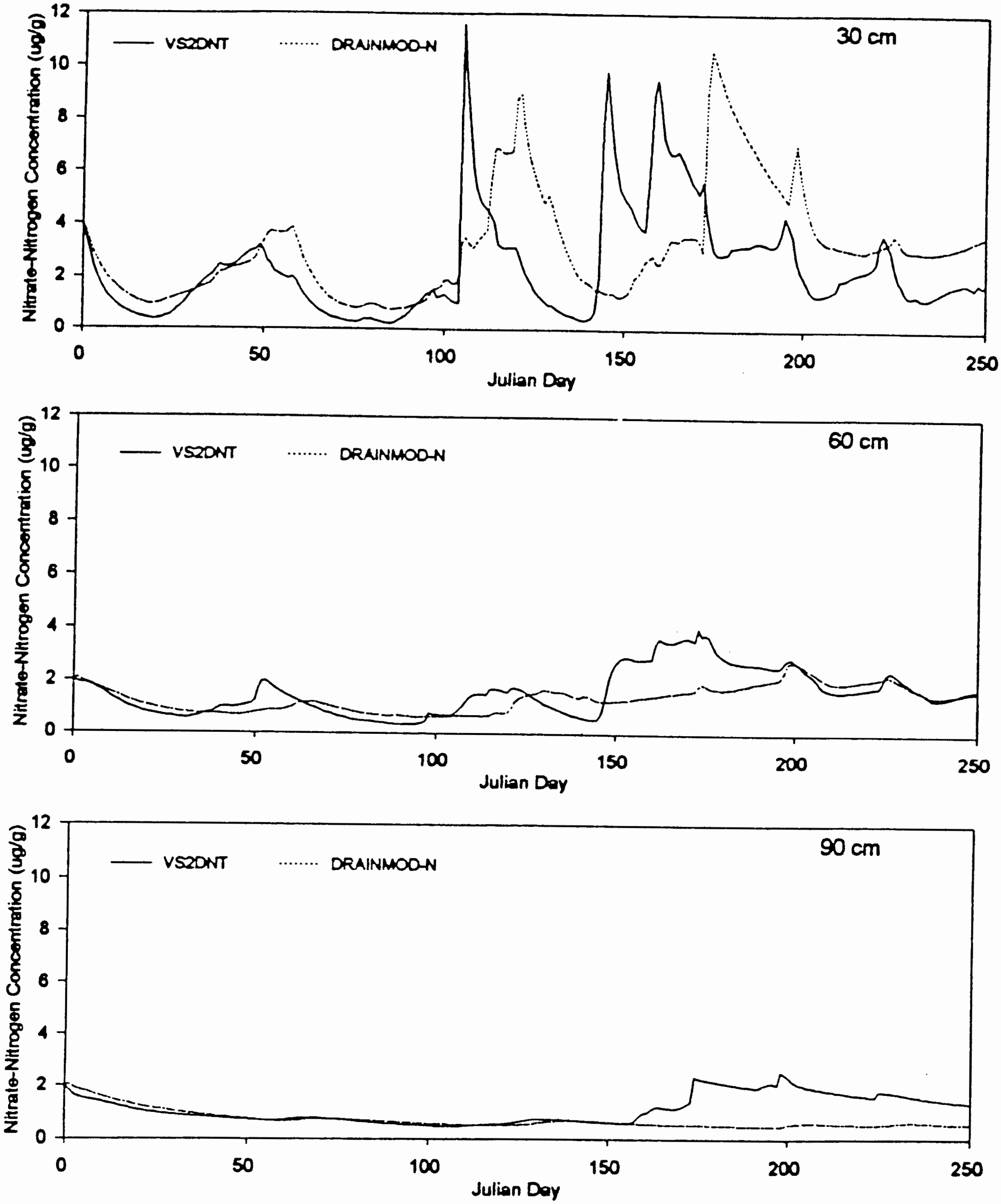


Figure 24 Simulated nitrate-nitrogen concentration in soil (µg/g) at three depths (30, 60 and 90 cm) for a 0.75-m drain depth and 30-m spacing.

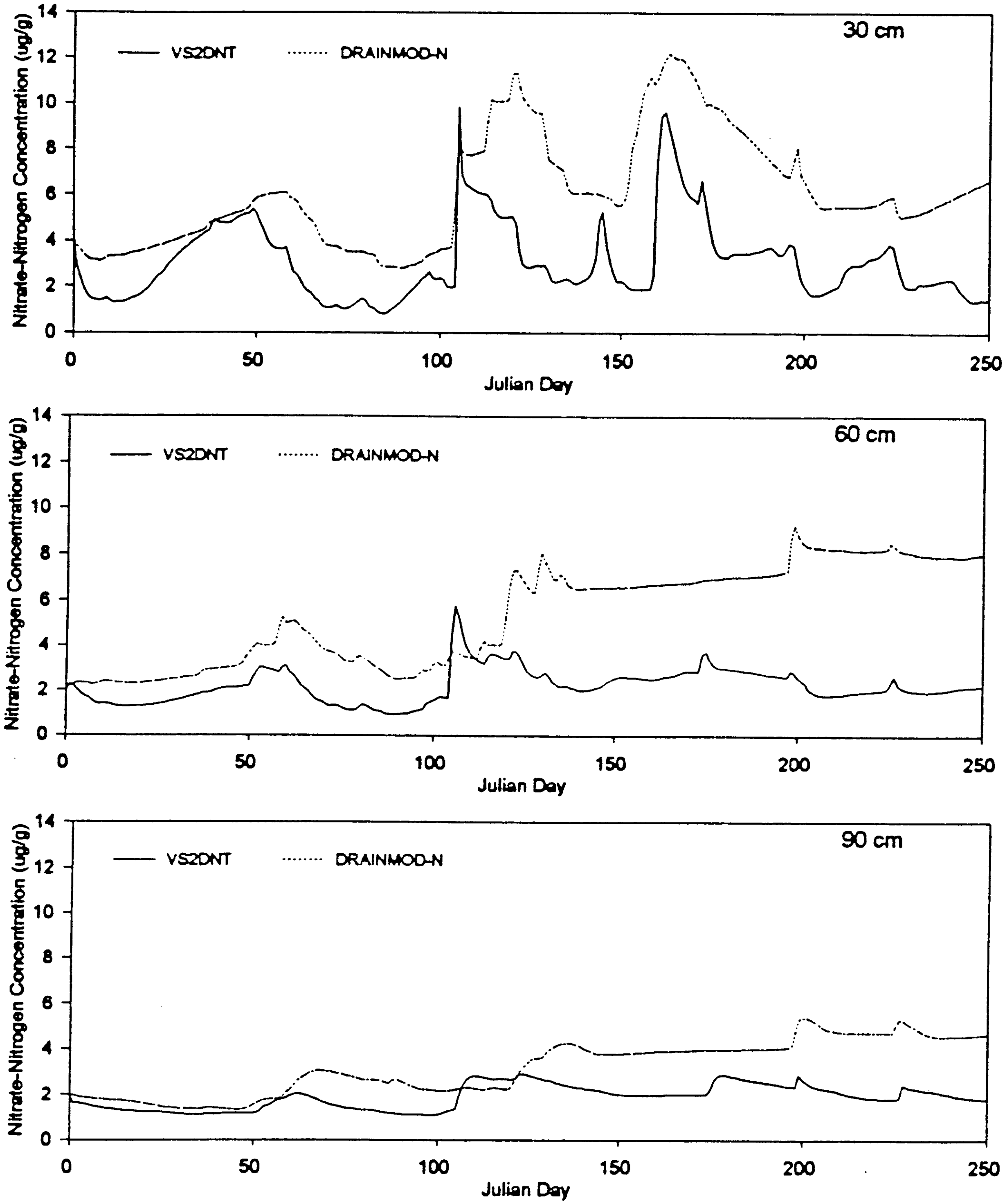


Figure 25 Simulated nitrate-nitrogen concentration in soil (μg/g) at three depths (30, 60 and 90 cm) for a 1.0-m drain depth and 15-m spacing.

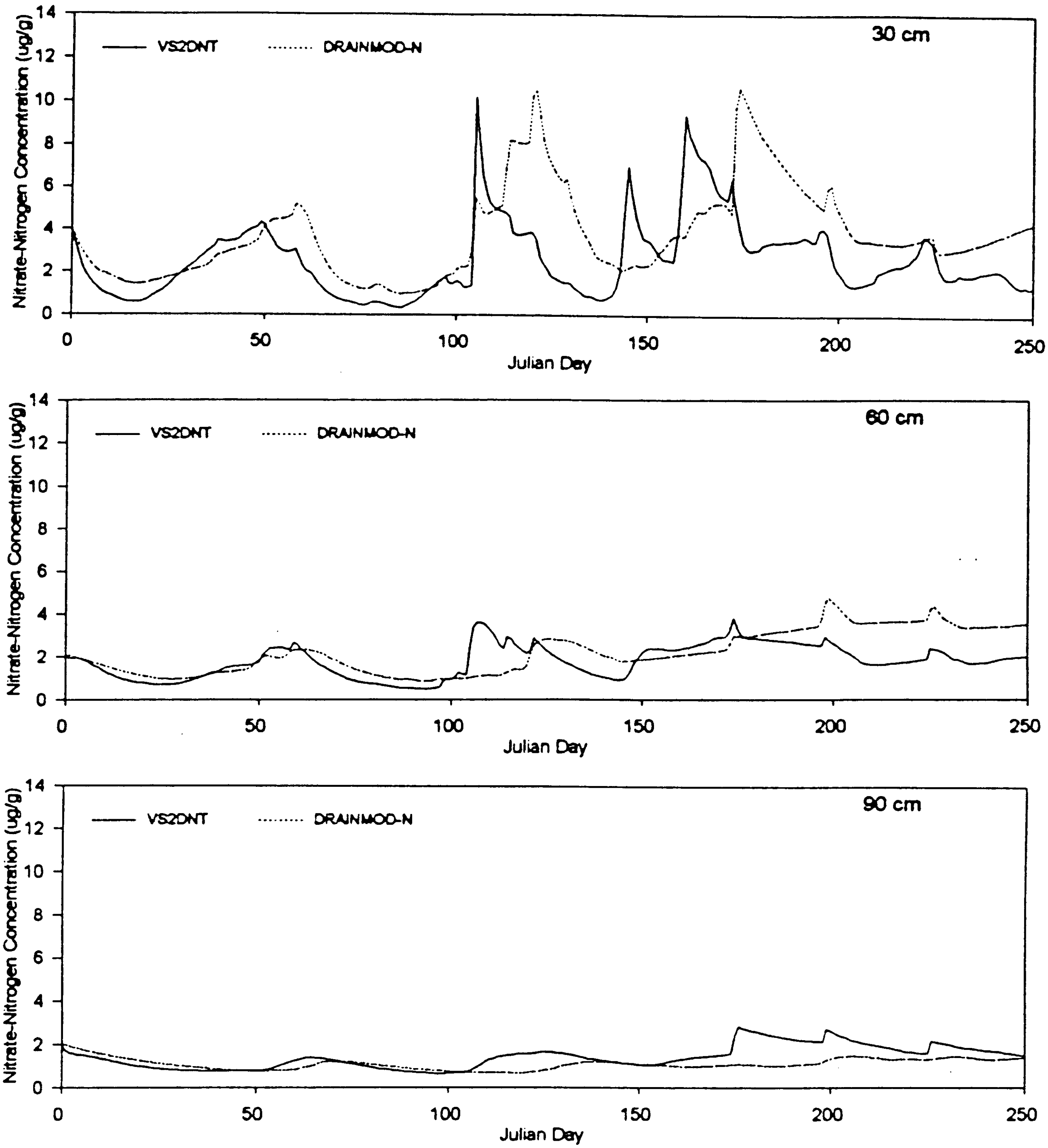


Figure 26 Simulated nitrate-nitrogen concentration in soil (µg/g) at three depths (30, 60 and 90 cm) for a 1.0-m drain depth and 30-m spacing.

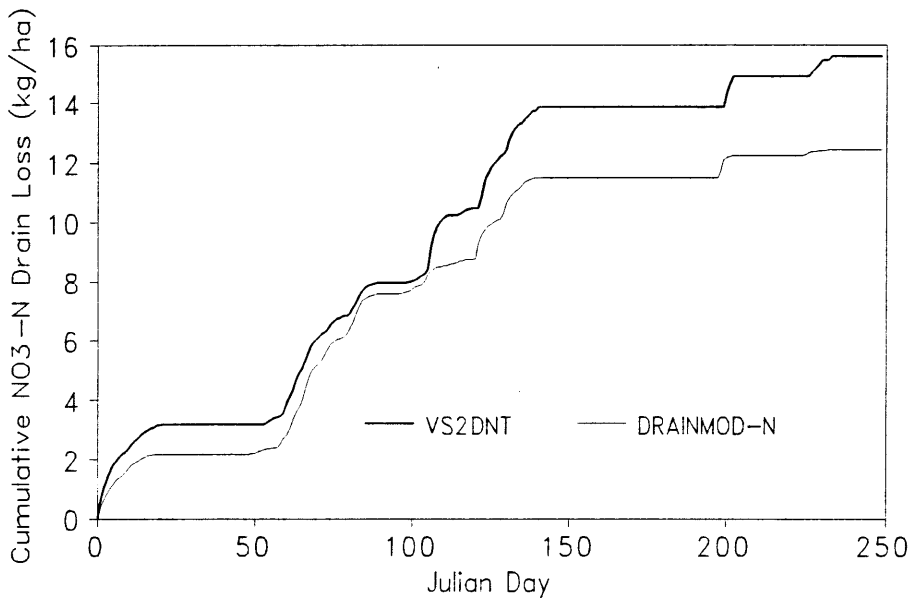


Figure 27 Simulated nitrate-nitrogen loss in drainage (kg/ha) for a 0.75-m drain depth and 15-m spacing.

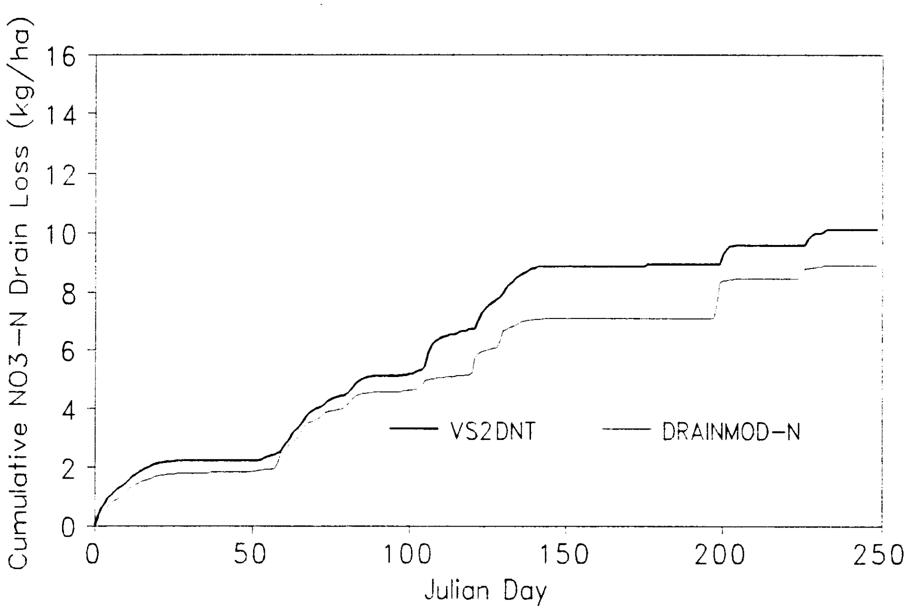


Figure 28 Simulated nitrate-nitrogen loss in drainage (kg/ha) for a 0.75-m drain depth and 30-m spacing.

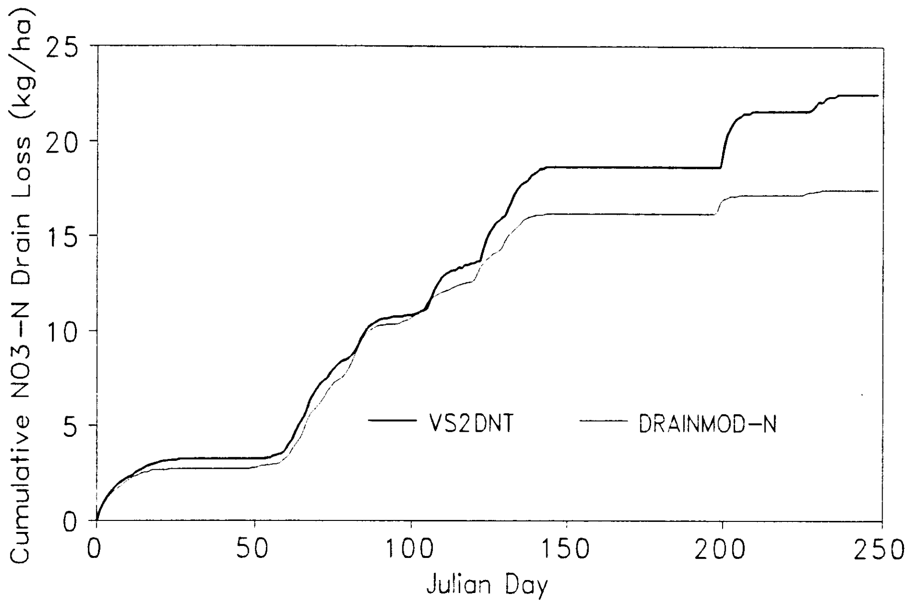


Figure 29 Simulated nitrate-nitrogen loss in drainage (kg/ha) for a 1.0-m drain depth and 15-m spacing.

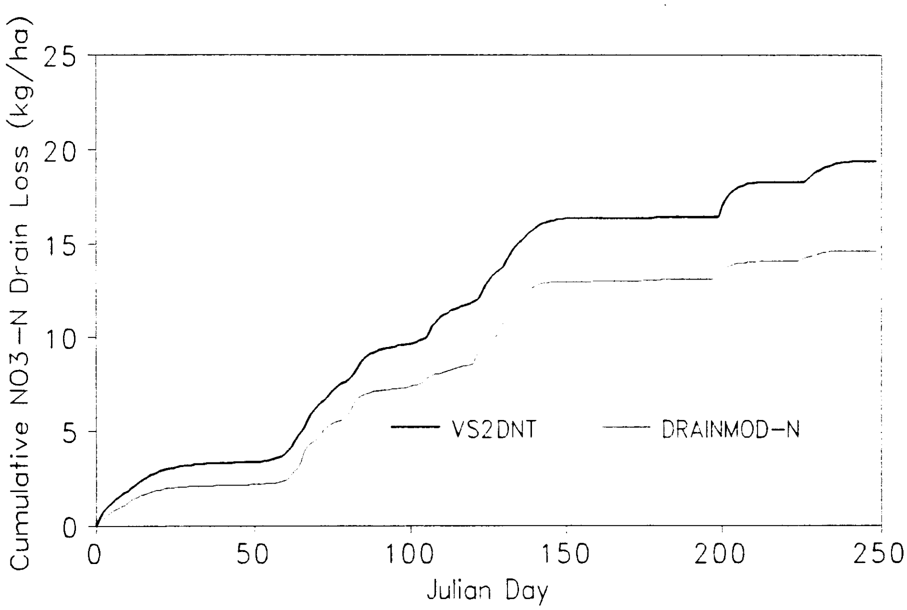


Figure 30 Simulated nitrate-nitrogen loss in drainage (kg/ha) for a 1.0-m drain depth and 30-m spacing.

Table 9. Summary of standard errors of estimate (s) and average absolute deviation (α) for nitrogen results simulated by *DRAINMOD-N* and *VS2DNT*.

Water Quality Variable	15-m Spacing s^1	15-m Spacing α^1	30-m Spacing s^1	30-m Spacing α^1
0.75 m Drain Depth				
NO_3-N Conc. at 30 cm	2.6	2.2	2.6	1.9
NO_3-N Conc. at 60 cm	1.2	1.0	0.8	0.5
NO_3-N Conc. at 90 cm	0.7	0.5	0.8	0.5
NO_3-N Conc. at 120 cm	0.4	0.3	0.2	0.1
Cumulative NO_3-N Drainage Loss	1.9	1.7	1.2	1.0
1.0 m Drain Depth				
NO_3-N Conc. at 30 cm	3.7	3.1	2.4	1.8
NO_3-N Conc. at 60 cm	3.8	3.2	1.0	0.8
NO_3-N Conc. at 90 cm	1.6	1.4	0.6	0.4
NO_3-N Conc. at 120 cm	0.4	0.4	0.5	0.5
Cumulative NO_3-N Drainage Loss	2.5	1.9	2.9	2.6

[1] Units are $\mu g\ g^{-1}$ for concentration and kg ha^{-1} for cumulative loss.

kg ha^{-1} of those predicted by *VS2DNT* for the 15 and 30 m spacings, respectively.

On the average, total drainage loss predictions by *DRAINMOD-N* are within -21% of those simulated by *VS2DNT* (Table 10). Agreement in predicted drainage losses is better for the 0.75 m than for 1.0 m drain depth (-19% versus -24%). Predictions are within -22% and -21% for the 15 and 30 m drain spacings, respectively.

Total simulated rates of NO_3-N loss in drainage, denitrification, net mineralization, and plant uptake are listed in Table 10. Predicted runoff losses are not shown because *VS2DNT* does not predict losses by surface runoff. Denitrification, plant uptake and net mineralization *DRAINMOD-N* predictions are within a -8%, +15% and +26% of those simulated by *VS2DNT*. The agreement in denitrification predictions is better for the 30-m spacing (+1%), but for plant uptake and net mineralization the agreement is better for the 15-m spacing (+11% and +24%).

Besides the 1D versus 2D nature of the models, the major difference between the models are the mineralization and plant uptake algorithms which may have a considerable impact on resulting NO_3-N concentrations in the root zone (0-40 cm) as well as in the overall cumulative rates. As described previously, *DRAINMOD-N* uses a simple, zero-order function to quantify plant uptake which is based on relative yield and N-uptake demand. The *VS2DNT* plant uptake component is based on a complex Michaelis-Menton approach which is dependent on NO_3-N concentration and transpiration flux (Harmsen et al., 1991). Furthermore, net

Table 10. Total rates (kg ha^{-1}) of NO_3-N loss in drainage, denitrification, net mineralization, plant uptake, rainfall deposition, and fertilizer dissolution simulated by *VS2DNT* and *DRAINMOD-N*.

Total Rate (kg ha^{-1})	15-m Spacing DRAINMOD-N	15-m Spacing VS2DNT	30-m Spacing DRAINMOD-N	30-m Spacing VS2DNT
0.75 m Drain Depth				
Drainage Loss	12.4	15.6	8.9	10.1
Denitrification	118.8	138.7	145.2	146.0
Plant Uptake	135.4	114.5	122.0	106.4
Net Mineralization	129.4	105.3	126.6	95.2
1.0 m Drain Depth				
Drainage Loss	17.4	22.5	14.6	19.4
Denitrification	89.4	114.1	132.1	128.7
Plant Uptake	138.3	132.8	129.9	106.1
Net Mineralization	140.5	112.1	131.3	108.2

mineralization in *DRAINMOD-N* is treated as a direct (zero order) reaction affected only by the soil water content and the amount of organic nitrogen in the soil. In *VS2DNT*, net mineralization is a complex process involving three reactions: nitrification and immobilization of NO_3 and NH_4 which are also affected by soil water content and organic nitrogen.

Overall, hydrologic results have shown that the standard *DRAINMOD* model compares well to the *VS2DNT* model when predicting water table depth profiles and drainage rates for a 250-day simulation at Plymouth, NC. Daily NO_3-N concentrations predicted by *DRAINMOD-N* and *VS2DNT* were in disagreement, unless the lag between the concentration profiles is taken into account. Simulated results also indicate that *DRAINMOD-N* compares well to *VS2DNT* when predicting cumulative nitrate-nitrogen losses in drainage, denitrification, net mineralization and plant uptake. Differences in total cumulative rates are largely due to differences in the plant uptake and net mineralization algorithms used by the models. Considering *DRAINMOD-N* is a simpler model and that *VS2DNT* has not been fully tested with field results, it is not possible to conclude which model will give the most reliable predictions. Overall results have shown that *DRAINMOD-N* can predict nitrogen movement and fate within an acceptable range compared to the truly 2D model *VS2DNT*. This is especially important for long-term applications, if one takes into account that both the water flow and nitrogen movement and fate simulations can be executed at least 300 times faster with *DRAINMOD-N*.

SUMMARY AND CONCLUSIONS

Computer simulation models are useful tools to evaluate the effects of agricultural practices on the movement and fate of nutrients and pesticides. Although many simulation models are available, only a few adequately incorporate the effects of improved drainage on pollutant transport and fate. *DRAINMOD-N*, a quasi two-dimensional model that simulates the movement and fate of nitrogen in shallow water table soils with artificial drainage, was described and compared with *VS2DNT*, a more complex, two-dimensional model.

DRAINMOD-N was developed to simulate a simplified version of the nitrogen cycle; thus only a nitrate-nitrogen pool is considered. As the name implies, *DRAINMOD-N* is based on the water balance calculations of the standard *DRAINMOD* model. It uses modifications to determine average daily soil water fluxes and water contents. The solute transport component is based on an explicit solution to the advective-dispersive-reactive equation. Functional relationships are used to quantify the controlling processes of rainfall deposition, fertilizer dissolution, net mineralization, denitrification, plant uptake, and runoff and drainage losses.

Water table depths, total subsurface drainage rates, and total surface runoff rates predicted by *DRAINMOD* were within 15 cm, 2.0 cm, and 0.5 cm, respectively, of those predicted by *VS2DNT* for a 250-day simulation at Plymouth, NC. Daily NO_3-N concentrations predicted by *DRAINMOD-N* and *VS2DNT* were in disagreement, unless a lag between the concentration profiles is taken into account. However, *DRAINMOD-N* predictions for total nitrate-nitrogen loss in drainage water are between 1.0-2.9 kg ha^{-1} of those predicted by *VS2DNT*. On the average, total drainage loss predictions by *DRAINMOD-N* are within 21% of those simulated by *VS2DNT*. Denitrification, plant uptake and net mineralization *DRAINMOD-N* predictions are within 8%, 15% and 26% of those simulated by *VS2DNT*.

Overall results indicate that *DRAINMOD-N* can be used to predict the fate and movement of nitrogen in artificially drained soil. More research is needed to test *DRAINMOD-N* against field data.

DRAINMOD-N, A NITROGEN MODEL FOR ARTIFICIALLY DRAINED SOILS: FIELD TESTING

Computer simulation models are useful to evaluate the complex mechanisms governing contaminant transport in agricultural fields. This is especially true for poorly drained soils with artificial drainage where hydrologic and water quality impacts depend on factors such as land use, management practice, soil type, site condition, and climate (Skaggs et al., 1994). Although several models are available to predict pollutant transport in agricultural fields, only a few adequately incorporate the effects of artificial drainage and related water management practices on the movement and fate of agricultural contaminants.

DRAINMOD-N is a quasi two-dimensional model that simulates the movement and fate of nitrogen in shallow water table, artificially drained soils. The flow component of the model is based on the water balance calculations in *DRAINMOD* (Skaggs, 1978). It also uses modifications to determine average daily soil water fluxes and water contents (Skaggs et al., 1991). The solute transport component is based on an explicit solution to the advective-dispersive-reactive (*ADR*) equation. Functional relationships are used to quantify the processes of rainfall deposition, fertilizer dissolution, net mineralization, denitrification, plant uptake, and runoff and drainage losses.

DRAINMOD-N is presented in detail and compared to a more complex numerical model (*VS2DNT*, Harmsen et al., 1991) in the previous chapter. The objective of this chapter is to evaluate the reliability of *DRAINMOD-N* based on predicted and observed hydrologic conditions and nitrogen losses on the experimental site in eastern North Carolina.

MATERIALS AND METHODS

Experimental Site. The reliability of *DRAINMOD-N* was evaluated using the data collected at the Plymouth, NC experimental site described in the "Field Experiments" section of this report. The cropping system was the wheat-soybean rotation from Nov. 15, 1991 to Nov. 16, 1992. These crops were grown with conventional tillage and fertilizer and pest management practices typical of the region. The field was fertilized on Nov. 15, 1991 at a rate of 16.3 kg N/ha and wheat was planted on Nov. 20, 1991. Wheat was fertilized on Feb. 21, 1992 at a rate of 145.6 kg N/ha and harvested on Jun. 18, 1992. Soybeans were planted on Jun. 30, 1992 and harvested on Nov. 16, 1992.

Water Flow Parameter Estimation. Input data and model parameters required in *DRAINMOD* include hourly rainfall, daily potential evapotranspiration (PET), lateral saturated hydraulic conductivities (K_{sat}), soil water characteristic (SWC) data, and upward flux-volume drained-water table depth relationships.

Field-measured, instantaneous rainfall was processed and is summarized in Appendix 3. Daily PET values, also shown in Appendix 3, were computed from collected weather data based on the Penman-Monteith method (Jensen et al., 1990).

Eight pits (one per plot) were dug to characterize the soil profile, and soil samples were taken to determine texture, K_{sat} and SWC parameters in the first four layers. Analyses of particle size distribution (Gee and Bauder, 1986) were conducted to determine soil texture. The constant head method (Klute and Dirksen, 1986) was used to measure saturated hydraulic conductivities of the cores. SWC curves were determined with a pressure apparatus (Klute, 1986). Other parameters estimated from the soil core samples were porosity (θ_{sat}) and bulk density (ρ_b). A summary of these soil properties for plots 1-6 is presented in Table 11. The data reported for layer 5 are based on a previous study by Munster (1992). Upward flux-volume drained-water table depth relationships were developed from SWC data using the SOILPREP program of *DRAINMOD*.

Observed subsurface drainage rates and water table depths were used to estimate field-scale hydraulic conductivities for each plot using an inverse method. The procedures for this method are explained in Appendix 4. Average K_{sat} values resulting from the analysis are also shown in Table 11.

The water table management parameters (dates of conventional drainage, controlled drainage and subirrigation, and their corresponding weir depths) for each experimental plot are listed in Table 12.

Nitrogen Movement and Fate Parameter Estimation. Nitrogen movement and fate parameters required in *DRAINMOD-N* include standard rate coefficients for denitrification and net mineralization, nitrate-nitrogen content in rainfall and crop(s), and dispersivity. Table 13 lists common ranges for these parameters, as reported in the literature (Davidson et al., 1978; Johnsson et al., 1987; Harmsen et al., 1991; Schepers and Mosier, 1991; Pierce et al., 1991). Other parameters that are also important include organic nitrogen in the soil and crop yield; they were measured for each field plot (Table 13).

Table 11. Soil properties of experimental site in Plymouth, N.C.

Plot	1	2	3	4	5	6
			Layer 1			
Thickness (cm)	0-29	0-33	0-27	0.27	0-24	0-31
Texture	SL	SL	SL	SL	SL	L
θ_{sat} (cm^3 cm^{-3})	0.44	0.42	0.41	0.41	0.43	0.46
ρ_b (g cm^{-3})	1.30	1.38	1.37	1.35	1.30	1.22
Lat. $Ksat_{core}$ (m d^{-1})	1.70	1.90	---	1.90	---	0.90
Lat. $Ksat_{field}$ (m d^{-1})	0.88	0.91	1.10	1.30	1.14	0.60
			Layer 2			
Thickness (cm)	29-83	33-85	27-64	27-69	24-69	31-81
Texture	SL	SL	SL	SL	SL	L
θ_{sat} (cm^3 cm^{-3})	0.35	0.27	0.31	0.34	0.37	0.41
ρ_b (g cm^{-3})	1.58	1.92	1.69	1.77	1.54	1.46
Lat. $Ksat_{core}$ (m d^{-1})	0.25	0.15	0.20	1.50	0.85	0.20
Lat. $Ksat_{field}$ (m d^{-1})	0.43	0.65	0.40	0.75	0.91	0.40
			Layer 3			
Thickness (cm)	83-105	85-105	64-100	69-98	69-97	81-99
Texture	SL	SL	SL	SL	SL	CL
θ_{sat} (cm^3 cm^{-3})	0.33	0.35	0.34	0.35	0.33	0.40
ρ_b (g cm^{-3})	1.74	1.74	1.69	1.72	1.54	1.54
Lat. $Ksat_{core}$ (m d^{-1})	0.10	0.45	0.20	---	0.20	0.05
Lat. $Ksat_{field}$ (m d^{-1})	0.10	0.09	0.10	0.12	0.10	0.10
			Layer 4			
Thickness (cm)	105-150	105-150	100-150	98-150	97-150	99-150
Texture	LS	LS	S	LS	SL	CL
θ_{sat} (cm^3 cm^{-3})	0.38	0.40	0.36	0.37	0.39	0.33
ρ_b (g cm^{-3})	1.53	1.48	1.48	1.45	1.54	1.59
Lat. $Ksat_{core}$ (m d^{-1})	0.05	0.05	0.50	0.50	0.20	0.15
Lat. $Ksat_{field}$ (m d^{-1})	0.10	0.11	0.14	0.13	0.12	0.10
			Layer 5			
Thickness (cm)	150-240	150-240	150-240	150-240	150-240	150-240
Texture	S	S	S	S	S	S
Lat. $Ksat_{field}$ (m d^{-1})	3.75	3.75	3.75	3.75	3.75	3.75

Soil temperature predictions are used by *DRAINMOD-N* to adjust coefficients in temperature-dependent processes. As explained in the previous chapter, soil temperature can be estimated by an equation whose key parameters are average yearly air temperature, wave amplitude, phase shift, and damping depth. These parameters were obtained by fitting the equation to observed air and soil temperature data for Plymouth, N.C. The resulting best-fit parameters are shown in Table 13.

Table 12. Water table management parameters for experimental site in Plymouth, N.C.[1]

	Conventional Drainage Dates (Weir depth)	Controlled Drainage Dates (Weir depth)	Subirrigation Dates (Weir depth)
Field 3	Nov 1,91-Dec 31,92 (115 cm)		
Field 4	Nov 1,91-Dec 31,92 (122 cm)		
Field 2	Nov 1,91-Mar 2,92 (116 cm) Jun 10,92-Jul 14,92 (116 cm) Nov 5,92-Dec 31,92 (116 cm)	Mar 3,92-Jun 9,92 (50 cm) Jul 15,92-Nov 4,92 (45 cm)	
Field 5	Nov 1,91-Mar 2,92 (118 cm) Jun 10,92-Jul 14,92 (118 cm) Nov 5,92-Dec 31,92 (118 cm)	Mar 3,92-Jun 9,92 (40 cm) Jul 15,92-Nov 4,92 (35 cm)	
Field 1	Nov 1,91-Mar 2,92 (130 cm) Jun 11,92-Jul 8,92 (130 cm) Nov 5,92-Dec 31,92 (130 cm)	Mar 3,92-Mar 23,92 (50 cm) Apr 22,92-Apr 28,92 (50 cm) Oct 6,92-Nov 4,92 (50 cm)	Mar 24,92-Apr 21,92[2] (50 cm) Apr 29,92-Jun 10, 92 (50 cm) Jul 8,92-Jul 14 92 (50 cm) Jul 15,92-Oct 5,92 (30 cm)
Field 6	Nov 1,91-Mar 2,92 (122 cm) Jun 10,92-Jul 14,92 (130 cm) Nov 5,92-Dec 31,92 (130 cm)	Mar 3,92-Apr 26,92 (55 cm) Oct 6,92-Nov 4,92 (50 cm)	Apr 27,92-Jun 9,92 (55 cm) Jul 15,92-Oct 5, 92 (30 cm)

[1]Wheat was planted on 20 Nov, 1991 and harvested on 18 Jun, 1992. Soybean was planted on Jun 30, 1992 and harvested on 16 Nov, 1992

[2]Used for simulation purposes only since a flow experiment was in progress in the field during this time.

Table 13. Nitrogen movement and fate parameters. Data listed as range are based on values reported in the literature. Single values given below were measured or developed for the experimental site.

Parameter	Range
Rate coefficient of denitrification (K_{den}, d^{-1})	0.05-1.00
Rate coefficient of net mineralization (K_{min}, d^{-1})	10^{-5}-10^{-4}
NO_3-N in rain (mg L^{-1})	0.05-1.20
Dispersivity (cm)	5-30
N in crop (%)	
Wheat grain	1-3
Soybean grain	4-7

	Organic nitrogen in top 15 cm ($\mu g\ g^{-1}$) Before wheat	After soybean	Wheat Yield (kg/ha)	Soybean Yield (kg/ha)
Field 1	1600	2000	4900	3000
Field 2	2000	2200	5100	3100
Field 3	2000	1900	5100	2900
Field 4	2300	2000	4800	2800
Field 5	2000	2200	4700	3000
Field 6	2600	2700	5400	2800

Soil temperature parameters	
Average yearly air temperature (°C)	15.61
Wave amplitude (°C)	9.93
Wave damping depth (cm)	50
Wave phase shift (d)	16

Sensitivity Analysis. A sensitivity analysis was performed to study the effect of input parameters on *DRAINMOD-N* predictions for NO_3-N losses in drainage and runoff, denitrification and mineralization rates, and NO_3-N concentration in the soil solution. The input parameters analyzed included the NO_3-N content in the precipitation and crops (wheat and soybean), the rate coefficients of denitrification and mineralization, and the value of dispersivity. A baseline set of these parameters was assumed based on values reported in the literature. Each parameter was individually varied downward and upward to determine the sensitivity of the model predictions to changes in the variable. The range of the values considered in the analysis is shown in Table 14. A set of *DRAINMOD-N* simulations was performed based on those parameters. Other key input parameters (i.e., hydraulic conductivity, soil water characteristic, weather data, etc.) were taken to be the same as those measured in the field and laboratory for plot 3 (Table 11).

Results of the analysis are shown in Figures 31-38. Figures 31-33 show effects of changing several input parameters on total (cumulative) rates of drainage and runoff NO_3-N losses, denitrification, and mineralization, and on maximum NO_3-N concentrations in soil solution. Figures 34-38 display those

Table 14. Ranges of the nitrogen movement and fate parameters considered in the sensitivity analysis.

Parameter	Values				
Rate coefficient of denitrification (K_{den}, d^{-1})	0.15	0.225	0.30	0.45	0.60
Rate coefficient of net mineralization (K_{min}, d^{-1})	$2.5x10^{-5}$	$5.0x10^{-5}$	$1.0x10^{-4}$		
Dispersivity (λ, cm)	5	10	20		
NO_3-N in rain (mg L^{-1})	0.4	0.8	1.2		
N in winter wheat (%)	1	2	3		
N in soybean (%)	4	5	6		

effects through time for selected parameters. These simulated results indicate that NO_3-N loss in drainage is most sensitive to the rate coefficients of denitrification and mineralization, mildly sensitive to N content in both crops, and practically insensitive to NO_3-N content in rainfall and dispersivity (Figures 32, 34, 36 and 38). On the other hand, NO_3-N loss in runoff is most sensitive to NO_3-N content in rainfall (Figures 31 and 38). The cumulative rate of denitrification was found to be sensitive to its rate coefficient (K_{den}), mineralization rate coefficient (K_{min}), and NO_3-N content in winter wheat, mildly sensitive to dispersivity, and insensitive to nitrogen content in soybeans and rainfall (Figures 32, 34 and 38). Predictably, the cumulative rate of net mineralization was most sensitive to its rate coefficient (Figures 33 and 36).

Maximum NO_3-N concentrations in the soil solution were found to be sensitive to the mineralization rate coefficient and N content in winter wheat, especially at low to medium depths (60 cm or less), and to the denitrification rate coefficient and dispersivity, especially at medium depths (30-60 cm) (Figure 33). Maximum NO_3-N concentrations are practically insensitive to all the parameters analyzed at deeper depths (90 cm or more) (Figure 33). Figures 35 and 37 show that the overall NO_3-N concentration profile in the soil solution is sensitive to the mineralization and denitrification rate coefficients.

Results of the sensitivity analysis for K_{den}, K_{min} and dispersivity were used to calibrate the nitrogen model. Simulations were conducted for a range of these parameters. Inputs for organic nitrogen in the soil and N content in wheat and soybean were based on observed data. Simulated results were compared to observed data (NO_3-N losses via subsurface drainage and surface runoff and NO_3-N concentrations in shallow ground water) for plot 3. The K_{den}, K_{min} and dispersivity values that resulted in the best agreement are shown in Table 15. These calibrated values were used as input for all other fields.

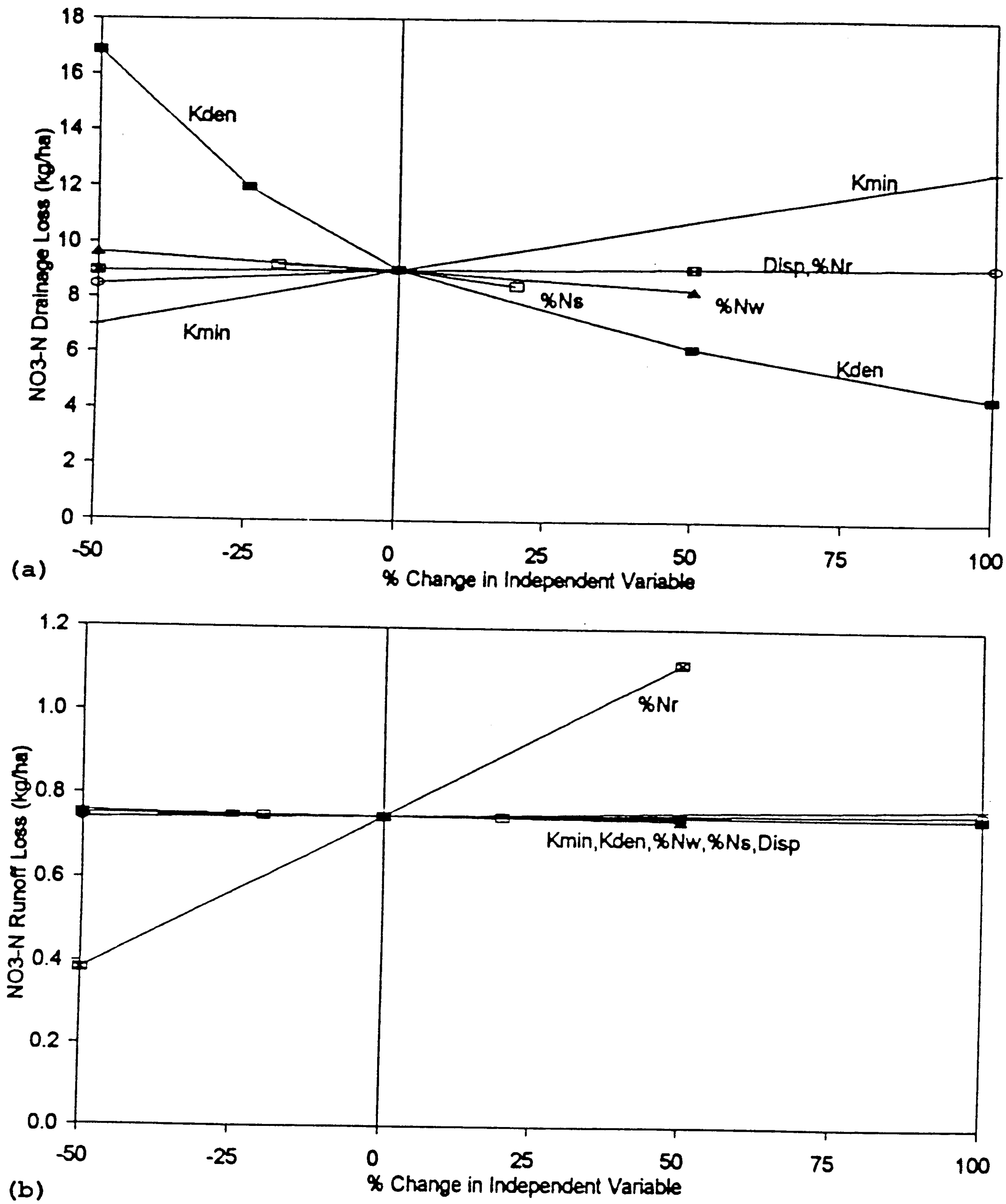


Figure 31 Predicted NO_3-N loss in drainage (a) and runoff (b), as affected by the denitrification (K_{den}) and mineralization (K_{min}) rate coefficients (1/d), dispersivity (Disp, cm), nitrogen content in rain (%Nr, mg/L), and percent of nitrogen (%) in soybean (%Ns) and wheat (%Nw).

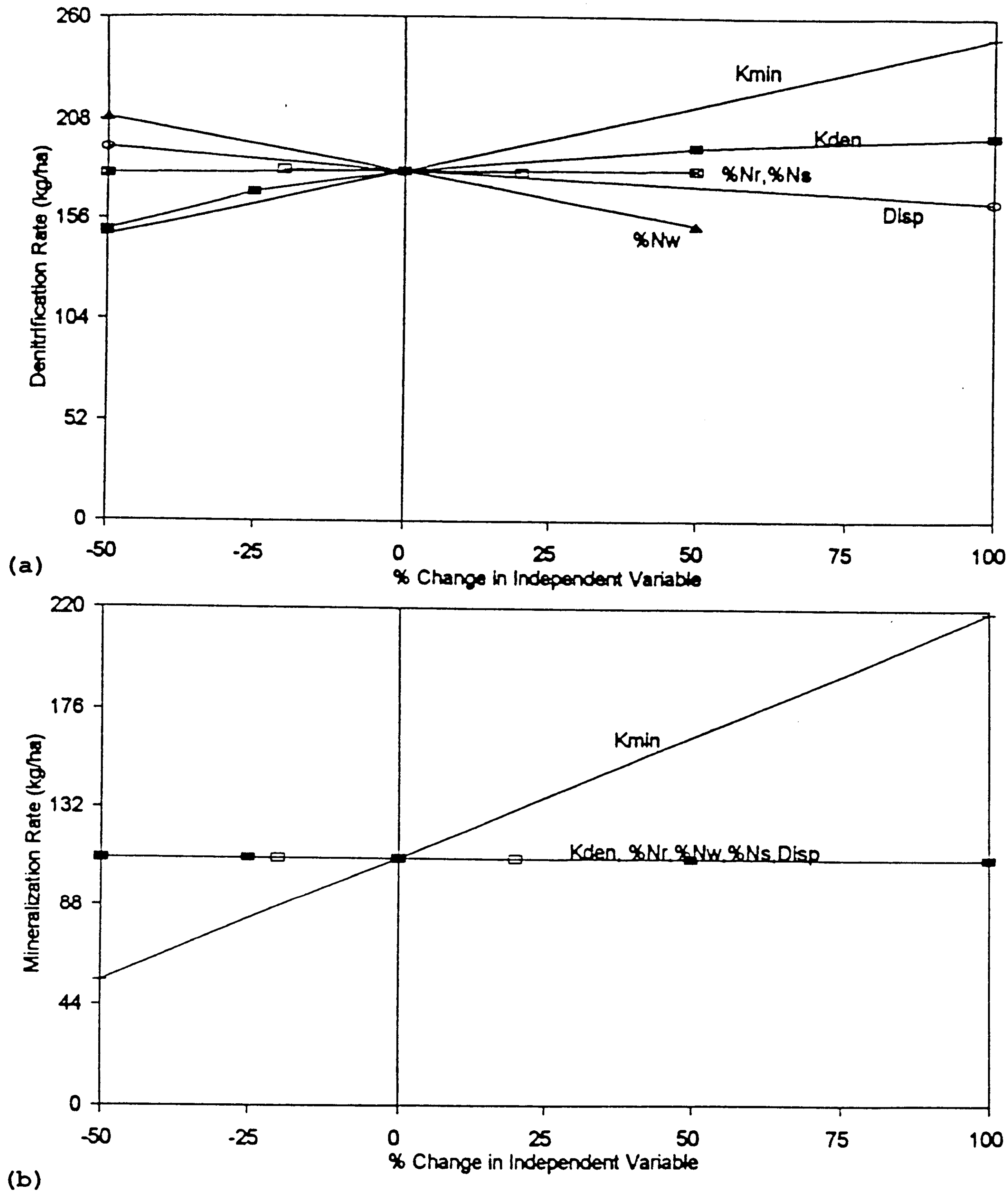


Figure 32 Predicted cumulative rates of denitrification (a) and mineralization (b), as affected by the denitrification (K_{den}) and mineralization (K_{min}) rate coefficients (1/d), dispersivity (Disp, cm), nitrogen content in rain (%Nr, mg/L), and percent of nitrogen (%) in soybean (%Ns) and wheat (%Nw).

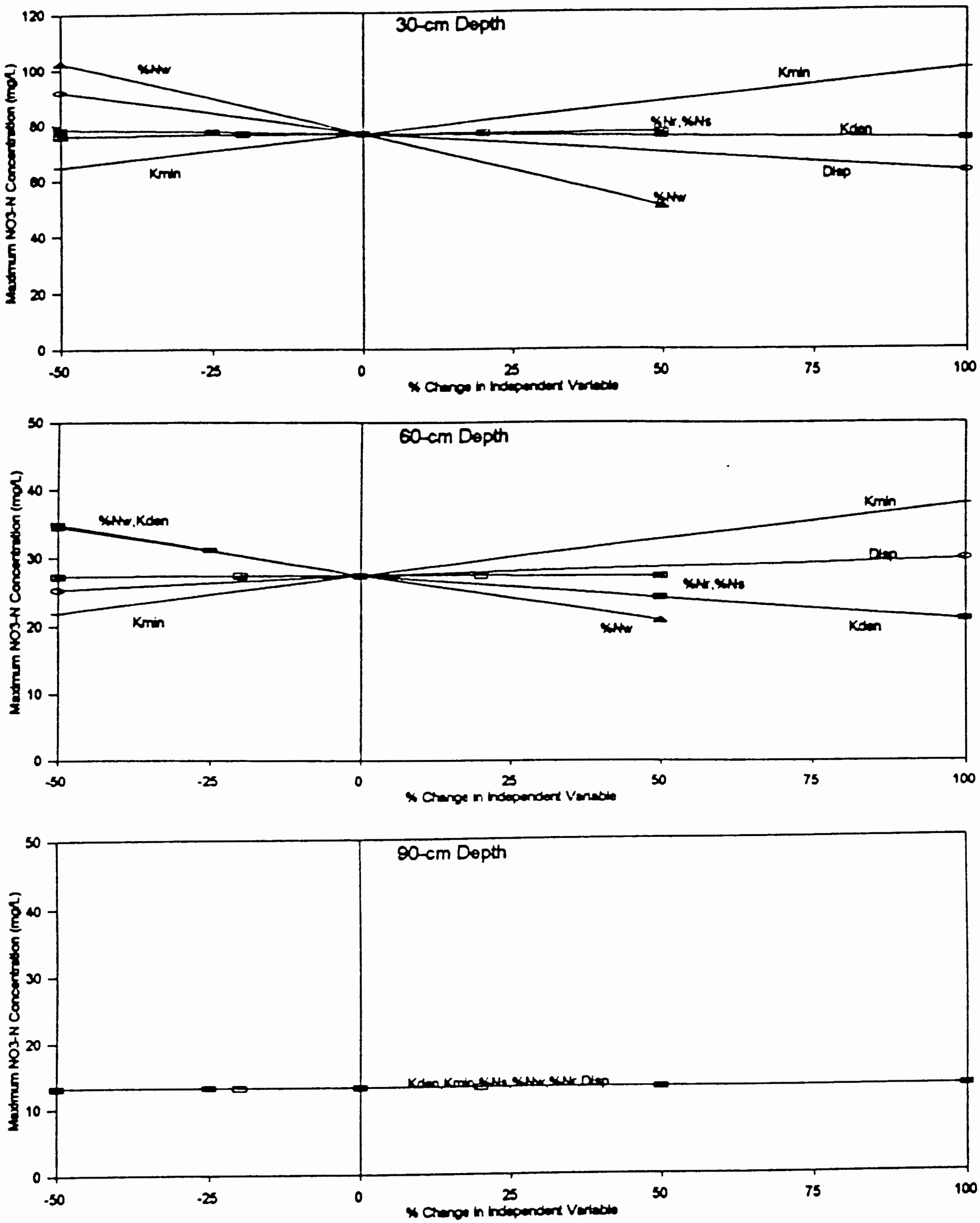


Figure 33 Predicted maximum NO_3-N concentration at different depths in the soil solution, as affected by the denitrification (K_{den}) and mineralization (K_{min}) rate coefficients (1/d), dispersivity (Disp, cm), nitrogen content in rain (%Nr, mg/L), and percent of nitrogen (%) in soybean (%Ns) and wheat (%Nw).

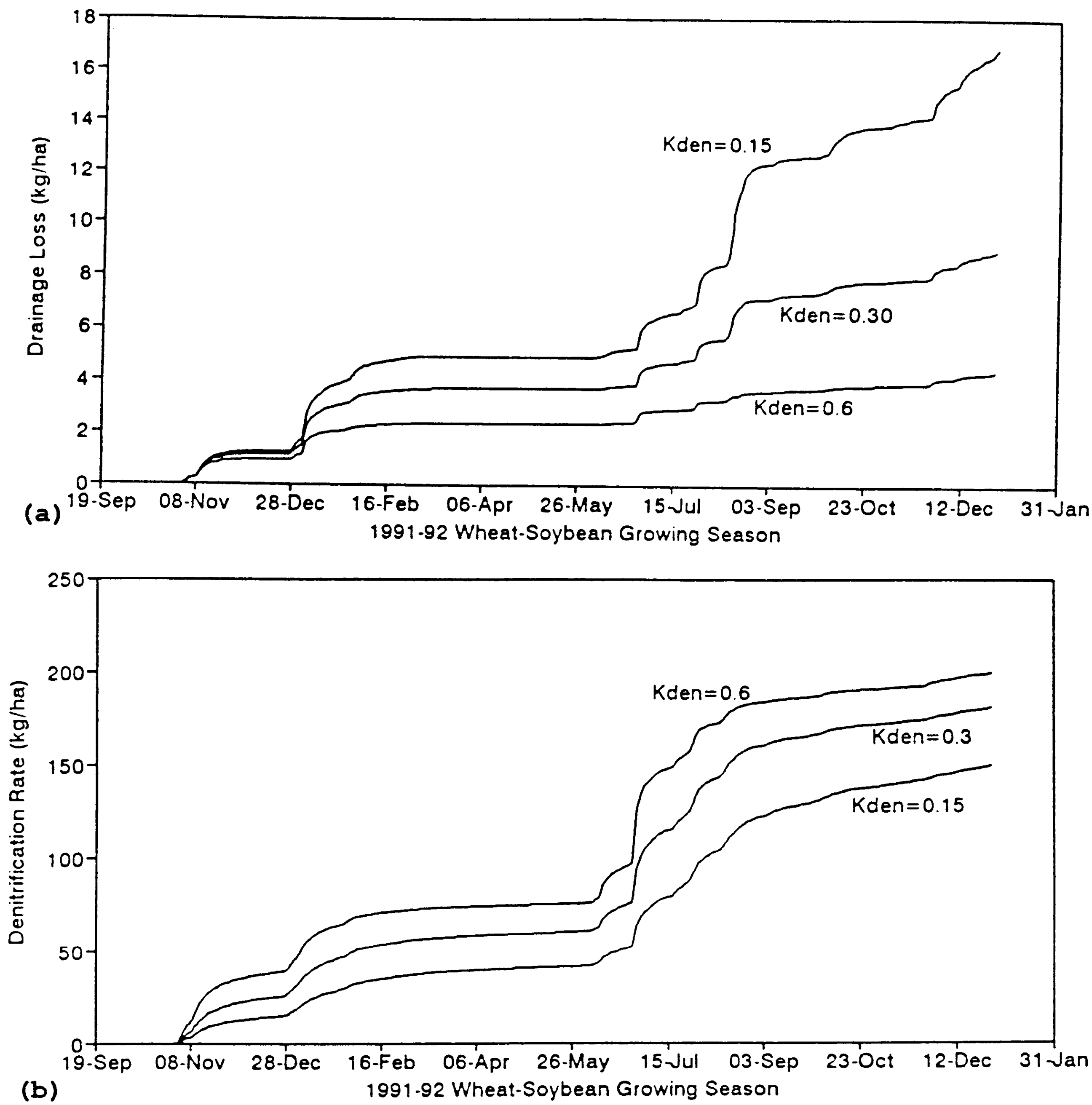


Figure 34 Predicted NO_3-N loss in drainage (a) and cumulative rate of denitrification (b), as affected by the denitrification rate coefficient (K_{den}, 1/d).

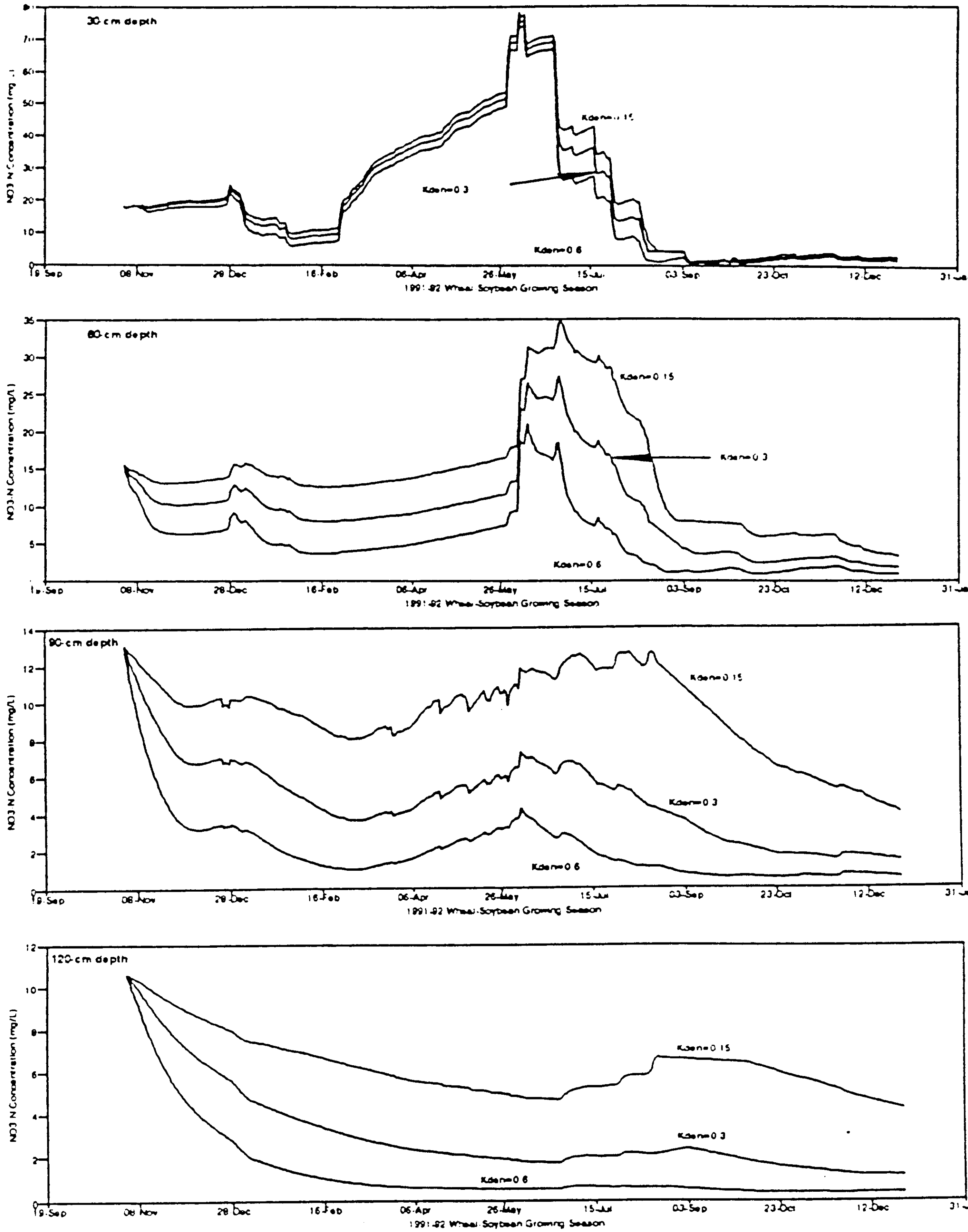


Figure 35 Predicted NO_3-N concentration for different depths in soil solution, as affected by the denitrification rate coefficient (K_{den}, 1/d).

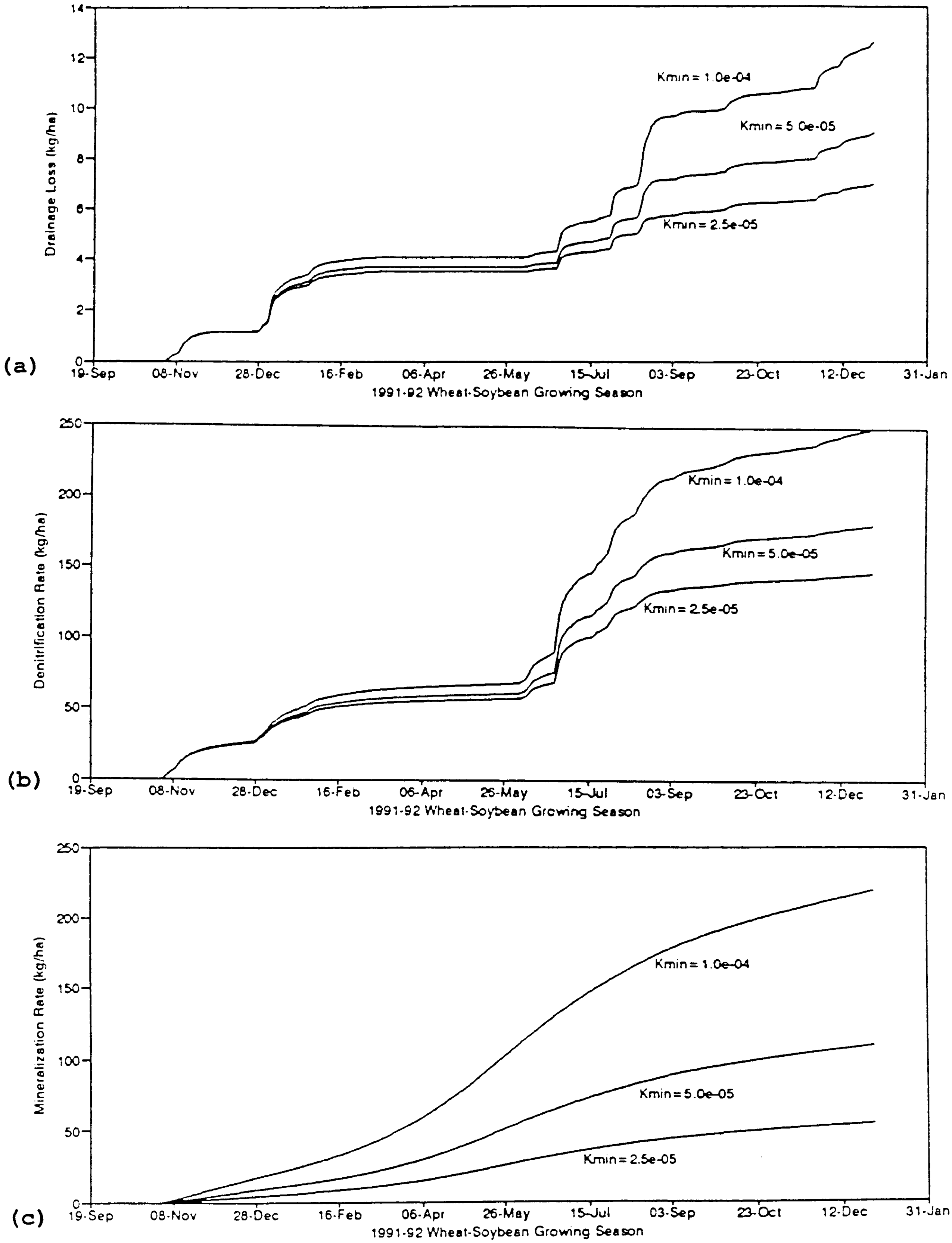


Figure 36 Predicted NO_3-N loss in drainage (a) and cumulative rates of denitrification (b) and mineralization (c), as affected by the mineralization rate coefficient (K_{min}, 1/d)

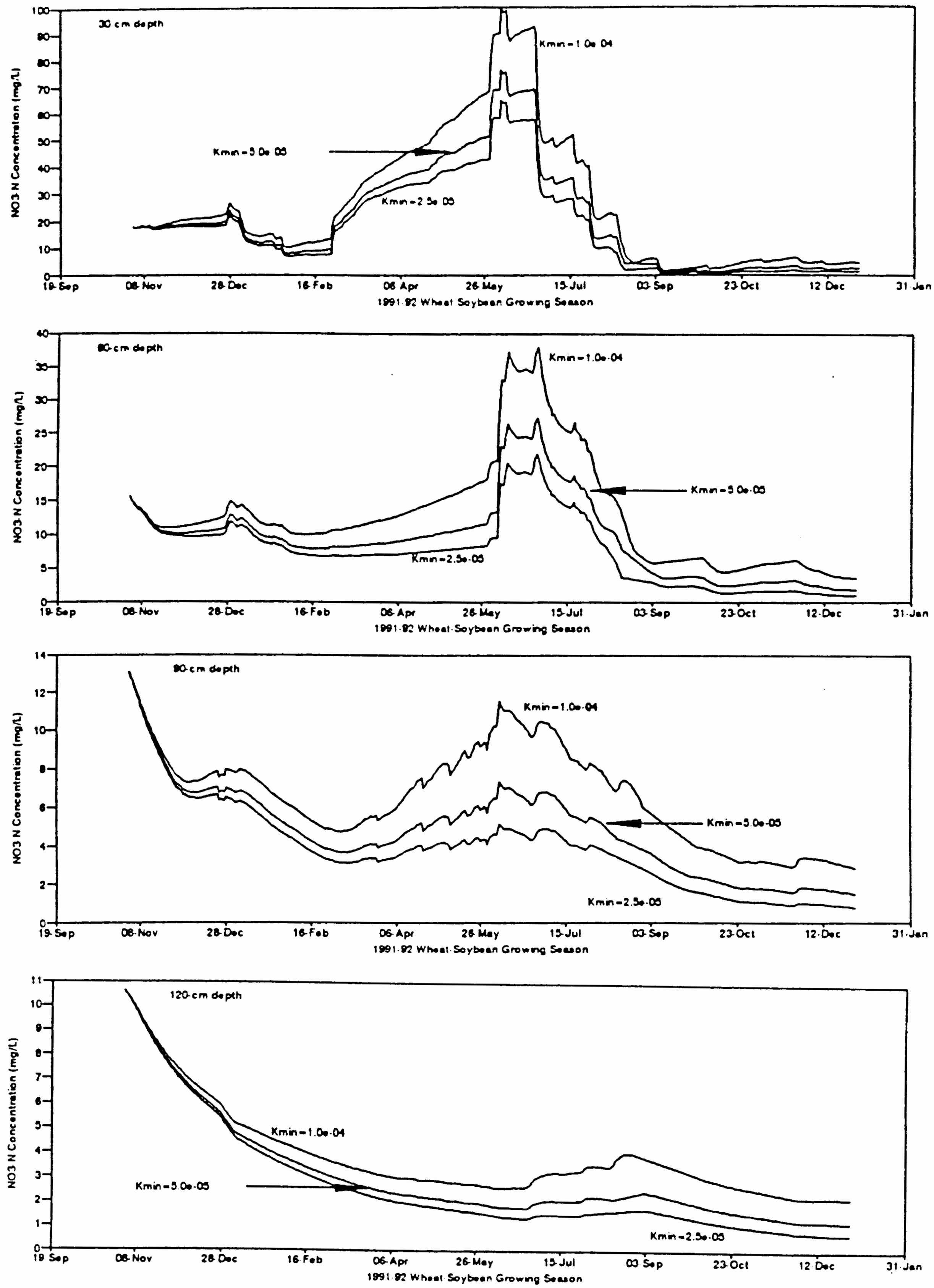
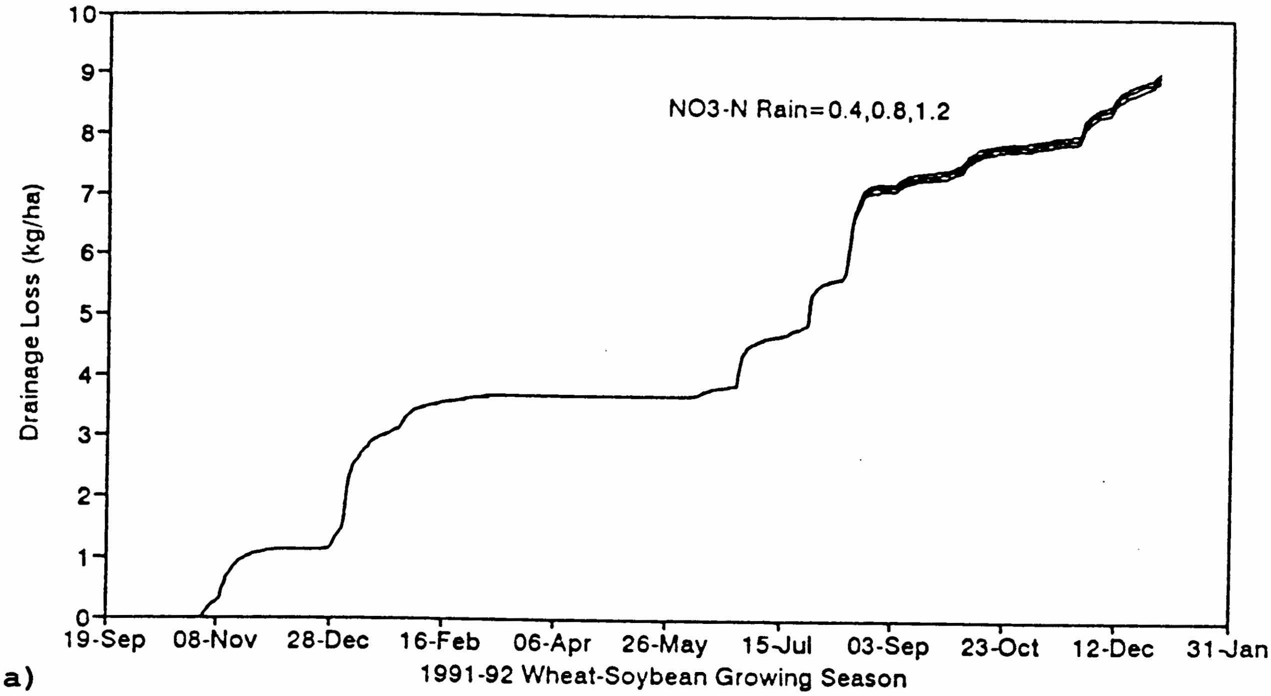
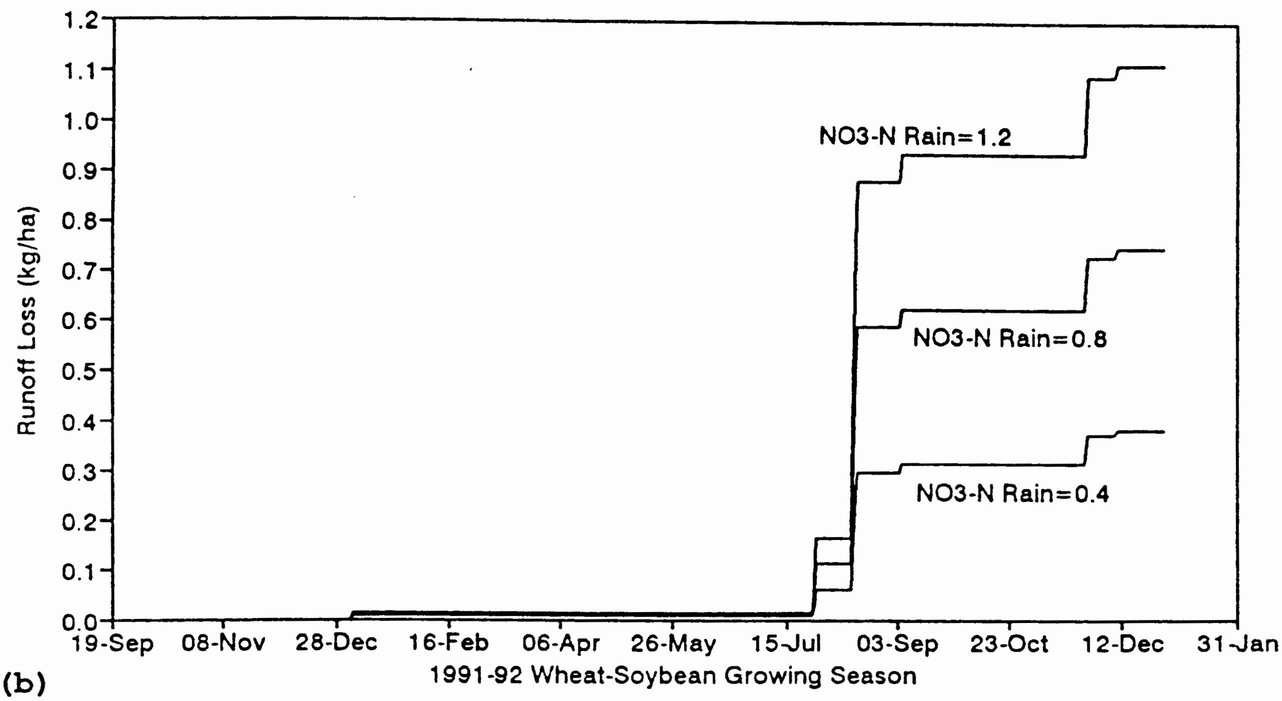


Figure 37 Predicted NO_3-N concentration for different depths in soil solution, as affected by the mineralization rate coefficient (K_{min}, 1/d).



(a)



(b)

Figure 38 Predicted NO_3-N loss (kg/ha) in drainage (a) and runoff (b), as affected by the nitrogen content in rain (NO_3-N Rain, mg/L).

Table 15. Nitrogen movement and fate parameters resulting from the calibrating procedure.

Parameter	Calibrated Value
Rate coefficient of denitrification (K_{den}, d^{-1})	0.30
Rate coefficient of net mineralization (K_{min}, d^{-1})	$5.0x10^{-5}$
Dispersivity (λ, cm)	5

RESULTS AND DISCUSSION

Simulations were conducted for each experimental field for the period of November 1, 1991, to December 31, 1992. Model predictions were compared to observed results for both the hydrologic variables and nitrogen losses. The comparison of hydrologic results was limited to the period of January 1 to December 31, 1992 because the water table measurements were not complete for all plots prior to January 1, 1992. Results for the water balance are discussed first followed by predicted and observed results for nitrogen status in the soil and losses via surface runoff and subsurface drainage.

Hydrology. As previously stated, key input parameters (K_{den}, K_{min} and dispersivity) were calibrated against observed data from field 3. Calibrated results are shown in Table 16 and Figure 39. This figure displays a comparison between simulated and observed water table depths, cumulative subsurface drainage, and cumulative surface runoff. The two observed surface runoff curves correspond to two runoff subplots located in each field. The calibrated results indicate simulated water table depths, subsurface drainage volumes and surface runoff volumes were within 7.7, 0.9 and 0.5 cm, respectively, of observed values (Table 16).

Results for the hydrologic components of the remaining plots are shown in Figures 40-44 (conventional drainage, field 4; controlled drainage, fields 2 and 5; controlled drainage-subirrigation, fields 1 and 6). A statistical summary of the results is shown in Table 16.

Table 16. Summary of simulated versus observed hydrologic results. (Jan. 1, 1992 to Dec. 31, 1992)

	Experimental Plots					
	3	4	2	5	1	6
Water table depth (cm)						
Avg. abs. dev.	7.7	11.9	13.3	10.1	12.8	13.5
Subsurface drainage volume (cm)						
Total obs.	33.1	46.7	28.8	37.9	26.0	31.7
Total sim.	34.0	37.0	32.6	33.0	32.6	30.3
% error	+2.7	-20.8	+13.2	-12.9	+25.4	-4.4
Surface runoff volume (cm)						
Total obs.	11.2	8.7	11.7	10.8	15.8	19.1
Total sim.	10.7	8.4	15.6	15.5	24.7	24.9
% error	-4.5	-3.4	+33.3	+43.5	+56.3	+30.4
Subirrigation volume (cm)						
Total obs.					8.7	8.4
Total sim.					8.3[1]	7.8
% error					-4.6	-7.1

[1]Total simulated subirrigation does not include simulated subirrigation of March 24-April 21, 1992, for plot 1.

Good agreement was found between the observed and predicted results for the conventionally drained field 4 (Figure 40). This is indicated, in Table 16, by the values of the average absolute deviation of the water table depth (12 cm) and percent error for subsurface drainage (21%) and surface runoff (4%). The largest deviation occurred during the months of June and July. This was the period when wheat was harvested and soybeans were planted. The deviation appeared to be due to the model overestimating ET during this period.

Agreement was also good for fields 2 and 5, under controlled drainage (Figures 41-42), especially for the water table depths and cumulative subsurface drainage. The average absolute deviation for the water table depth in the two fields were 10 and 13 cm, respectively, and the percent error of the subsurface drainage was about 13% (Table 16). Surface runoff was overpredicted for both fields, as the simulated values were 33-43% greater than observed, but the simulated values were still

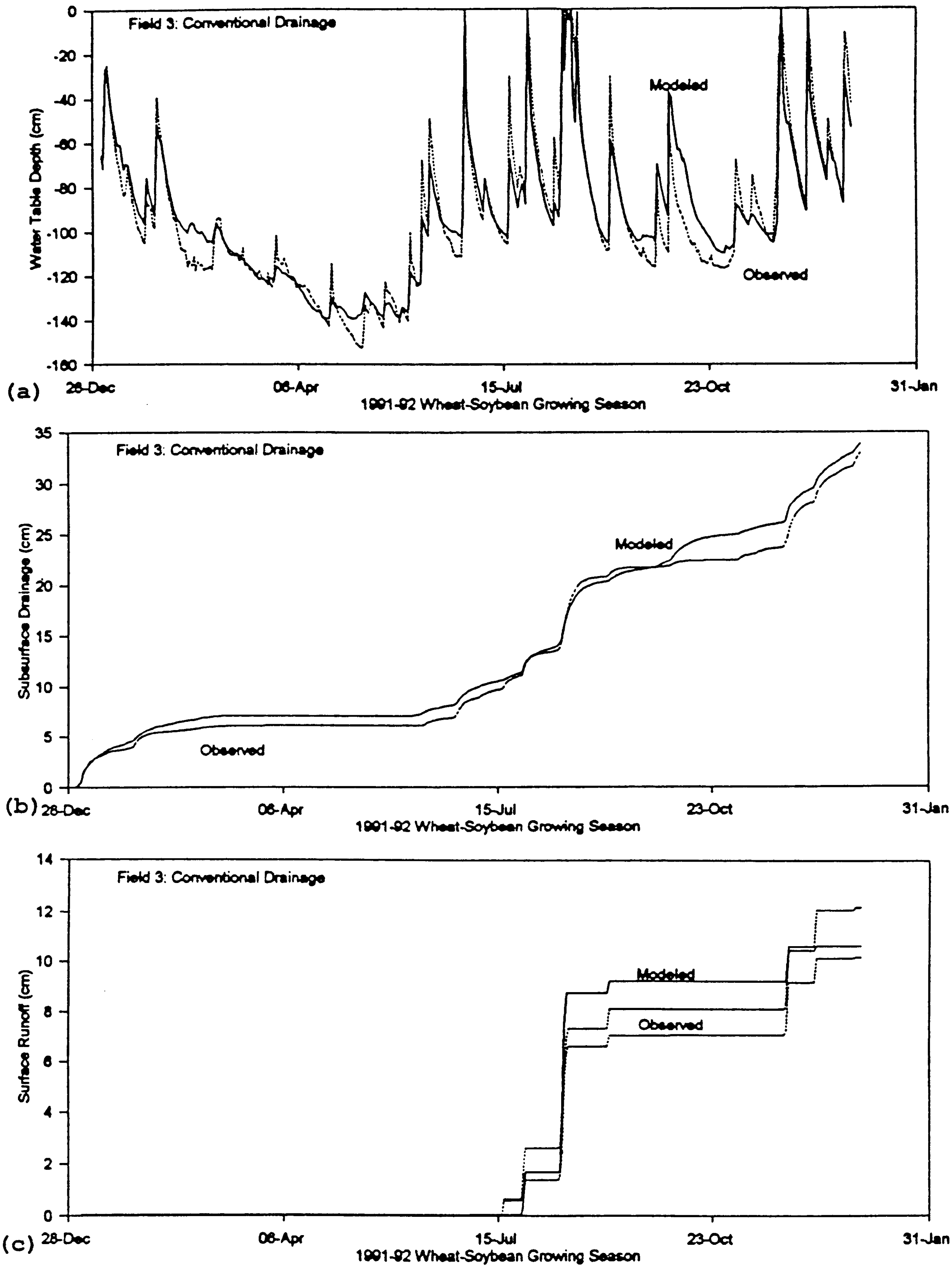


Figure 39 Simulated versus observed water table depth (a), subsurface drainage (b) and surface runoff (c) for field 3, conventional drainage.

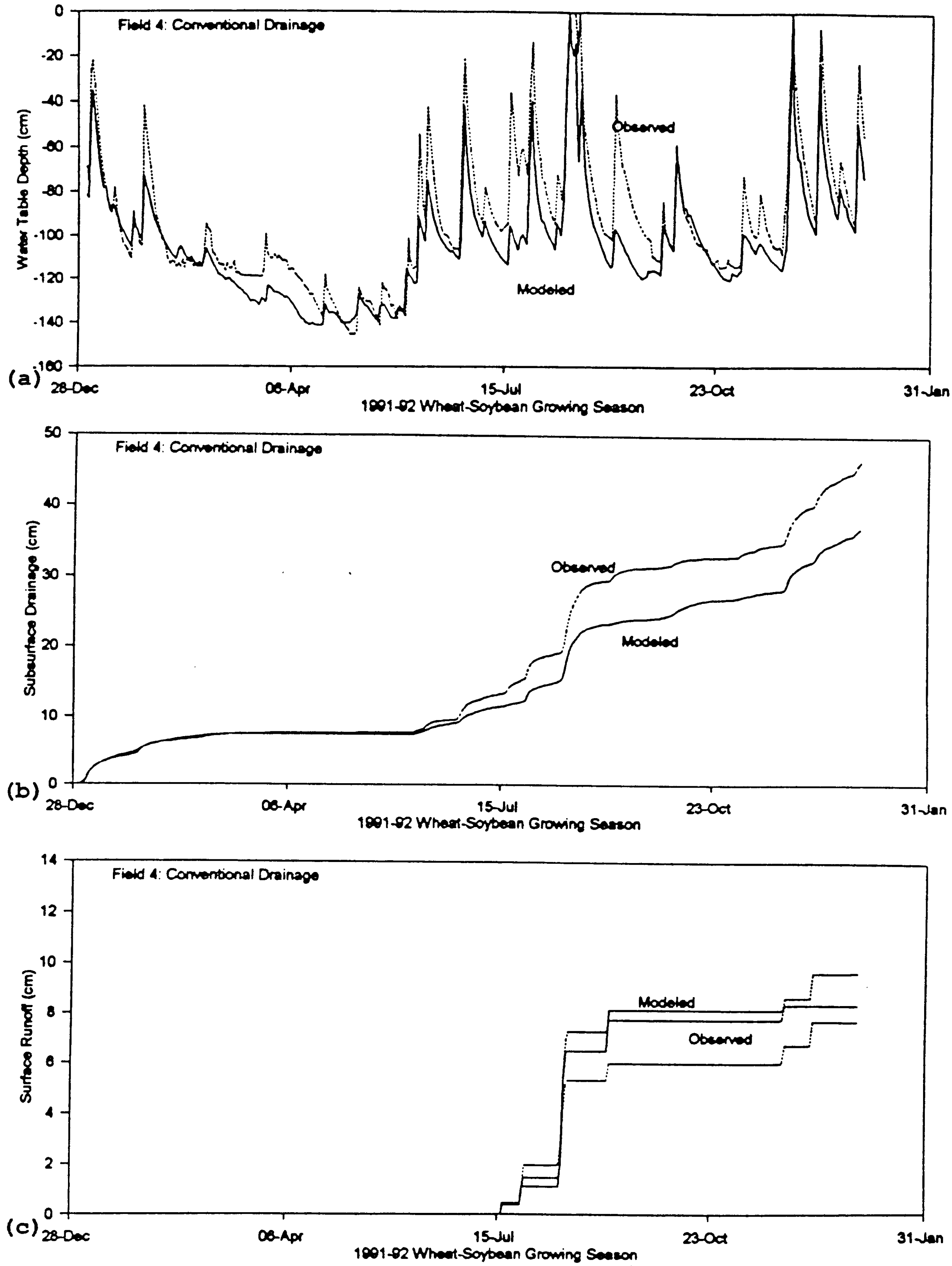


Figure 40 Simulated versus observed water table depth (a), subsurface drainage (b) and surface runoff (c) for field 4, conventional drainage.

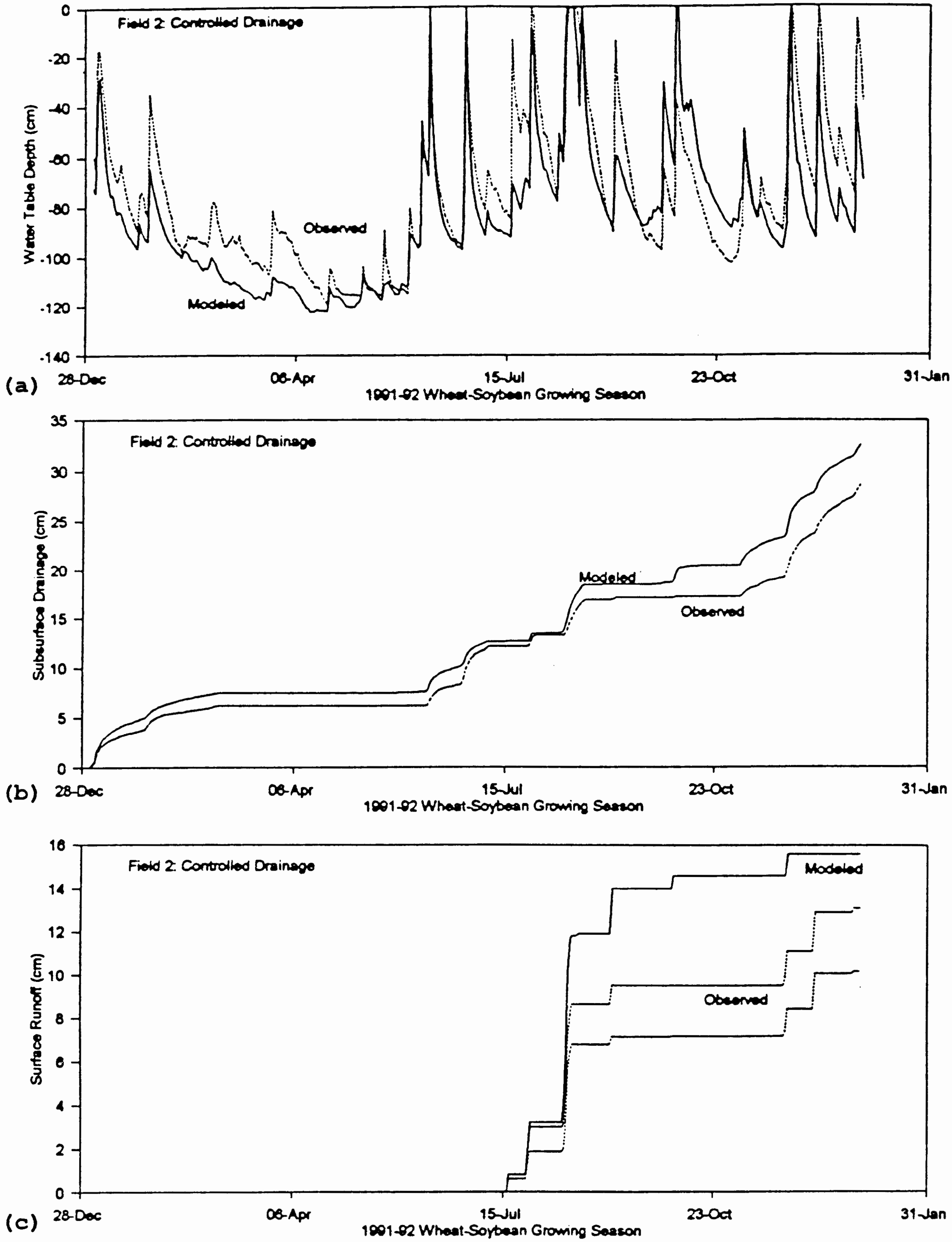


Figure 41 Simulated versus observed water table depth (a), subsurface drainage (b) and surface runoff (c) for field 2, controlled drainage.

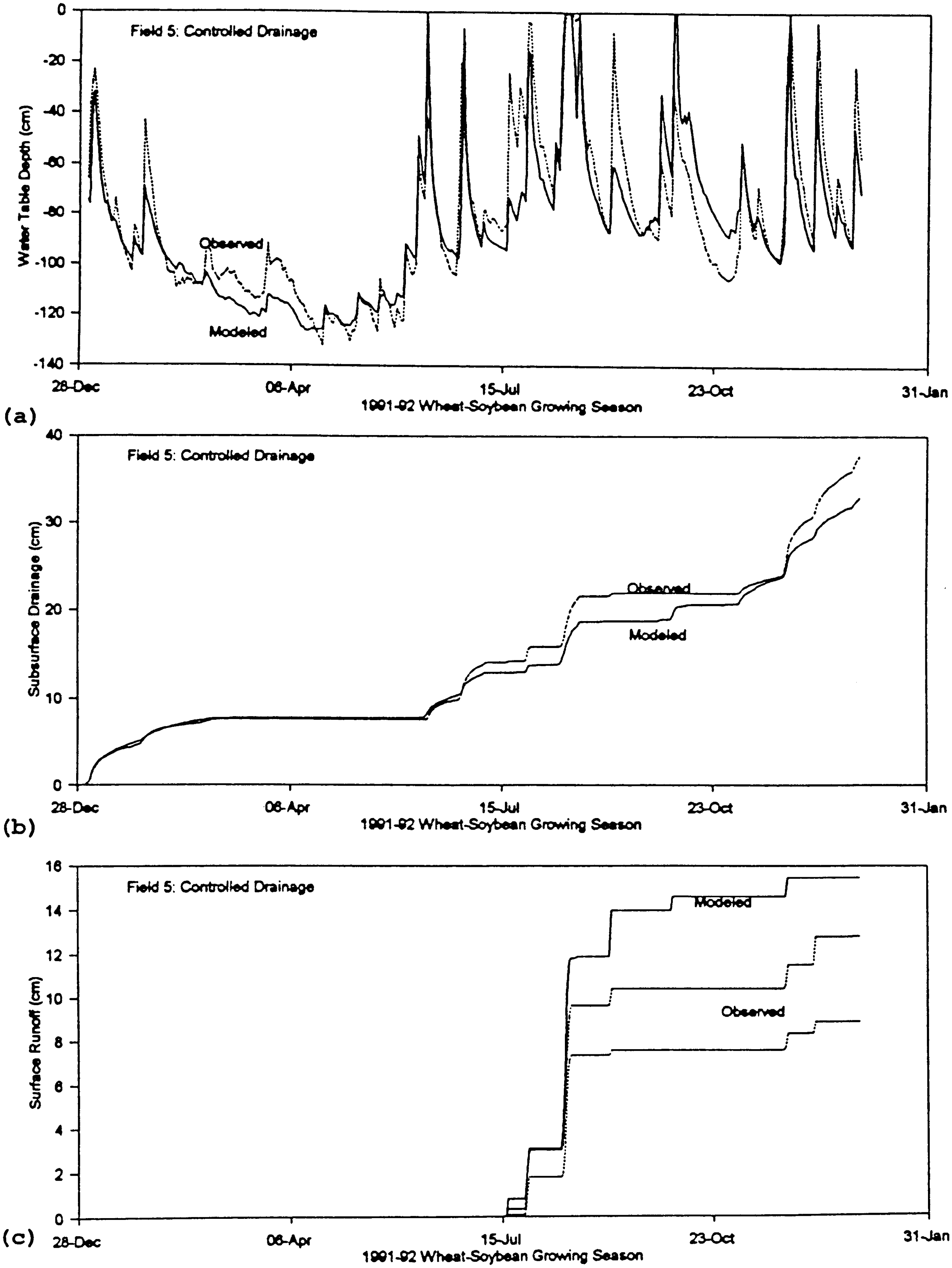


Figure 42 Simulated versus observed water table depth (a), subsurface drainage (b) and surface runoff (c) for field 5, controlled drainage.

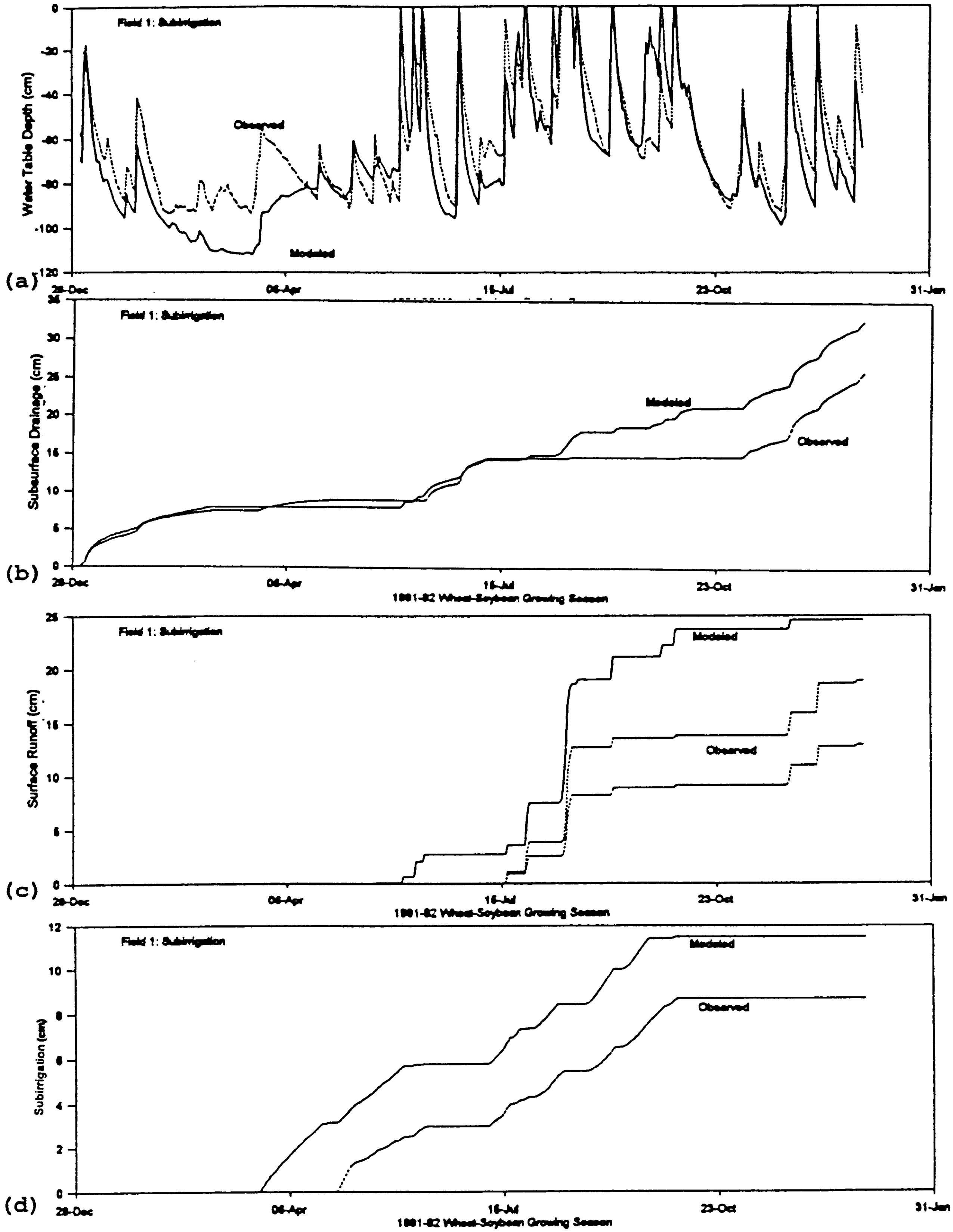


Figure 43 Simulated versus observed water table depth (a), subsurface drainage (b), surface runoff (c) and subirrigation (d) for field 1, subirrigation.

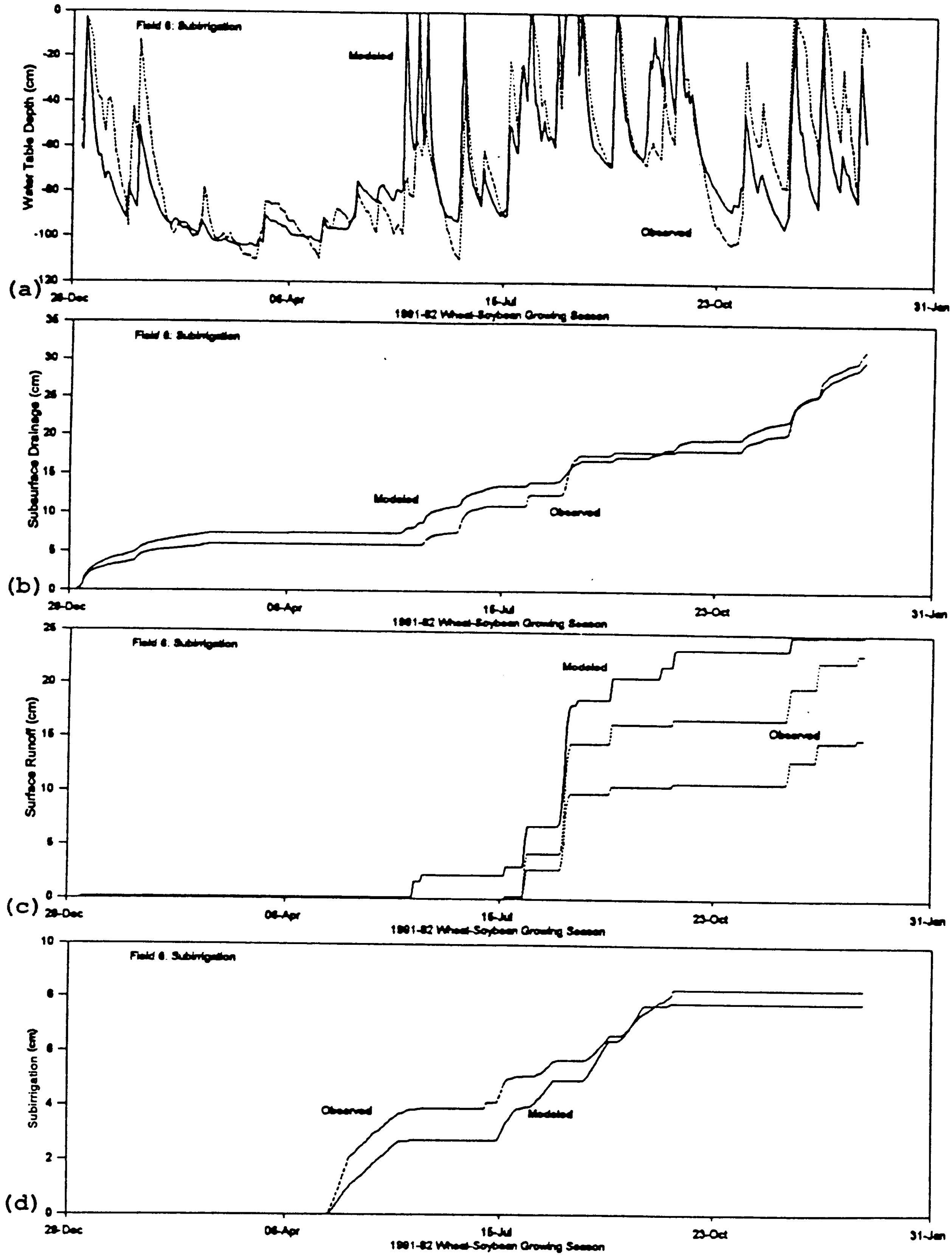


Figure 44 Simulated versus observed water table depth (a), subsurface drainage (b), surface runoff (c) and subirrigation (d) for field 6, subirrigation.

within 4-5 cm of the observed data (Table 16). There was again evidence that ET was overestimated and subsurface drainage underestimated during the June-July period in fields 2 and 5 (Fig. 41 and 42). The predicted water table and subsurface drainage were both lower than observed for that period. Furthermore, underprediction of subsurface drainage in field 5 was nearly the same as the overprediction of surface runoff (Table 16 and Fig. 42).

Good agreement was found between the observed and simulated results for field 6 (subirrigation), as shown in Figure 44. The agreement was not good for field 1 (Fig. 43). Part of this discrepancy can be explained by a situation that occurred during the early spring of 1992. An experiment to monitor water table drawdown was conducted from March 23 to April 22, which consisted of pumping water through both guard lines in field 1. This caused the water table to rise in early April (Fig. 43). This situation is difficult to model since water is being subirrigated through the guard lines and drained through the control line. An attempt was made to approximate this situation by setting the model under subirrigation (Table 16), which is reflected in the water table depth and subirrigation plots (Fig. 43). After the conditions normalized, the agreement was good for water table depth and subirrigation, but not good for drainage and runoff (Fig. 43). Another factor that affected results for field 1, when water tables were high, was seepage to the drainage ditch on the south side of the field (Fig. 1). This seepage reduced observed subsurface drainage and surface runoff volumes compared to what they would have been if the seepage had been eliminated. Conversely, model drainage and runoff volumes would have been reduced had the seepage been accounted for in the model. Results in Table 16 indicate that the average absolute deviation of the water table depth for fields 1 and 6 was about 13 cm, and the percent errors were 4% and 25% (1.4 and 6.6 cm) for subsurface drainage, 30% and 56% (5.8 and 8.9 m) for surface runoff, and 7% and 5% (0.6 and 0.4 cm) for subirrigation, respectively.

<u>Nitrogen</u>. Nitrogen results (NO_3-N losses in subsurface drainage and surface runoff, plant uptake of nitrogen, and NO_3-N concentrations in soil solution) are shown in Figures 45-56, for all six experimental fields. Table 17 gives a statistical summary of the results for nitrogen predictions and observations.

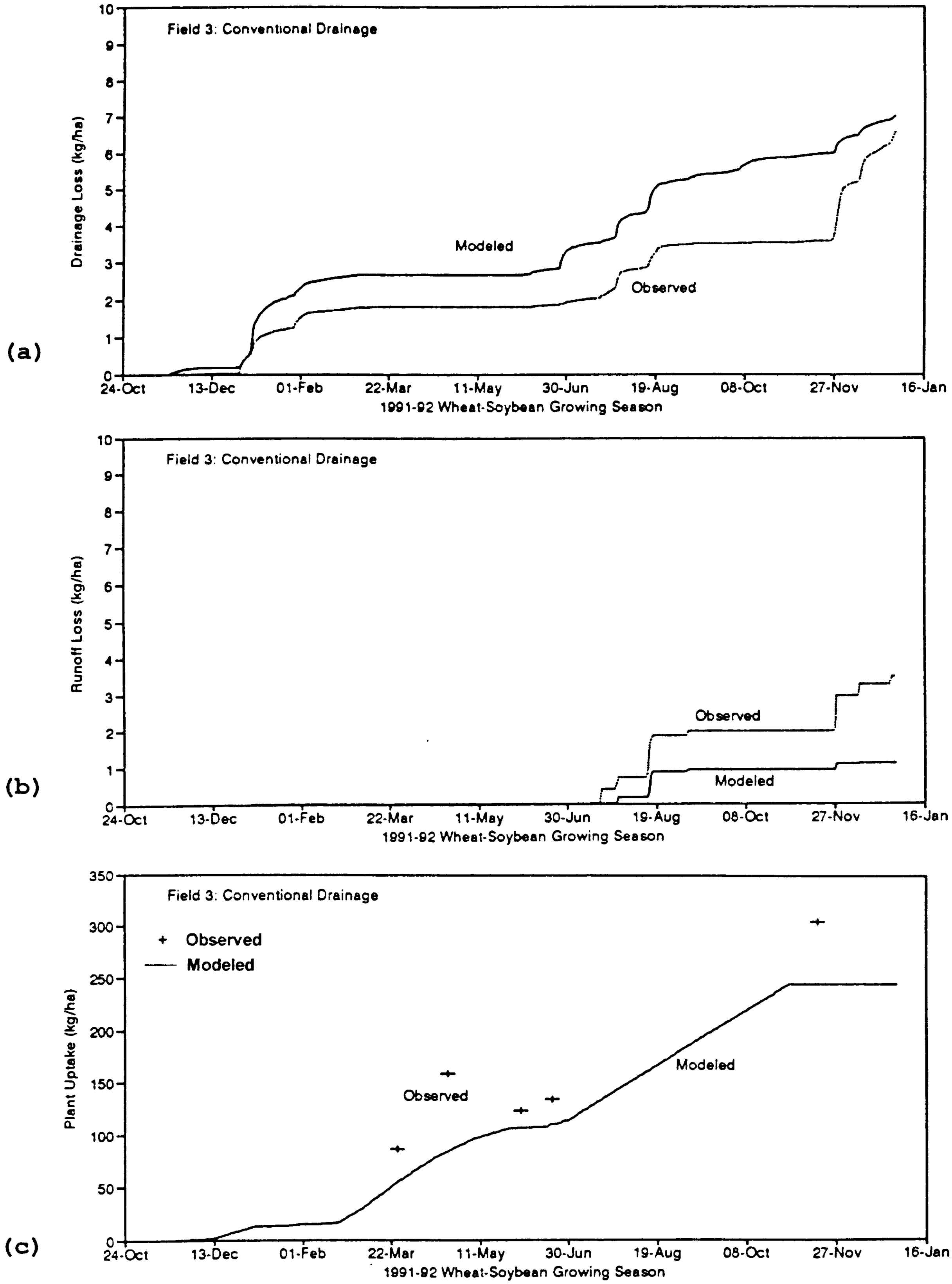


Figure 45 Simulated versus observed NO_3-N losses in subsurface drainage (a) and surface runoff (b), and plant uptake (c) for field 3, conventional drainage.

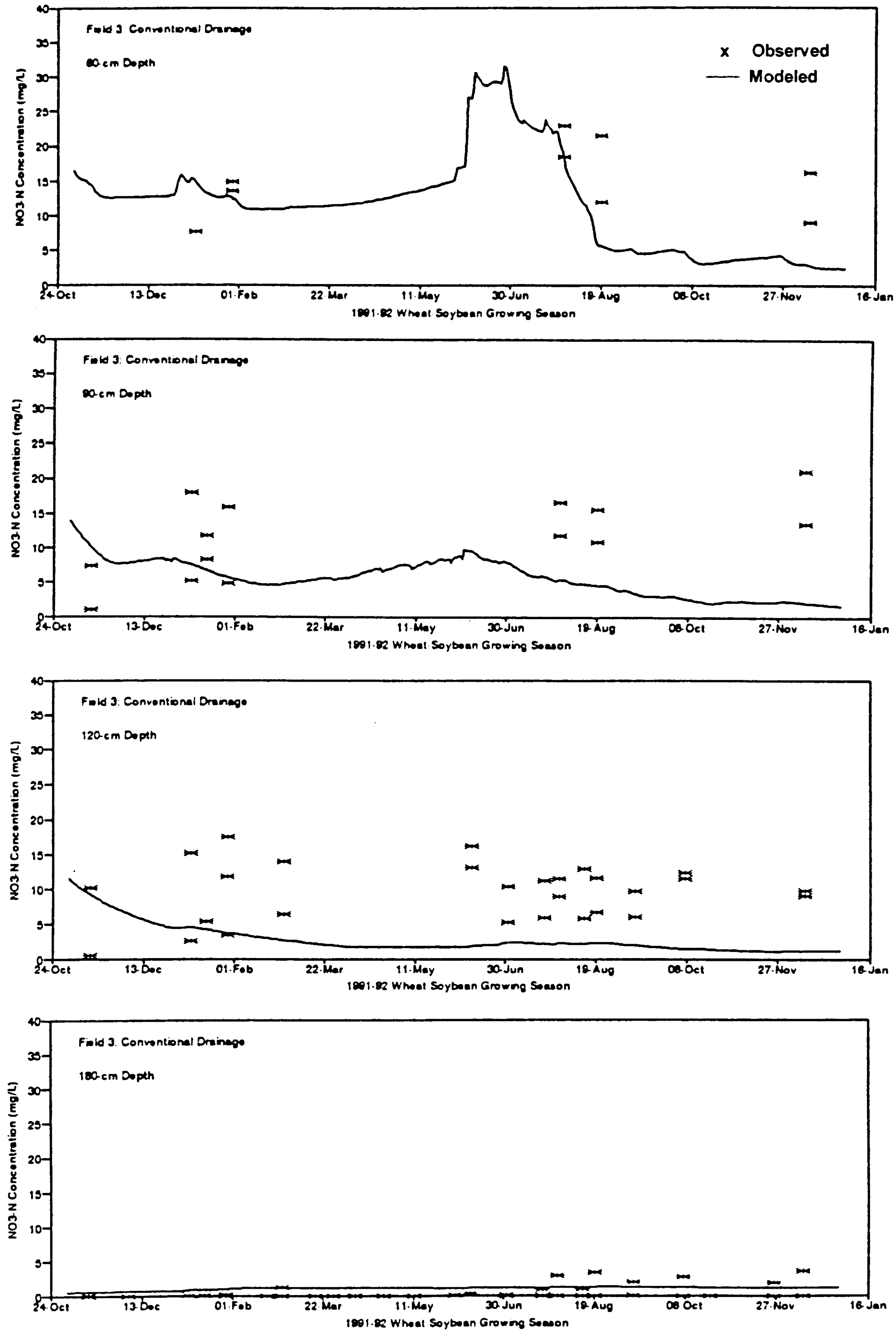


Figure 46 Simulated versus observed NO_3-N concentrations in soil solution at different depths for field 3, conventional drainage.

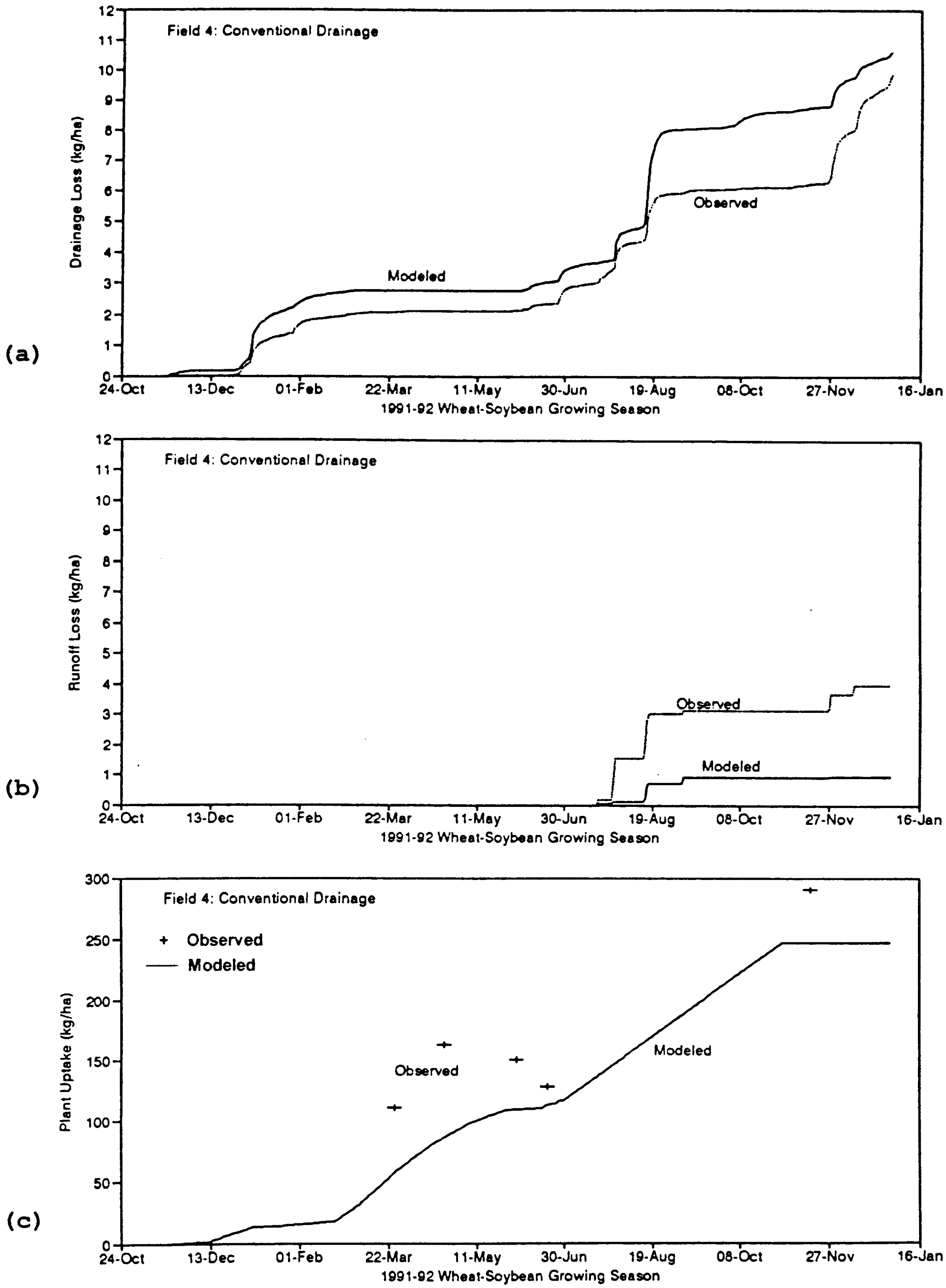


Figure 47 Simulated versus observed NO_3-N losses in subsurface drainage (a) and surface runoff (b), and plant uptake (c) for field 4, conventional drainage.

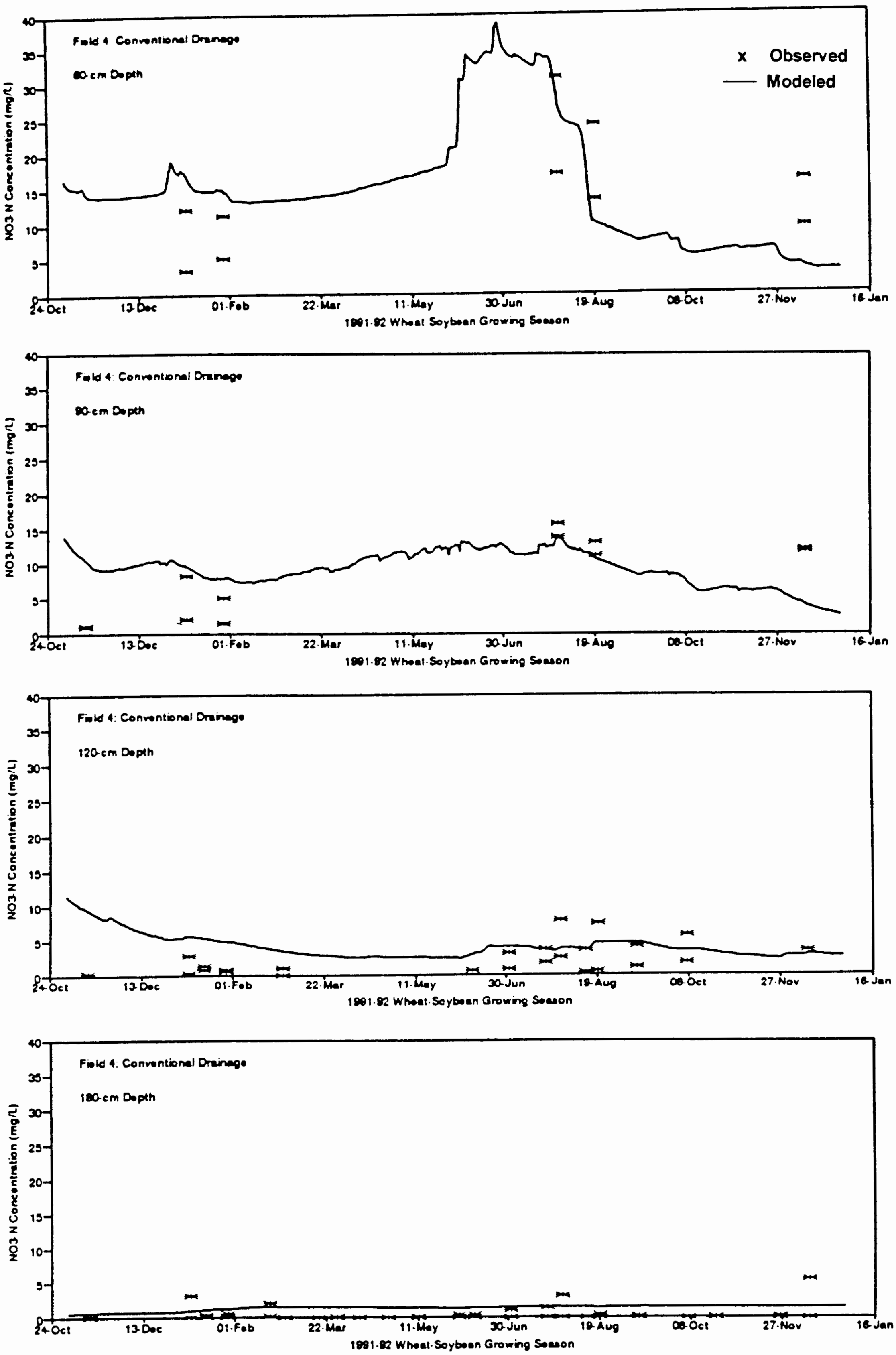


Figure 48 Simulated versus observed NO_3-N concentrations in soil solution at different depths for field 4, conventional drainage.

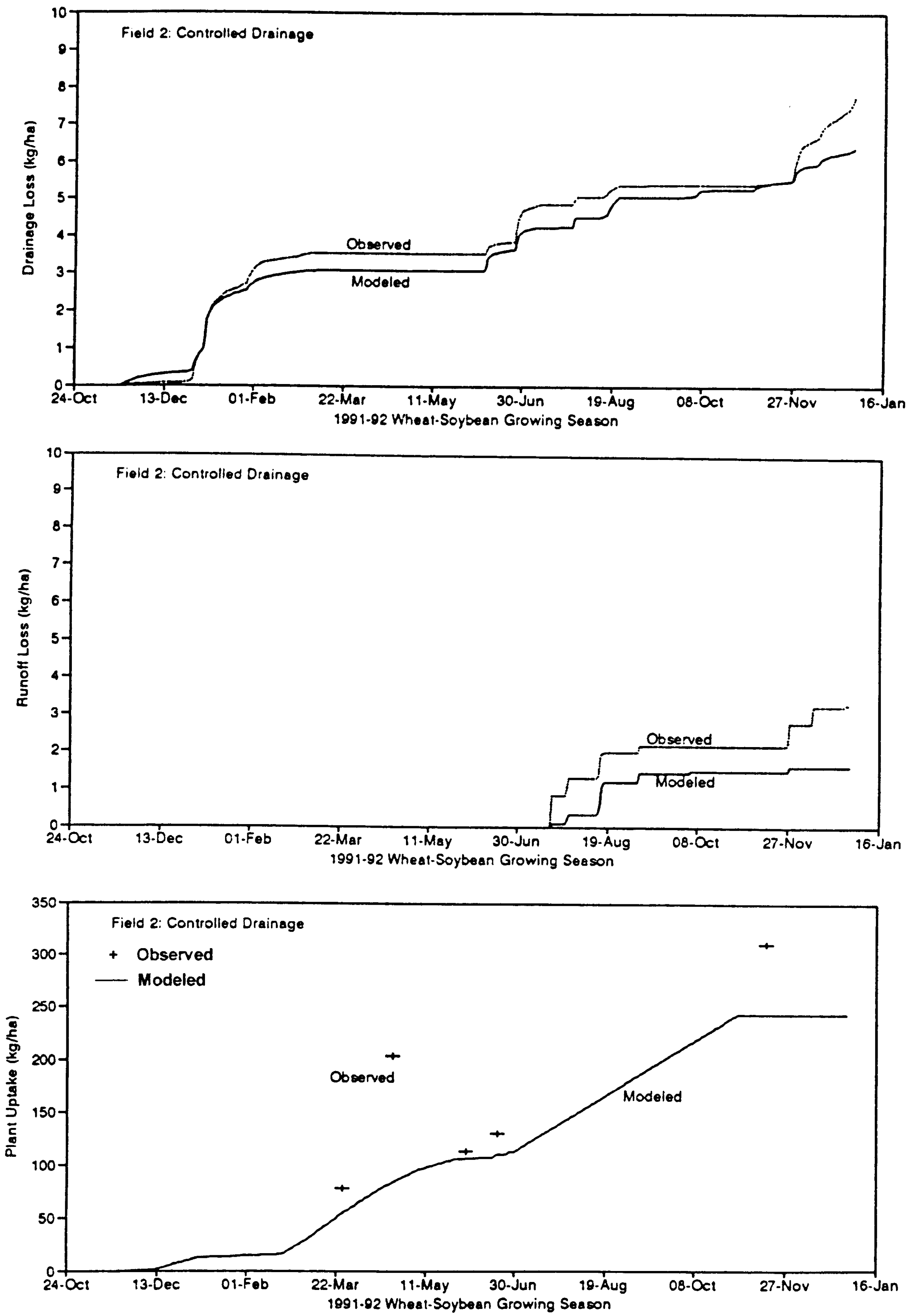


Figure 49 Simulated versus observed NO_3-N losses in subsurface drainage (a) and surface runoff (b), and plant uptake (c) for field 2, controlled drainage.

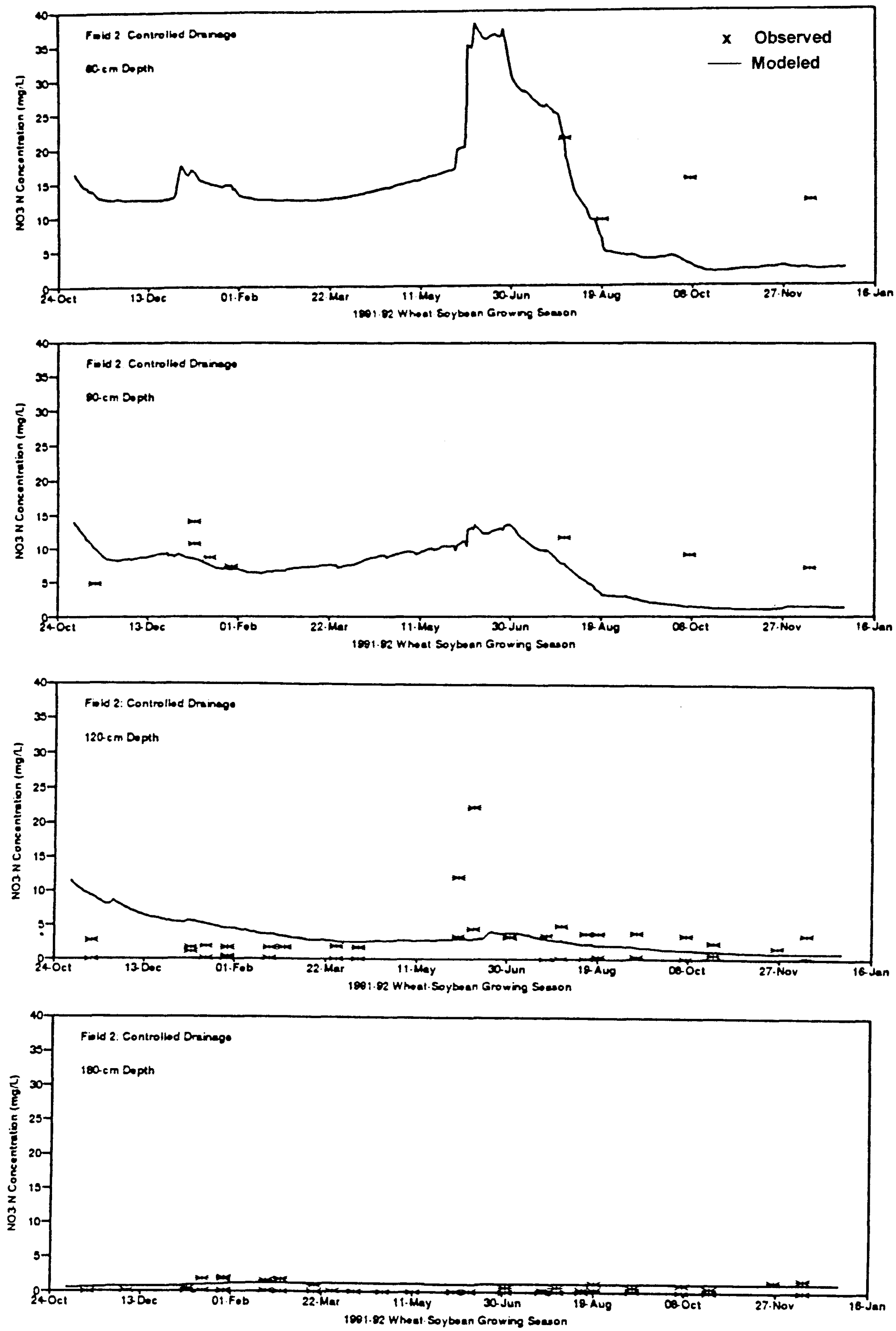


Figure 50 Simulated versus observed NO_3-N concentrations in soil solution at different depths for field 2, controlled drainage.

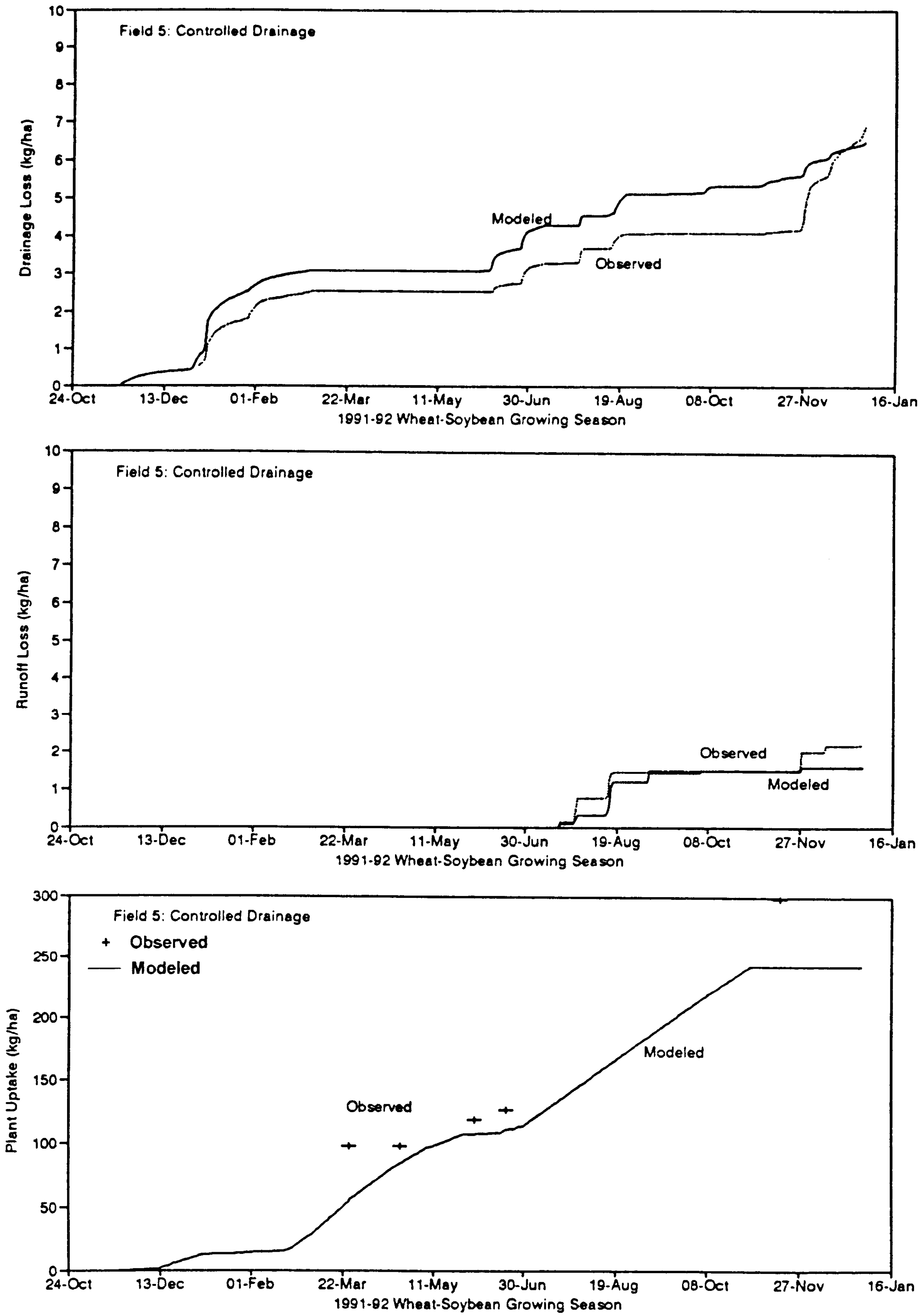


Figure 51 Simulated versus observed NO_3-N losses in subsurface drainage (a) and surface runoff (b), and plant uptake (c) for field 5, controlled drainage.

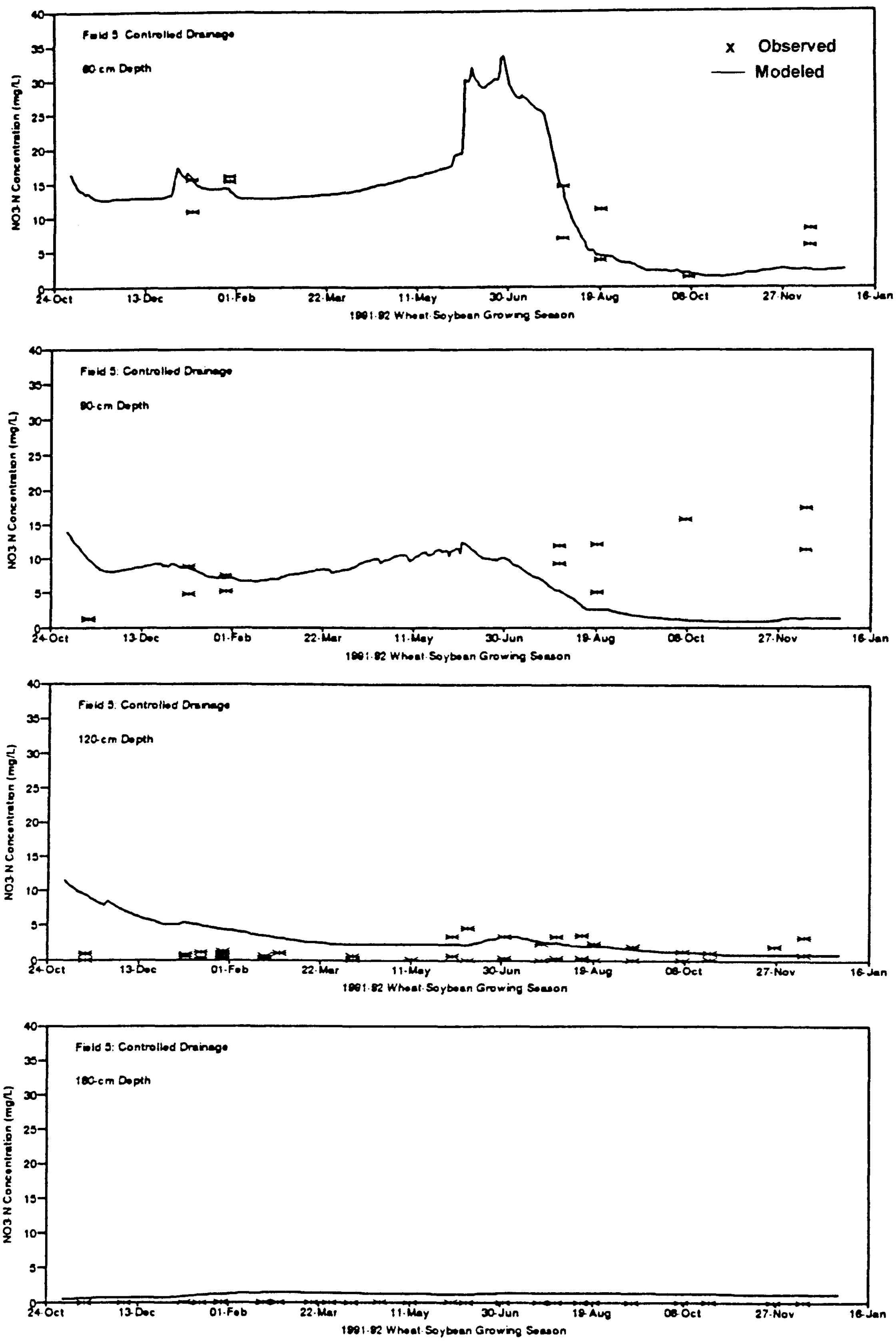
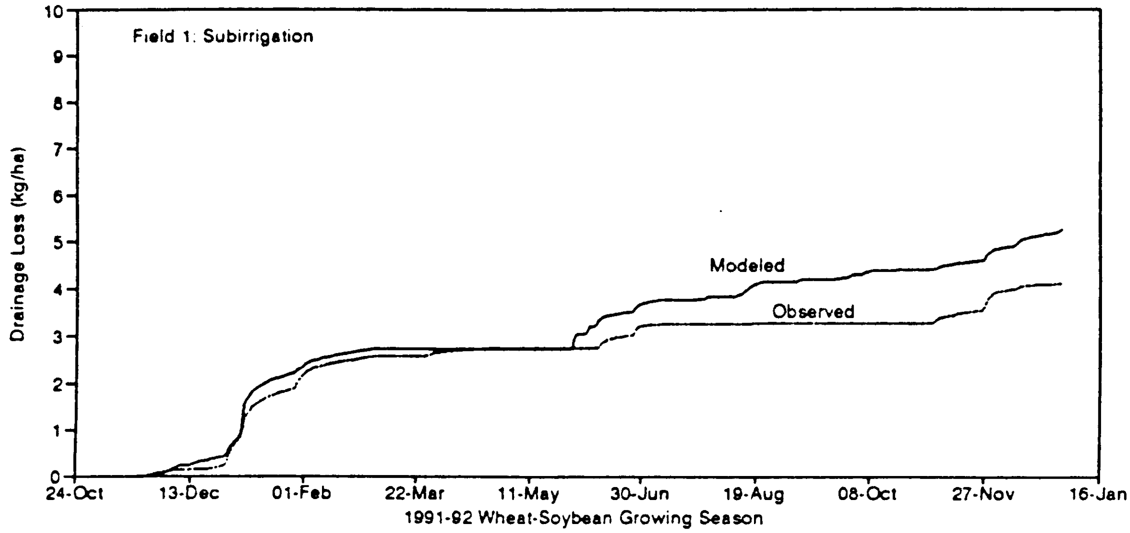
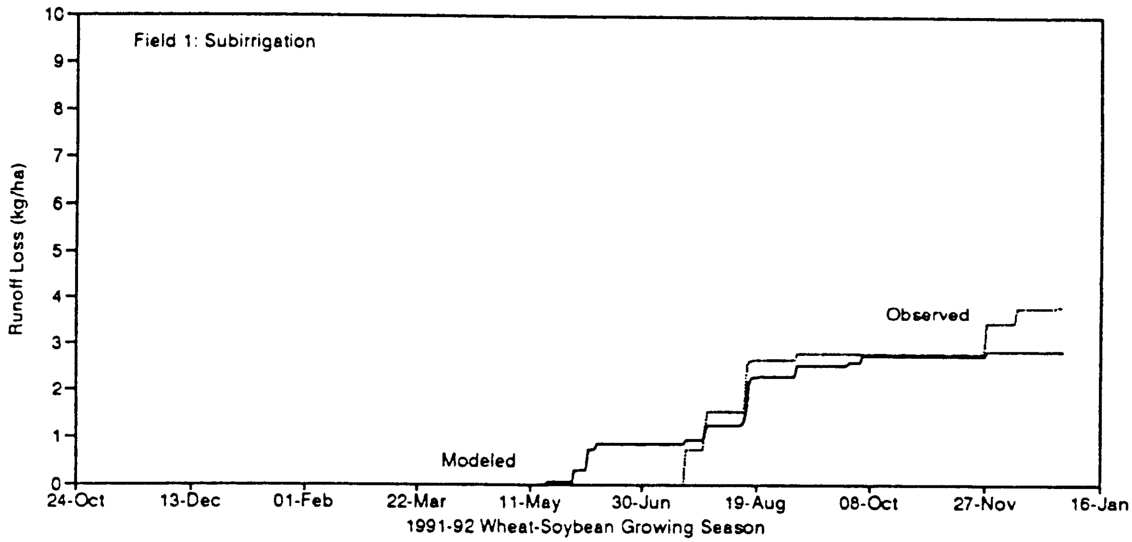


Figure 52 Simulated versus observed NO_3-N concentrations in soil solution at different depths for field 5, controlled drainage.

(a)



(b)



(c)

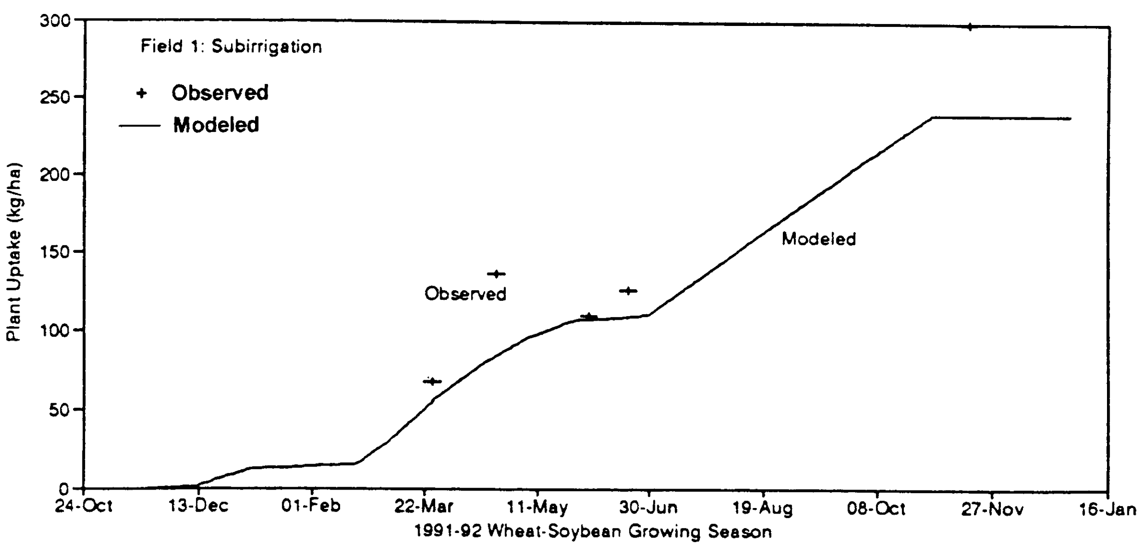


Figure 53 Simulated versus observed NO_3-N losses in subsurface drainage (a) and surface runoff (b), and plant uptake (c) for field 1, subirrigation.

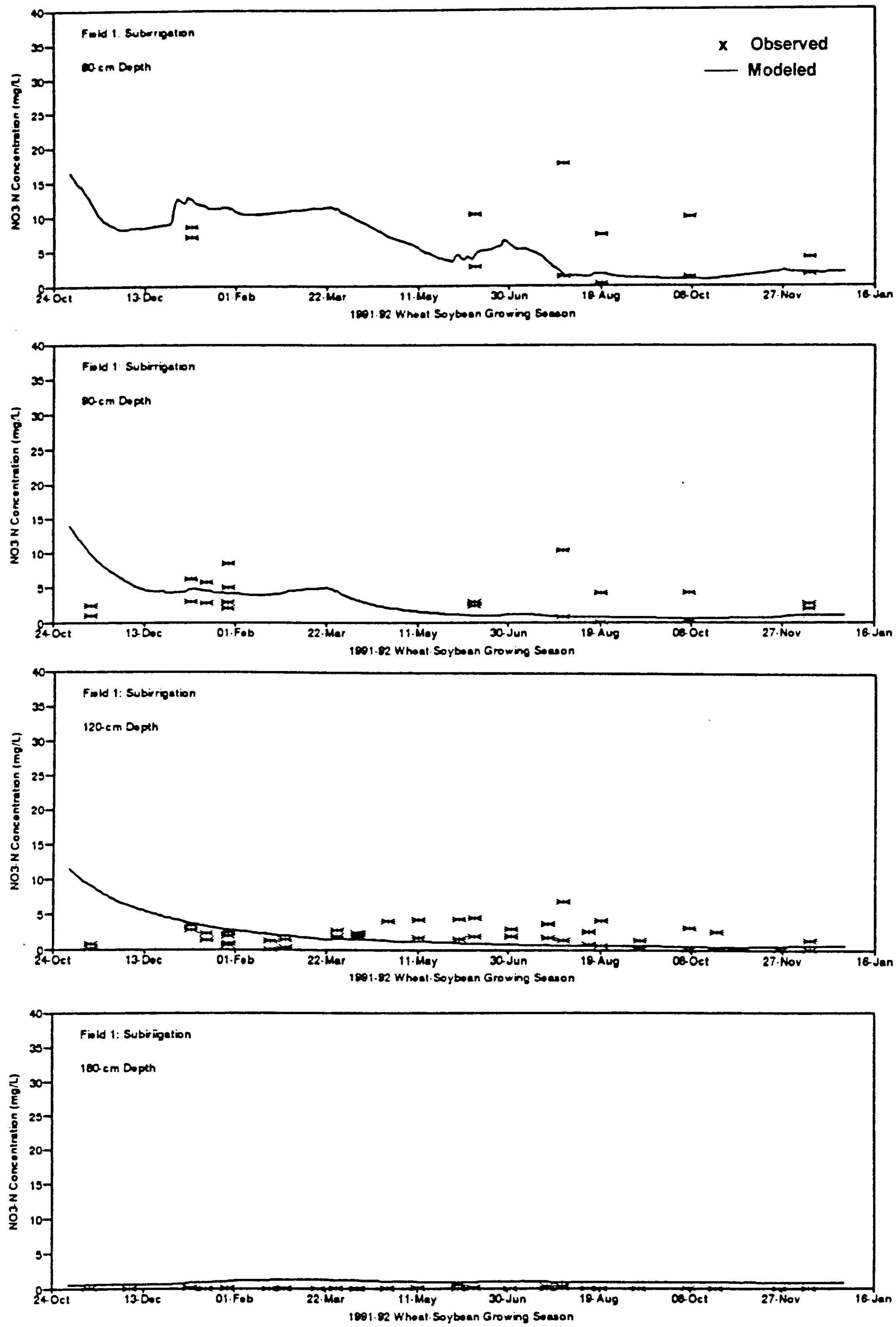


Figure 54 Simulated versus observed NO_3-N concentrations in soil solution at different depths for field 1, subirrigation.

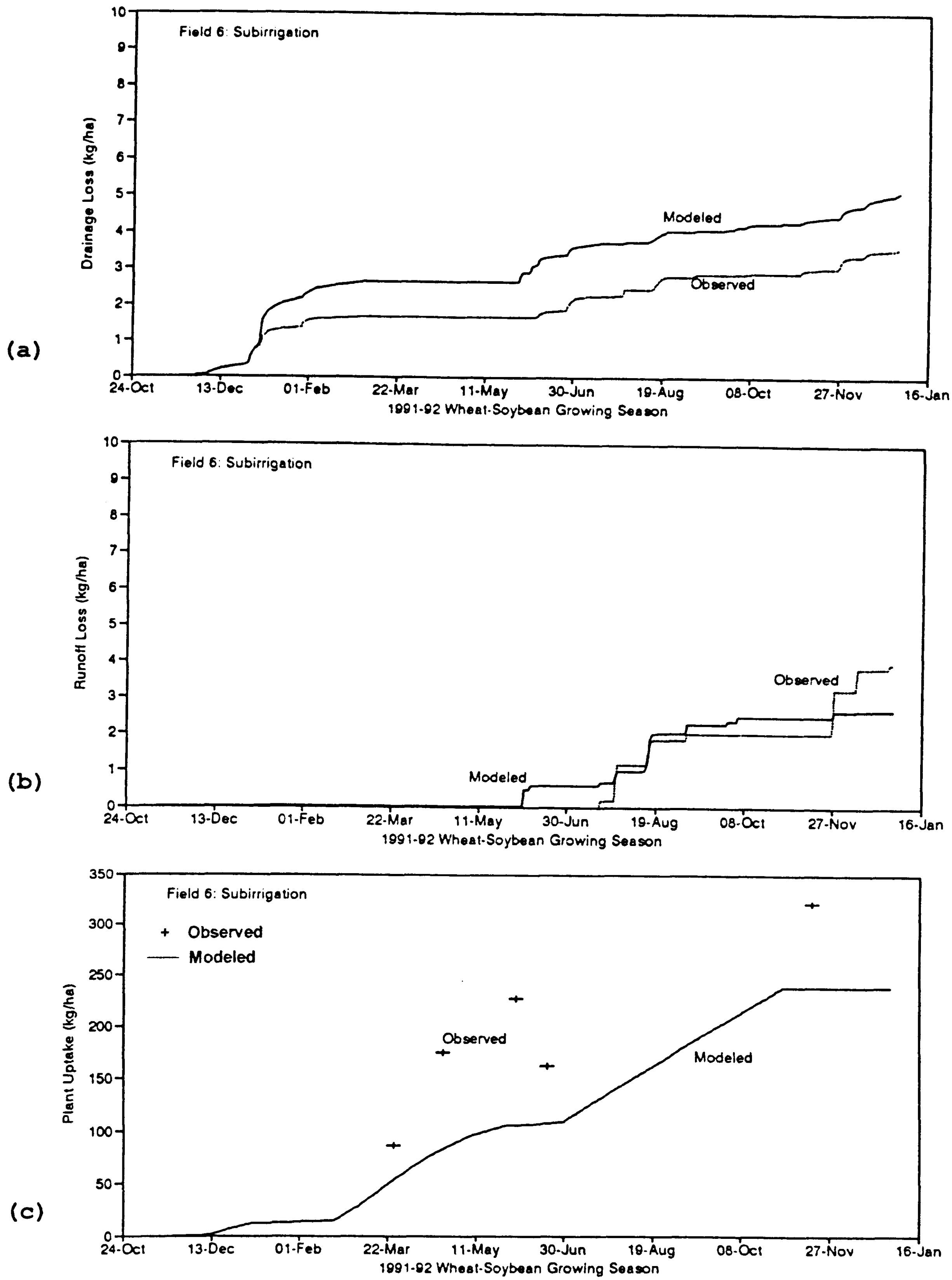


Figure 55 Simulated versus observed NO_3-N losses in subsurface drainage (a) and surface runoff (b), and plant uptake (c) for field 6, subirrigation.

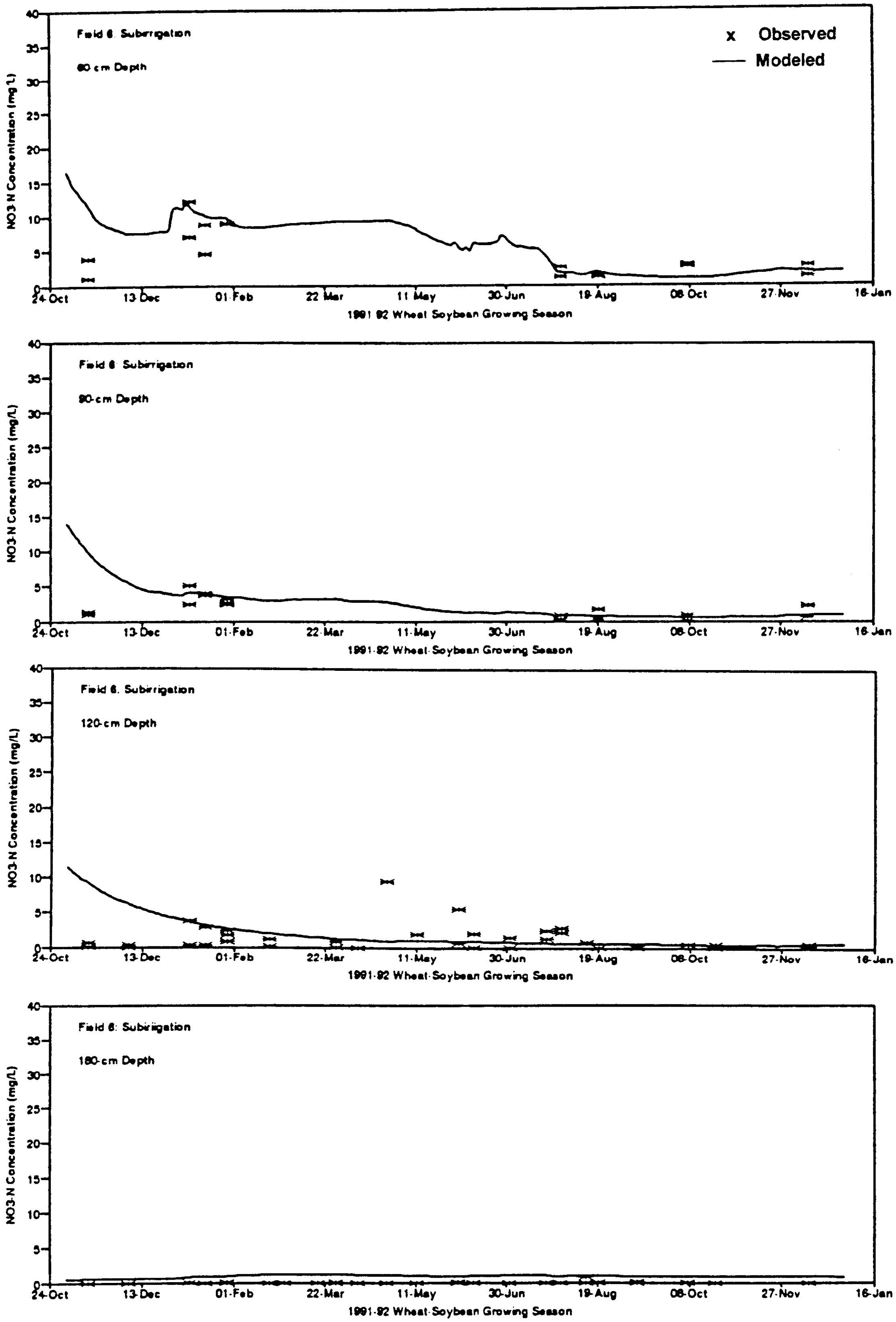


Figure 56 Simulated versus observed NO_3-N concentrations in soil solution at different depths for field 6, subirrigation.

Table 17. Summary of simulated versus observed nitrogen results for the period of Nov 1, 1991 to Dec 31, 1992.

	Experimental Plots					
	3	4	2	5	1	6
	Conventional Drainage		Controlled Drainage		Subirrigation	
NO_3-N losses in subsurface drainage (kg/ha)						
Total obs.	6.7	10.0	7.9	7.0	4.1	3.6
Total sim.	7.1	10.7	6.4	6.5	5.3	5.1
% error	+6.0	+7.0	-19.0	-7.1	+29.3	+41.7
NO_3-N losses in surface runoff (kg/ha)						
Total obs.	3.5	4.0	3.3	2.2	3.8	4.0
Total sim.	1.1	0.9	1.6	1.6	2.9	2.7
% error	-68.6	-77.5	-51.5	-27.3	-23.7	-32.5
Total NO_3-N losses (drainage plus runoff, kg/ha)						
Obs.	10.2	14.0	11.2	9.2	7.9	7.6
Sim.	8.2	11.6	8.0	8.1	8.2	7.8
% error	-19.6	-17.1	-28.6	-12.0	+3.8	+2.6
Plant uptake (kg/ha)						
Total obs.	304	290	311	299	299	322
Total sim.	244	247	244	243	240	240
% error	-19.6	-14.9	-21.7	-18.6	-19.8	-25.6

Calibrated results for field 3 indicate that predicted total nitrogen losses in drainage (subsurface and surface) were within 2 kg/ha of observed data for the 14-month study period (Figure 45 and Table 17). Plant uptake predictions were within 20% of observed data (Table 17).

Simulated results for the conventionally drained field 4 indicate subsurface drainage losses of N were consistently overestimated and surface runoff losses consistently underestimated by *DRAINMOD-N*. The magnitude of the observed runoff losses is small compared to the observed drainage losses. Overprediction of the subsurface drainage losses occurred mostly during two periods: in January and February during wet periods, and following heavy rains in early August. These-higher-than observed losses were balanced by underprediction of drainage losses in November and December, 1992, resulting in a difference of the cumulative predicted and observed drainage losses for the wheat-soybean growing season of only 7% (Table 17). Predicted and measured runoff losses were off by 77%, but the difference was only about 3.1 kg/ha. Total losses (subsurface drainage plus surface runoff) were underestimated by 17%. The difference in total losses was approximately 2.4 kg/ha. Plant uptake was underpredicted by about 15%.

Agreement between predicted and observed nitrogen losses for fields 2 and 5 under controlled drainage was better, in most respects (Fig. 49 and 51), than conventional drainage (Fig. 47).

In both fields, losses were underpredicted for the Nov.-Dec. 1992 period. *DRAINMOD-N* predictions for NO_3-N losses on the two fields under controlled drainage were within 7 and 19% of observed values for subsurface drainage; 27 and 51% for surface drainage and 19 and 22% for plant uptake (Table 17). Note that the maximum errors for this treatment were 1.5 kg/ha for the simulated period for subsurface drainage losses and 1.7 kg/ha for surface runoff. Total losses (subsurface drainage plus surface runoff) were predicted within 3.2 kg/ha on field 2 and 1.1 kg/ha in field 5 (Table 17).

For fields 1 and 6 under subirrigation, subsurface drainage losses were overestimated by about 29 and 42%, but the difference in predicted and observed losses for the study period was only 1.2 and 1.5 kg/ha, respectively (Table 17). Predicted runoff losses were 0.9 to 1.3 kg/ha less than measured for the same period (Table 17). Overprediction of the surface losses somewhat compensated for underprediction of the subsurface losses, resulting in total losses being overpredicted by less than 0.3 kg/ha for fields 1 and 6 (Table 17). Plant uptake of N was underpredicted by 20 to 26% (Table 17).

In general, simulated losses for the 14-month period (Nov 1, 1991 to Dec 31, 1992) were within 1.5 kg/ha of the observed for subsurface drainage for all six plots. Except for one case (plot 2), the predicted total losses (subsurface plus surface) were within 2.4 kg/ha for the same observation period.

Both predicted and observed results showed that controlled drainage and subirrigation reduced total nitrogen losses. Table 17 shows that controlled drainage reduced the total loss of nitrogen by 16% (from 12.1 to 10.2 kg/ha) based on the observed data compared to a predicted reduction of 18% (from 9.9 to 8.1 kg/ha). The reduction in total nitrogen losses was greater when subirrigation was in place: 36% (12.1 to 7.8 kg/ha) observed versus 19% (9.9 to 8.0 kg/ha) predicted (Table 17).

Calibrated results for NO_3-N concentrations in the soil solution are shown in Figure 46. They indicate *DRAINMOD-N* generally underestimated observed concentrations. This was also the case for the concentration results for fields 2, 4 and 5 (Fig. 48, 50, 52). Observed NO_3-N concentrations showed some variability, as reflected by differences in concentration levels between replicated samples of the same treatment (Fig. 46, 48, 50, 52, 54, and 56). The agreement in concentration improved for subirrigation (fields 1 and 6), as both observed and simulated nitrate-nitrogen concentrations approached low levels (Fig. 54 and 56). Both observed and simulated NO_3-N concentrations decreased with depth, reaching negligible levels at 180 cm deep.

SUMMARY AND CONCLUSIONS

Computer simulation models are useful to evaluate the complex mechanisms governing contaminant transport in poorly drained soils with artificial drainage. Although several models are available to study pollutant transport in agricultural fields, only a few adequately incorporate the effects of artificial drainage and related water management practices on the movement and fate of agricultural contaminants.

DRAINMOD-N is a quasi two-dimensional model that simulates the movement and fate of nitrogen in shallow water table, drained soils. The flow component of the model is based on the water balance calculations in *DRAINMOD*. It also uses modifications to determine average daily soil water fluxes and water contents. The solute transport component is based on an explicit solution to the advective-dispersive-reactive (*ADR*) equation. Functional relationships are used to quantify the processes of rainfall deposition, fertilizer dissolution, net mineralization, denitrification, plant uptake, and runoff and drainage losses. This paper evaluated the reliability of *DRAINMOD-N* based on predicted and observed hydrologic conditions and nitrogen losses on an experimental site in eastern North Carolina.

A field study was conducted on a 13.8-ha field with subsurface drainage at the Tidewater Research Station near Plymouth, N.C. between November 1991 and December 1992. Crops grown were wheat followed by soybeans. These crops were grown with conventional tillage and fertilizer and pest management practices, typical of the region. The water table management treatments of conventional drainage, controlled drainage and controlled drainage-subirrigation were imposed in the experiment. Field measurements included soil properties, weather data, surface and subsurface drainage rates, and water table depth. Soil samples, samples of the shallow ground water, and plant and grain samples were collected to quantify nitrogen content in the unsaturated and saturated zones of the profile and nitrogen uptake by the crop.

A sensitivity analysis of *DRAINMOD-N* indicated that predicted NO_3-N loss via subsurface drainage is most sensitive to the rate coefficients of denitrification and mineralization. Predicted NO_3-N loss in surface runoff is most sensitive to NO_3-N content in rainfall.

Hydrologic conditions simulated by *DRAINMOD-N* were compared to measured hydrologic conditions for a one year period from January 1992 through December 1992. Simulated water table depths were on average within 8-13 cm of the observed data for conventional drainage, controlled drainage and subirrigation. Differences between simulated and observed subsurface drainage volumes were within 0.9-6.6 cm for all cases. Predicted surface runoff volumes were within 0.5-8.9 cm of observed values.

DRAINMOD-N consistently underestimated NO_3-N concentrations in the soil solution. However, simulated nitrate-nitrogen losses for the 14-month observation period were within 1.5 kg/ha of the observed for subsurface drainage for all six experimental plots. Except for one case, the predicted total losses (subsurface plus surface) were within 2.4 kg/ha for the observation period. Both predicted and observed results showed that controlled drainage and subirrigation reduced total nitrogen losses.

Overall results indicate that *DRAINMOD-N* can be used to simulate nitrogen losses in poorly drained soils and the effect of water table management practices on those losses.

DRAINMOD-N predictions could be improved to more accurately characterize hydraulic head losses near the drain and the transitions that occur during drainage and subirrigation processes. Additional work is needed to improve our understanding of these processes and to develop new algorithims for subsurface drainage, controlled drainage, and subirrigation. Research to make these modifications is recommended.

DRAINMOD-N should be tested on this site for an extended period of time that would include several corn-wheat-soybean rotations. This would allow evaluation of the model under a wider range of eastern North Carolina weather conditions. The model should also be tested in other locations with different soils, crops and climatological conditions. Modifications to the model are needed to improve methods used to predict and to handle freezing, thawing, and snowmelt processes. Research to make these modifications and to conduct expanded and extended field tests of *DRAINMOD-N* is recommended.

PREDICTION OF NITROGEN LOSSES VIA DRAINAGE WATER WITH *DRAINMOD-N*

DRAINMOD-N was developed to simulate to movement and fate of nitrate-nitrogen (NO_3-N) in artificially drained soils. Results from the field validation study presented in the previous chapter showed that the model reliably simulated annual NO_3-N losses in surface and subsurface drainage outflows from a Portsmouth sandy loam soil in eastern North Carolina. *DRAINMOD-N* can be applied to conduct long-term simulations to predict the effects of different factors that influence NO_3-N losses. The objective of this paper is to use *DRAINMOD-N* to evaluate long-term effects of drainage system design and management on the fate and movement of nitrate-nitrogen in artificially drained soils in eastern North Carolina.

MODEL DESCRIPTION

A detailed description of the methods used in *DRAINMOD-N* is given a preceding chapter. As the name implies, *DRAINMOD-N* is based on the water balance calculations of *DRAINMOD* (Skaggs, 1978). It uses modifications described by Skaggs et al. (1991) to determine average daily soil-water fluxes and water contents by breaking the profile into increments and conducting a water balance for each increment. *DRAINMOD-N* is based on a simplified version of the nitrogen cycle. Nitrate-nitrogen is the main N pool considered.

MODEL APPLICATION

Procedure. *DRAINMOD-N* was applied to evaluate long-term effects of several drainage and related water table control systems on nitrate-nitrogen losses from two eastern North Carolina (NC) soils. Simulations were conducted for a 20-year period (1971-1990) of continuous corn production at Plymouth, NC. The soils used in the simulations are Portsmouth sandy loam (fine-loamy, Mixed, Thermic *Typic Umbraquults*) and Tomotley sandy loam (fine-loamy, Mixed, Thermic *Typic Ochaquults*). The physical and chemical properties of each soil are listed in Table 18. Additional properties are given in Appendix 5.

The field was assumed to have a drainage system consisting of parallel, 10-cm diameter, corrugated plastic drains. Several design and management treatments were simulated for each soil. The drainage designs evaluated consisted of three drain depths (0.75, 1.0, and 1.25 m), eight drain spacings (10, 15, 20, 25, 30, 40, 50, and 100 m), and two surface conditions (0.5 and 2.5 cm depressional storage). The management treatments included conventional drainage, controlled drainage at 50 cm during the summer season (May 15 to August 15), and controlled drainage both

Table 18. Summary of inputs for *DRAINMOD-N*.

1.	**Soil Properties:**	Tomotley	Portsmouth
	θ_{sat} (cm^3 cm^{-3})	0.46	0.37
	θ_{wp} (cm^3 cm^{-3})	0.25	0.17
	Bulk Density (g cm^{-3})	1.4	1.6
	Organic-N in top soil (μg g^{-1})	2000	2000
	K_{mn1} (d^{-1})	3.0×10^{-5}	3.5×10^{-5}
	K_{den} (d^{-1})	0.30	0.40
	Lateral Sat. Hyd. Cond. (m d^{-1})	0.96 (0-30 cm)	3.60 (0-30 cm)
		0.24 (30-110 cm)	0.48 (30-100 cm)
		0.72 (110-170 cm)	1.92 (100-215 cm)
2.	**Drainage System Parameters:**		
	Drain Depth (m)	0.75, 1.0, 1.25	
	Drain Spacing (m)	10, 15, 20, 25, 30, 40, 50, 100	
	Surface Storage (cm)	0.5, 2.5	
	Effective Drain Radius (cm)	1.5	
3.	**Controlled Drainage Parameters:**	Weir Depth (cm)	
	Summer (Su) only (May 15-Aug 15)	50	
	Summer and Winter (Wi, Nov 1-Mar 15)	50 (Su), 40 (Wi)	
4.	**Corn Production Parameters:**		
	Desired Planting Date	April 15	
	Length of Growing Season (d)	130	
	Potential Yield (kg ha^{-1})	10000	
	N Content of Corn (%)	1.55	
	Max. Effective Root Depth (cm)	30	
	N-Fertilizer Input (kg ha^{-1})	100 (April 15) + 50 (May 22)	
	Depth Fertilizer Incorporated (cm)	10	
5.	**Other Parameters:**		
	Dispersivity (cm)	5.0	
	NO_3-N Concentration of Rain (mg L^{-1})	0.8	

in the summer (at 50-cm) and in the winter (at 40-cm between November 1 and March 15). A total of 288 20-year simulations were conducted for all combinations of treatments. Detailed inputs for the corn production practices and NO_3-N transport and transformation variables are listed in Table 18.

The corn production practices used in the simulations are characteristic of eastern North Carolina. The reaction rate coefficients were obtained from ranges published in the literature (Davidson et al., 1978; Johnsson et al., 1987; Harmsen et al., 1991; Schepers and Mosier, 1991; Pierce et al., 1991), and they were comparable to values previously used to test the model with field data in the previous chapter.

A cost-benefit analysis was performed to determine the optimum drain spacing-drain depth-surface condition-water management combination for each soil. Annual costs included production, drainage system and maintenance costs. A detailed description of the production costs is presented in Appendix 5. Drainage system costs were based on estimated prices of drain tubing installation, surface grading for drainage and control structure costs (Appendix 5) amortized over 30 years at a 10% interest rate. Annual maintenance costs consisted of a fraction (2%) of the annual amortized drainage system cost. An additional $20/ha was included in the annual maintenance costs for systems with intensive surface drainage (0.5-cm depressional storage). Annual income figures were based on a maximum potential yield of 10000 kg/ha and a corn market price of $0.10/kg.

Results and Discussion. Effects of drainage system management, drain spacing and depth, and surface condition on subsurface drainage, surface runoff, evapotranspiration (ET) and relative yield are shown in Figures 57-60 and Appendix 5, for both Portsmouth and Tomotley soils. Simulation results show that, for any equivalent design and management scenario, subsurface drainage is greater and surface runoff lower for the Portsmouth soil than for the Tomotley soil (Fig. 57). This can be explained by the greater lateral hydraulic conductivity of the Portsmouth soil (Table 18).

Predicted results also indicate that increasing the drain spacing reduces subsurface drainage while it increases surface runoff and ET in both soils (Fig. 57). Increasing the drain depth increases drainage and decreases ET and runoff (Fig. 58). Furthermore, improving surface drainage by filling potholes and grading the surface to reduce depressional storage causes an increase in surface runoff, a decrease in subsurface drainage, and a slight increase in ET (Fig. 59). Controlled drainage (CD) reduces subsurface drainage and increases surface runoff, as compared to conventional drainage (Fig. 60). The magnitude of these changes increases with the intensity of CD, as a more pronounced effect is observed when controlled drainage is used during both the summer and winter seasons (Fig. 60).

Results of the economic analysis are presented in Figures 61-64. More detailed information, such as predicted average annual gross income, annual costs and net profit, for both soils, is given in Appendix 5.

Figures 61-64 summarize the predicted net profits for all simulations performed. Cost-benefit results indicate that the optimum drainage system design and management scenario for corn production in the two eastern North Carolina soils studied is a conventionally drained system with a 1.25-m drain depth and a 2-5-cm depressional storage (Fig. 61-64). The optimum spacings are 40 and 20 m for the Portsmouth and Tomotley soils, respectively (Fig. 61 and 63). These results are consistent with those reported by Skaggs and Nassehzadeh-Tabrizi (1986) for both soils. The predicted net profits associated with these two optimum systems are $169/ha for the Portsmouth soil and $126/ha for the Tomotley soil (Fig. 61 and 63).

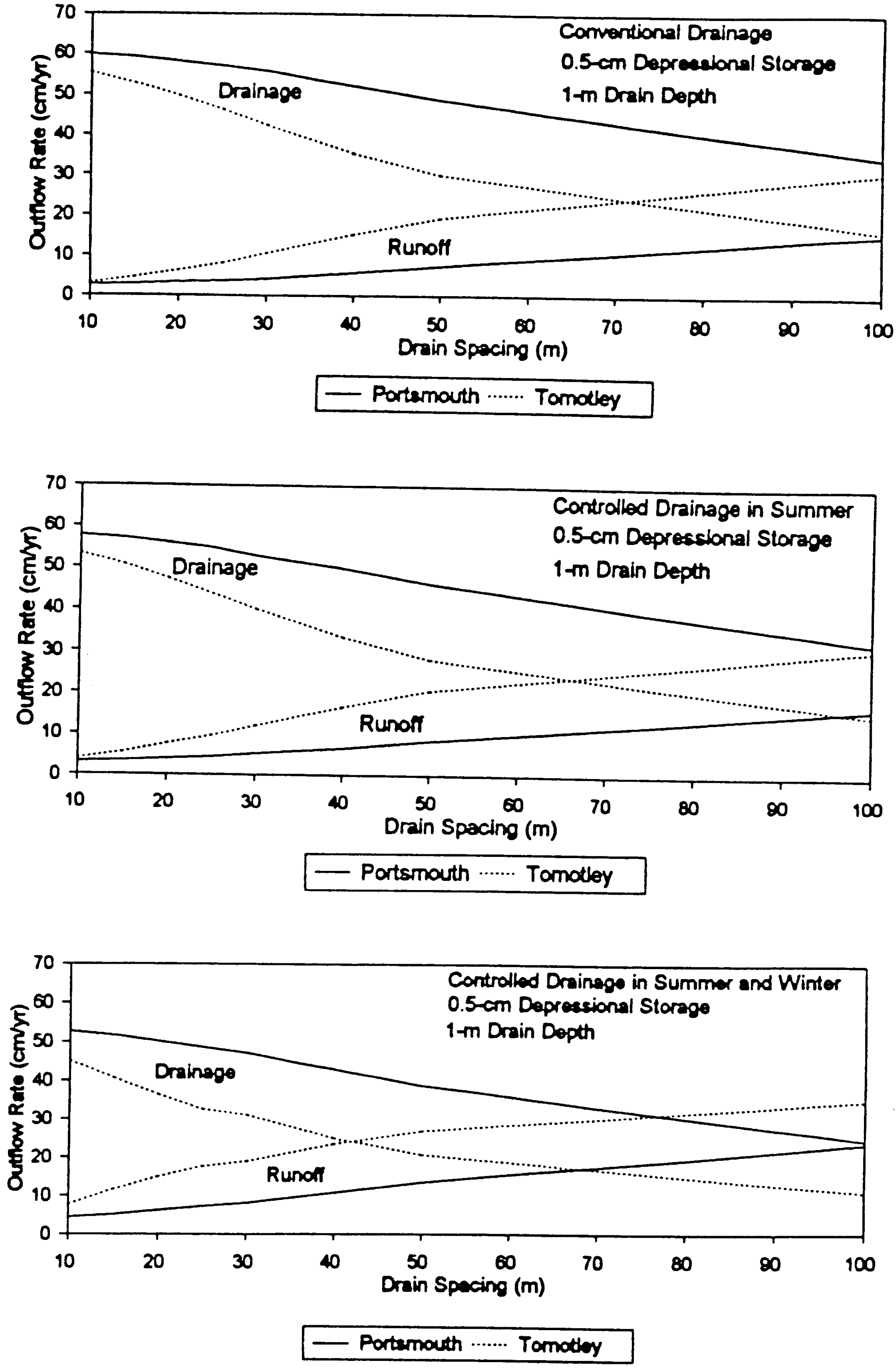
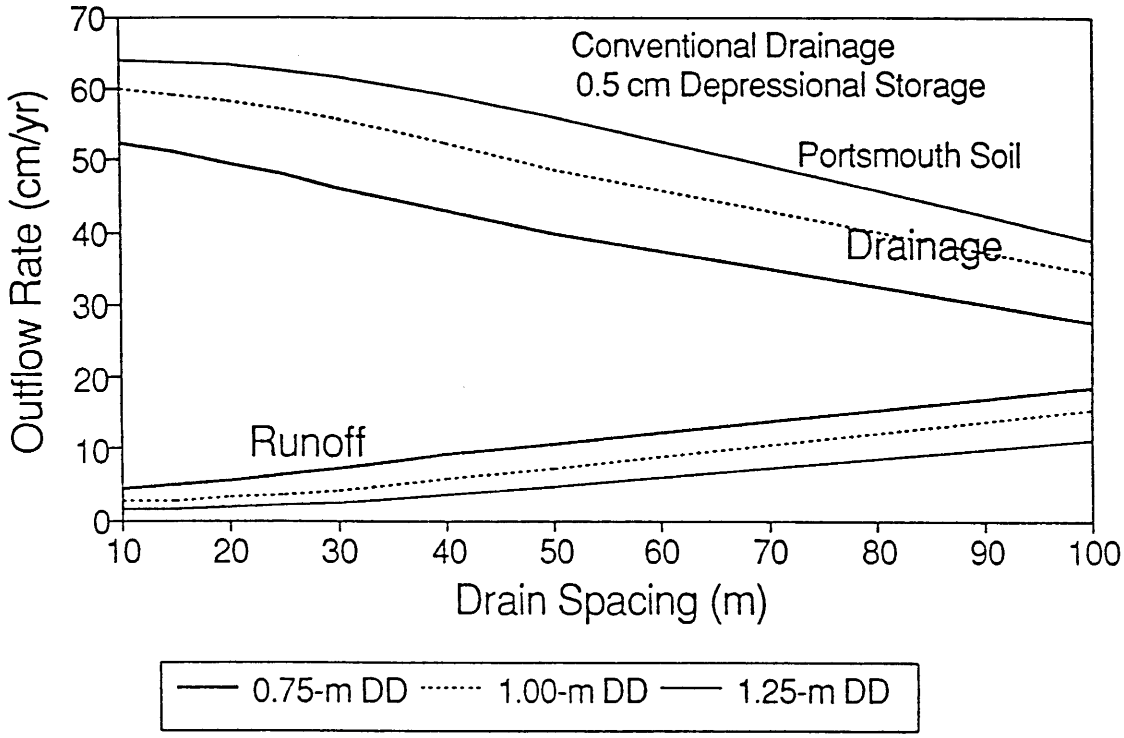


Figure 57 Predicted average annual subsurface drainage and surface runoff as affected by system management, drain spacing and soil type. Results are for a system with a 1-m drain depth and 0.5-cm depressional storage.



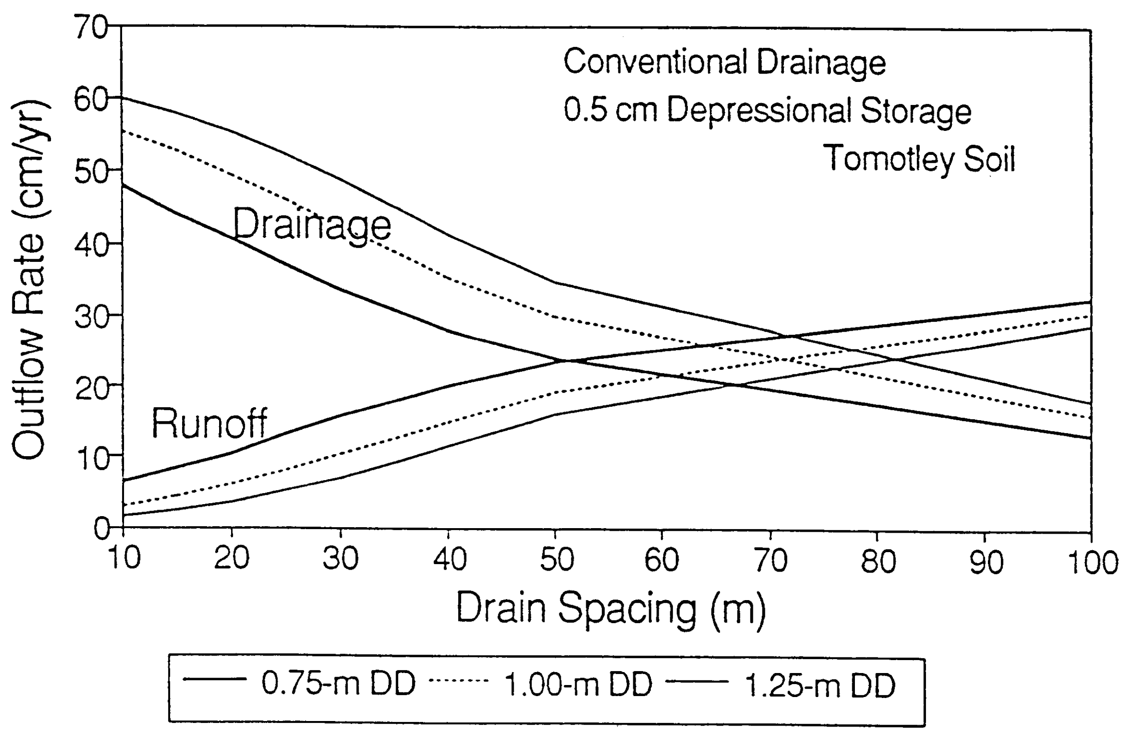
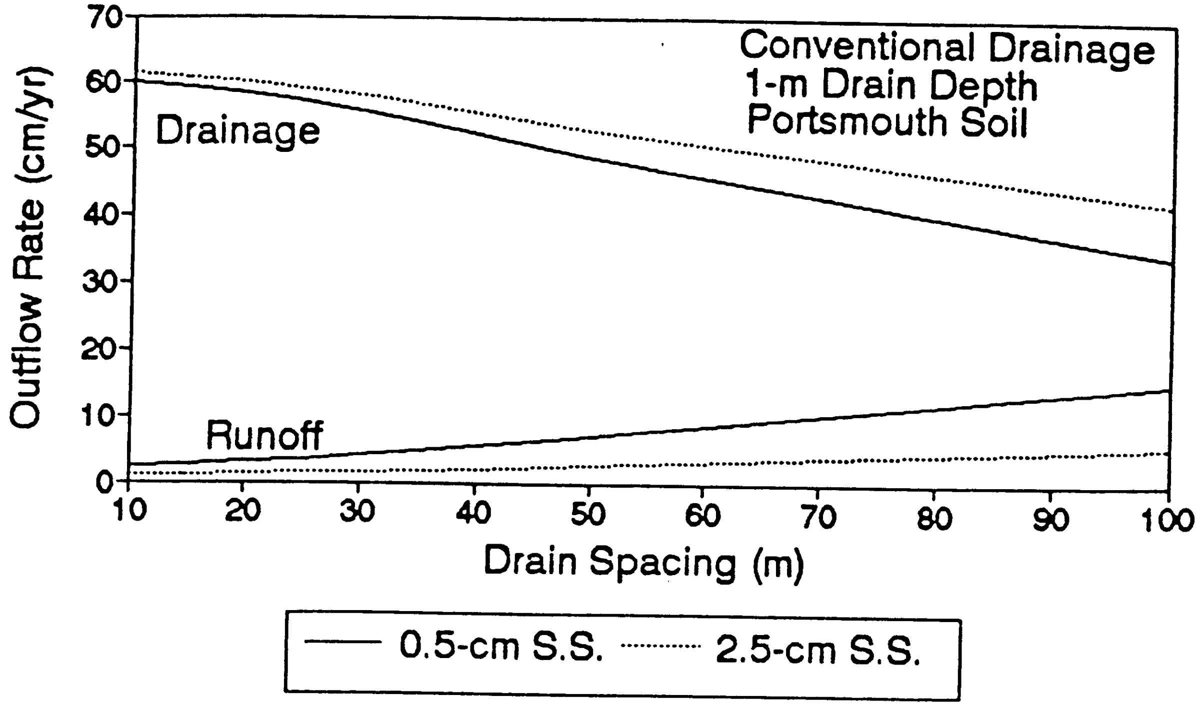


Figure 58 Predicted average annual subsurface drainage and surface runoff as affected by drain depth (DD), drain spacing and soil type. Results are for a conventionally drained system with a 0.5-cm depressional storage.



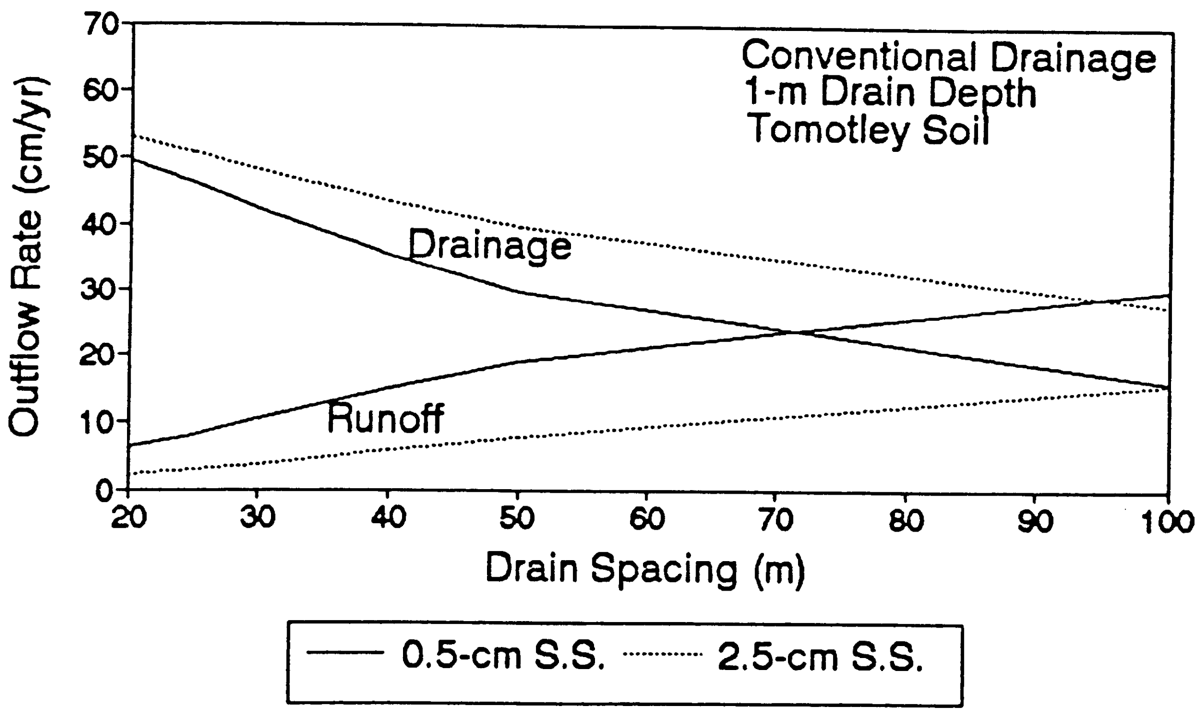
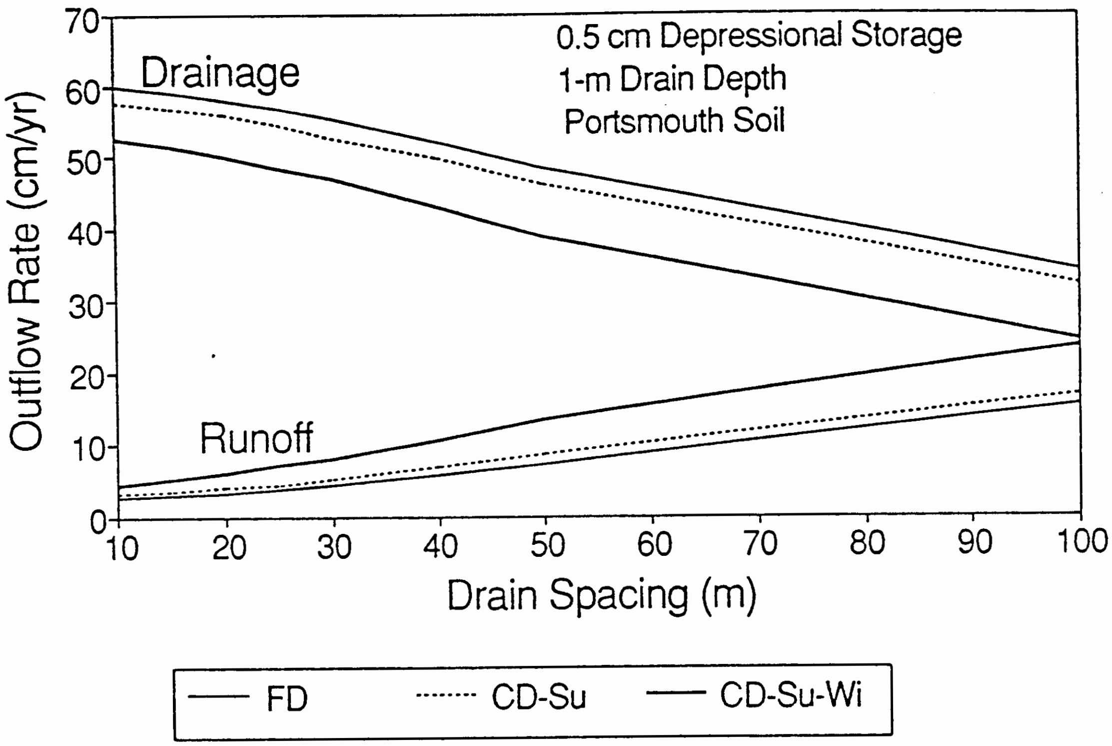


Figure 59 Predicted average annual subsurface drainage and surface runoff as affected by surface storage (S.S.), drain spacing and soil type. Results are for a conventionally drained system with a 1-m drain depth.



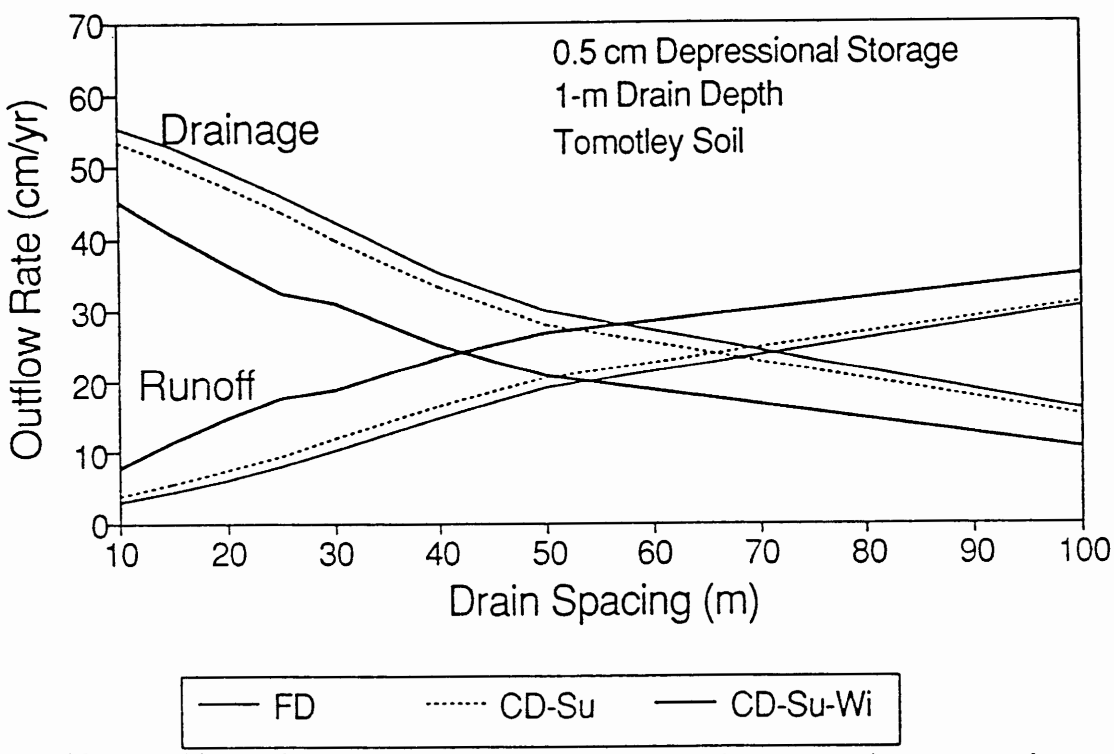


Figure 60 Predicted average annual subsurface drainage and surface runoff as affected by system management, drain spacing and soil type. Results are for a system with a 1-m drain depth and 0.5-cm depressional storage. Notation: FD=free or conventional drainage, CD=controlled drainage, Su=summer, and Wi=winter).

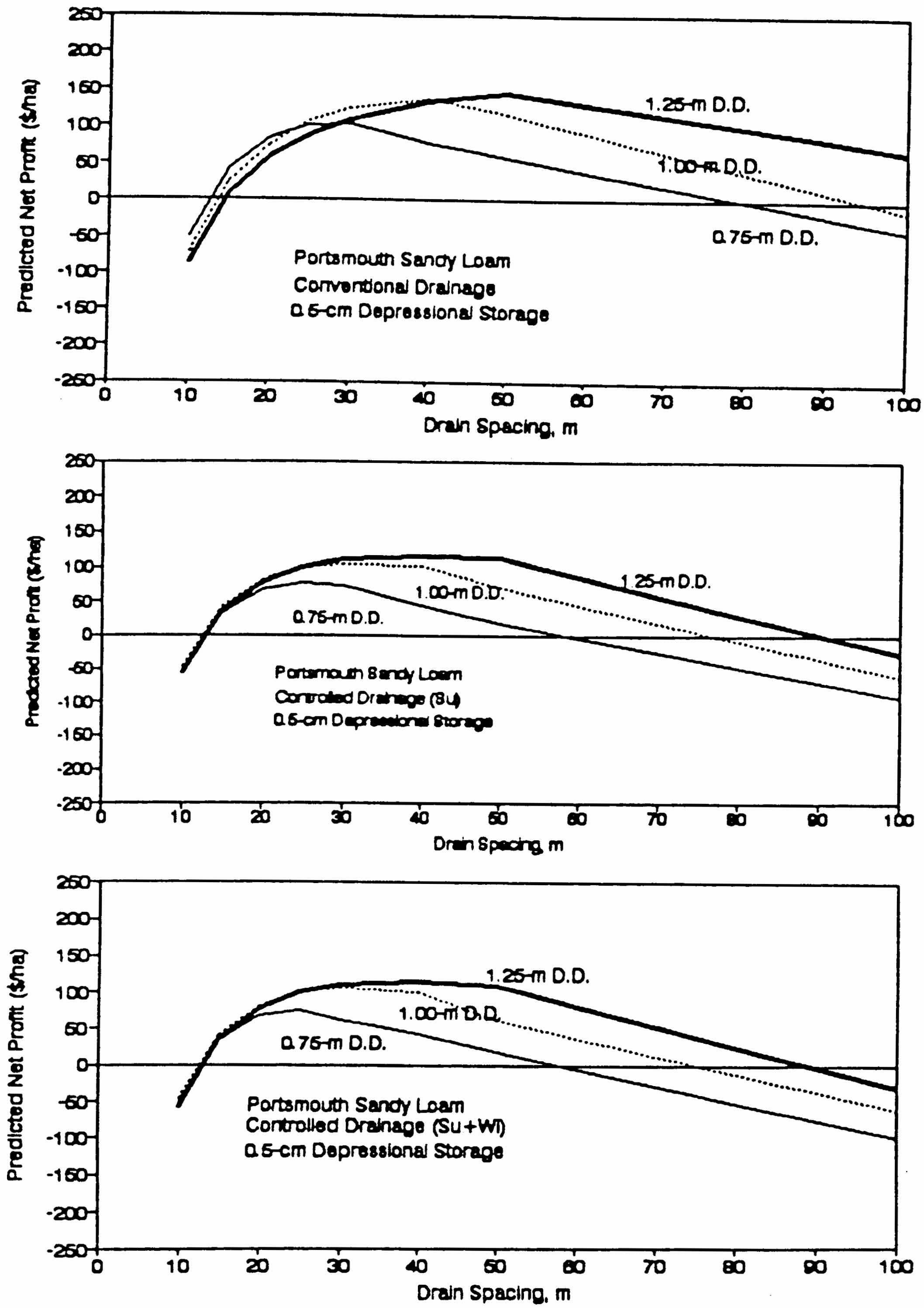


Figure 61 Predicted average annual net profit ($/ha), as affected by drain depth, drain spacing and system management, for corn production in a **Portsmouth** sandy loam with a **0.5-cm depressional storage** in eastern North Carolina.

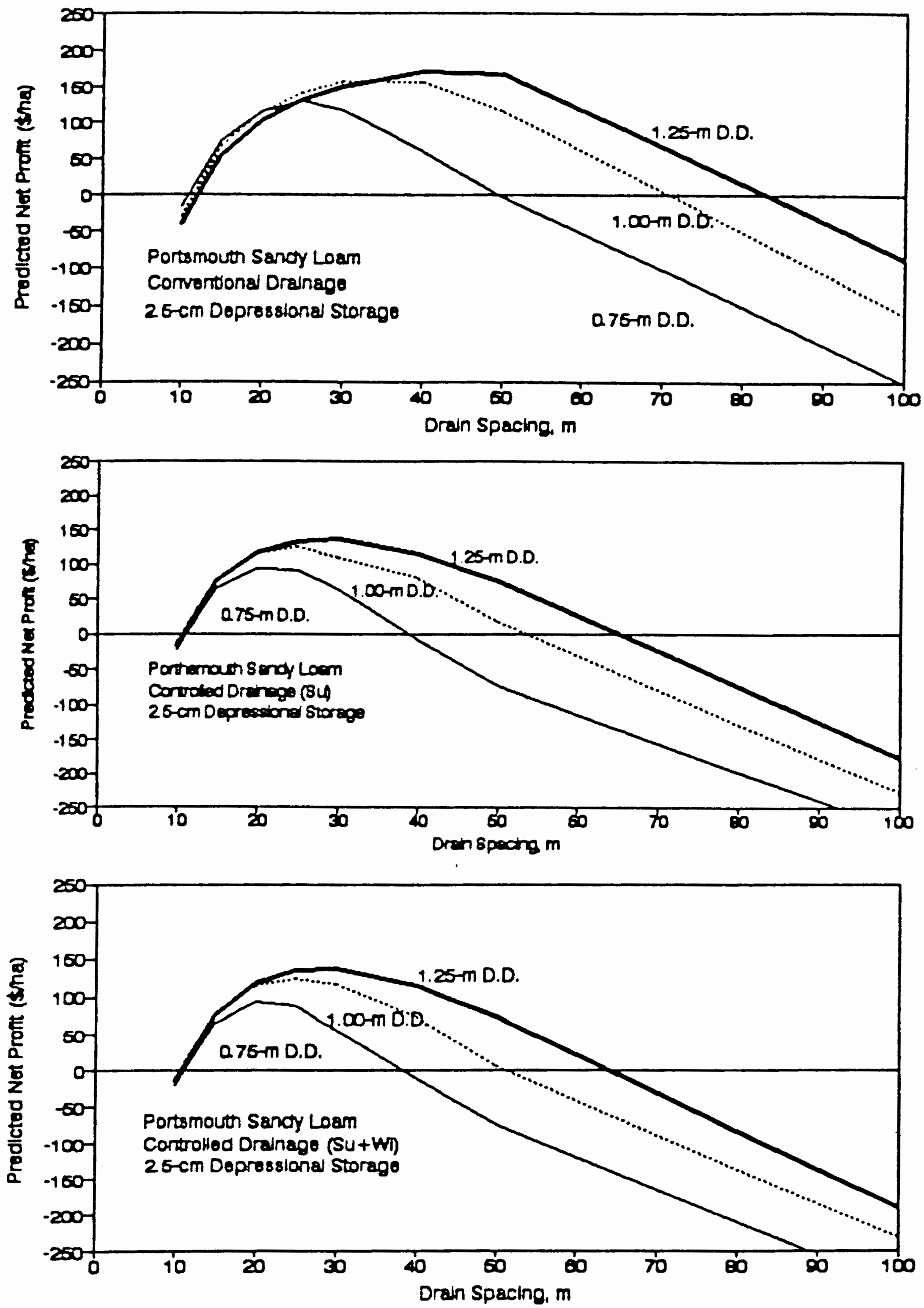


Figure 62 Predicted average annual net profit ($/ha), as affected by drain depth, drain spacing and system management, for corn production in a **Portsmouth** sandy loam with a **2.5-cm depressional storage** in eastern North Carolina.

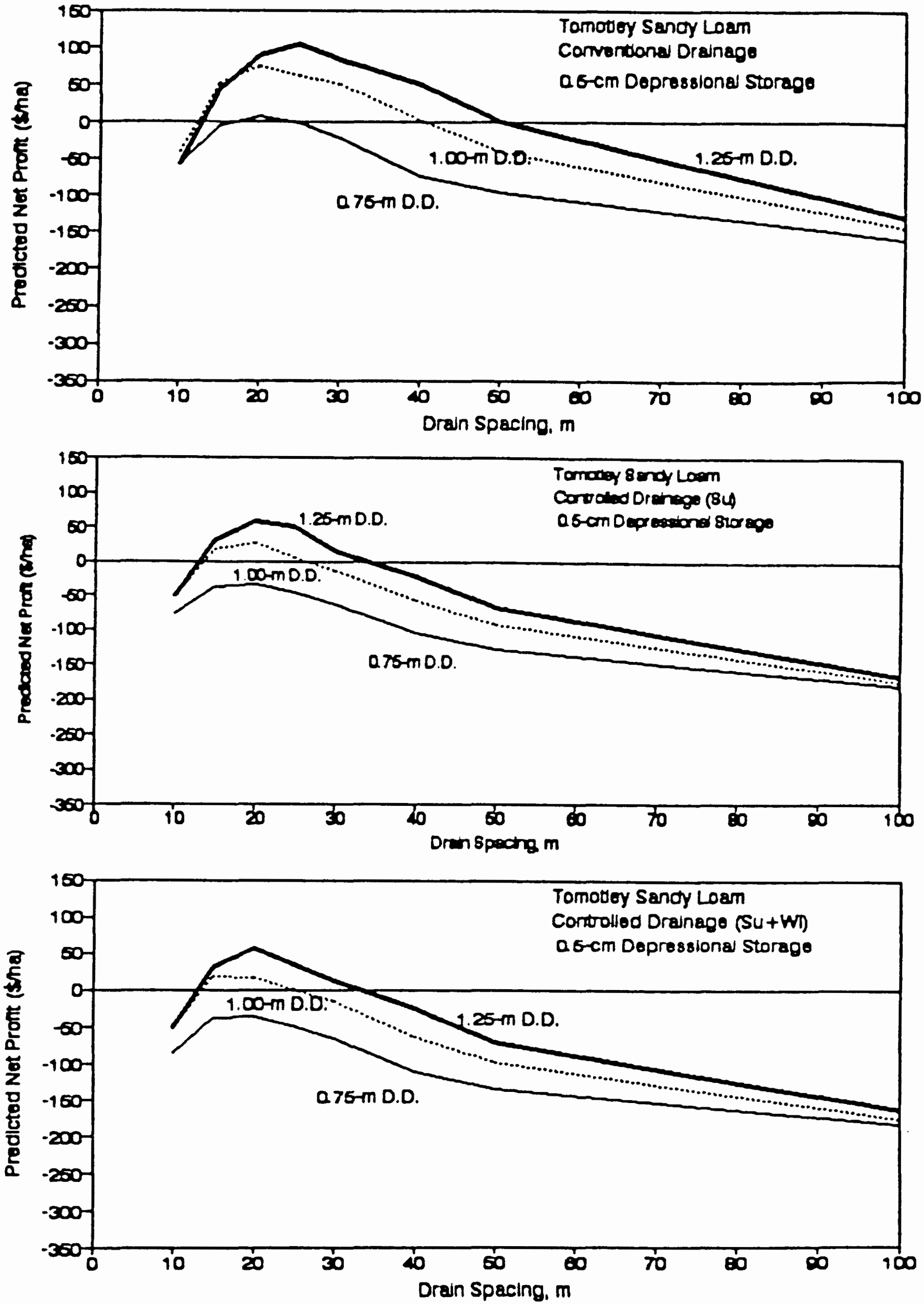


Figure 63 Predicted average annual net profit ($/ha), as affected by drain depth, drain spacing and system management, for corn production in a **Tomotley** sandy loam with a **0.5-cm depressional storage** in eastern North Carolina.

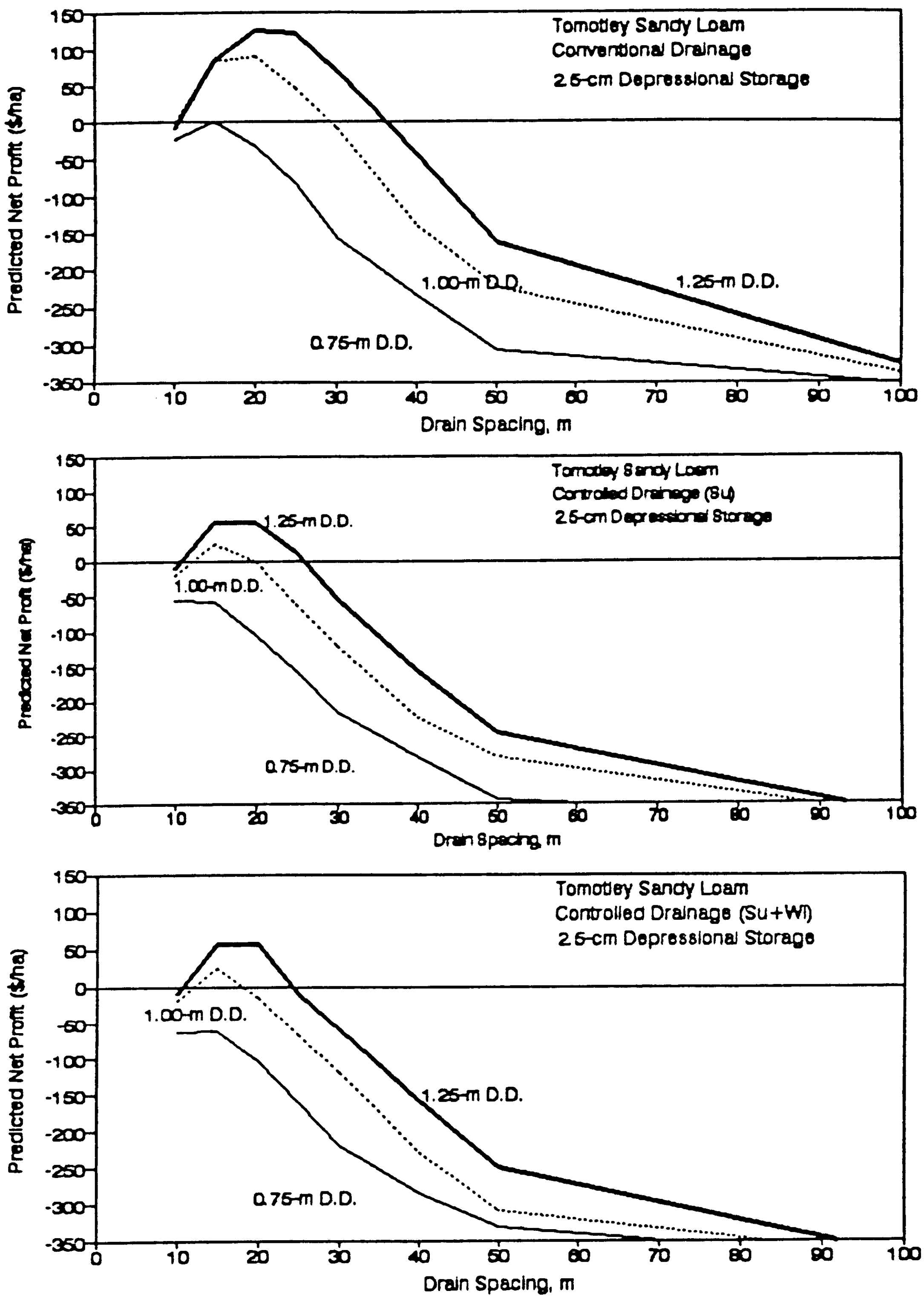


Figure 64 Predicted average annual net profit ($/ha), as affected by drain depth, drain spacing and system management, for corn production in a **Tomotley** sandy loam with a **2.5-cm depressional storage** in eastern North Carolina.

For a drain depth of 1.0 m, profit is maximum for a 30 m spacing (with a 2.5-cm depressional storage) for Portsmouth and 20 m for Tomotley. The profit will be reduced by \$12/ha for Portsmouth and \$36/ha for Tomotley, but drainage outlets 1.25 m deep may not be available in some cases. Furthermore, deeper drains increase NO_3-N losses as will be discussed below.

The economic analysis further shows that the use of controlled drainage does not increase profits for either soil. This is due to a slight decrease in simulated relative yields resulting from CD and to an increase in the annual drainage system costs related to the cost of the control structures. These results are in contrast to experiences in the field which has shown that CD, if properly managed, can result in an increase in corn yields (Evans et al., 1994). The open ditch outlets typically used in eastern North Carolina have more storage than was considered in the simulations. This enables CD to have a greater effect in conserving water and relieving drought stresses than considered here. Because of these limitations, the maximum predicted profits associated with controlled drainage are \$115/ha for the Portsmouth soil (\$54/ha reduction in profit as compared to the optimum system) and \$56/ha for the Tomotley soil (\$69/ha reduction in profit) (Appendix 5). Simulated results also show that controlled drainage in the winter does not have an impact on simulated corn yields for drain spacings in the design range (Appendix 5), and, thus, in net profits (Fig. 61-64).

Effects of drainage system management, drain spacing and depth, and surface condition on the nitrogen budget components are shown in Fig. 65-68 and Appendix 5 for both the Portsmouth and Tomotley soils. Simulation results show that, in general, net mineralization rates and drainage losses are greater for the Portsmouth soil than for the Tomotley soil (Fig. 65) with similar drainage treatments. Likewise, greater denitrification rates and runoff losses are associated in general with the Tomotley soil (Fig. 65).

Simulated results also indicate that increasing the drain spacing reduces NO_3-N drainage losses and net mineralization, but it increases NO_3-N runoff losses and denitrification for both soils (Fig. 65). On the other hand, increasing the drain depth increases drainage losses and net mineralization, and it decreases runoff losses and denitrification (Fig. 66). Furthermore, improving surface drainage decreases drainage losses and denitrification but increases runoff losses (Fig. 67). The effect on net mineralization is not evident. The use of controlled drainage decreases the subsurface drainage intensity. Hence it reduces drainage losses and increases denitrification and runoff losses, compared to the use of conventional drainage (Fig. 65-68). The effect of controlled drainage on net mineralization is not clear.

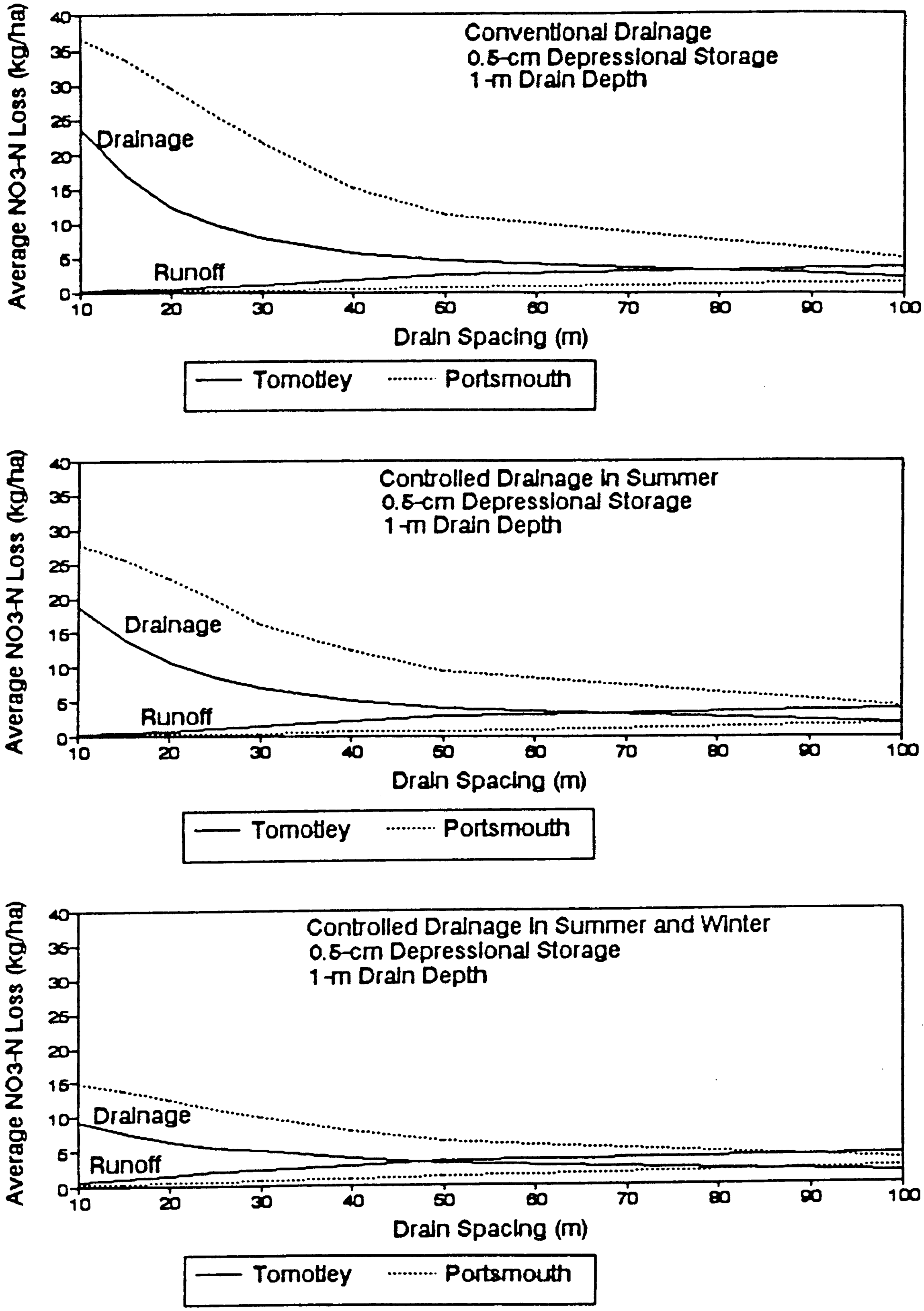


Figure 65 Predicted average annual nitrate-nitrogen losses in drainage and runoff as affected by system management, drain spacing and soil type. Results are for a system with a 1-m drain depth and good surface drainage.

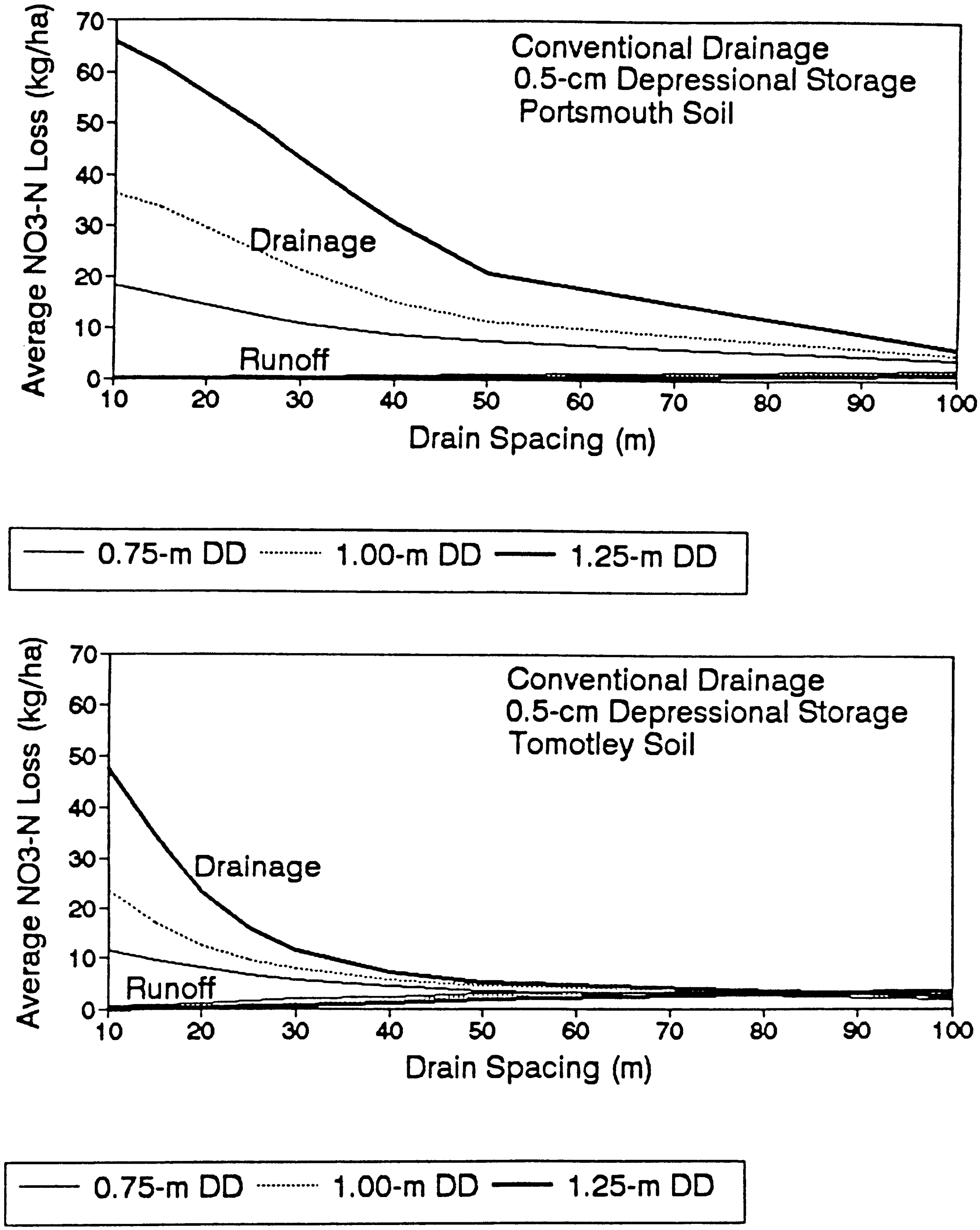
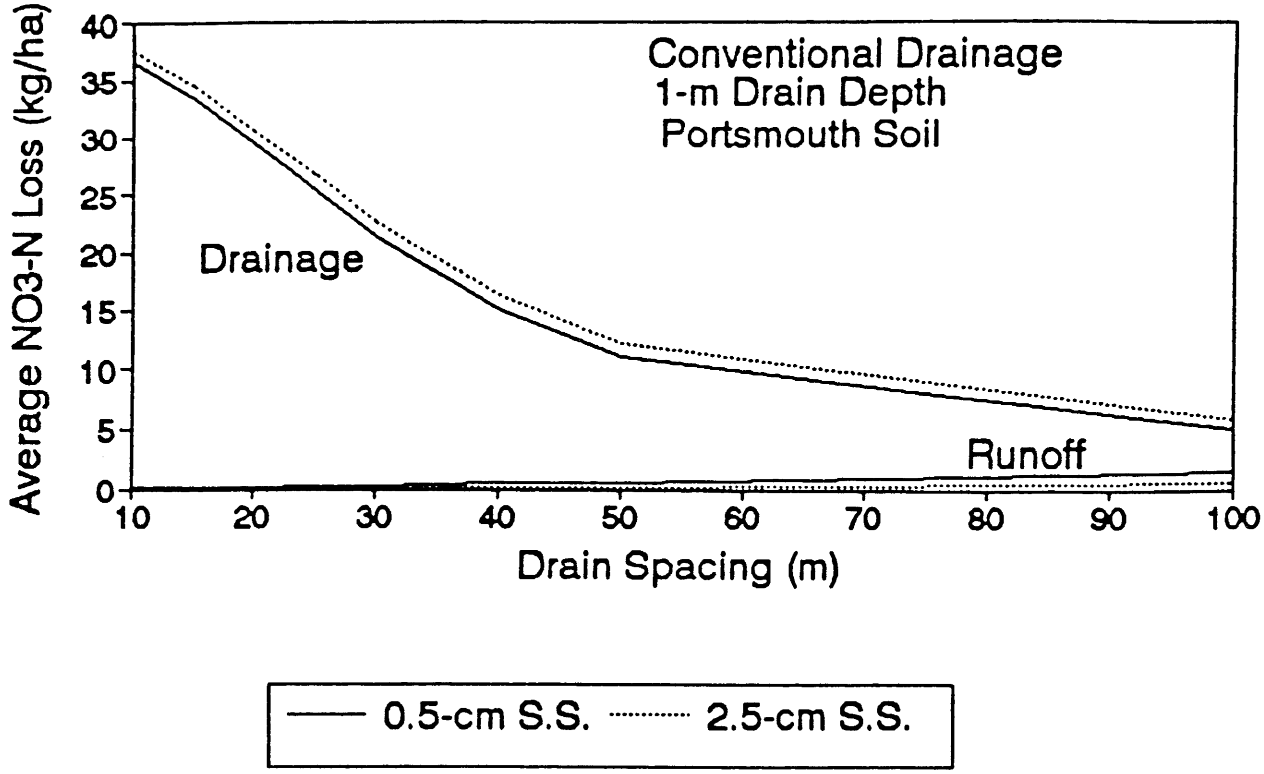


Figure 66 Predicted average annual nitrate-nitrogen losses in drainage and runoff as affected by drain spacing, drain depth and soil type. Results are for a conventionally drained system with good surface drainage.



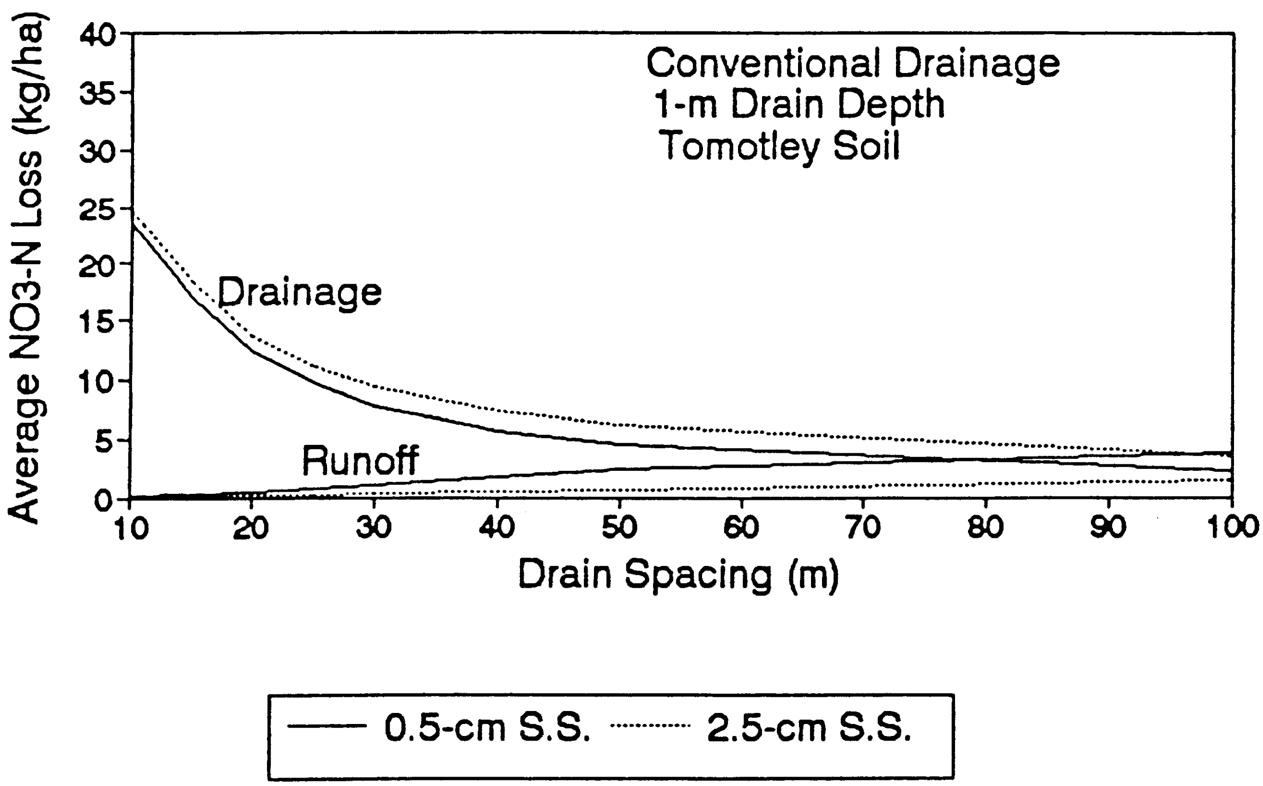


Figure 67 Predicted average annual nitrate-nitrogen losses in drainage and runoff as affected by surface drainage (S.D.) condition, drain spacing and soil type. Results are for conventionally drained system with a 1-m drain depth.

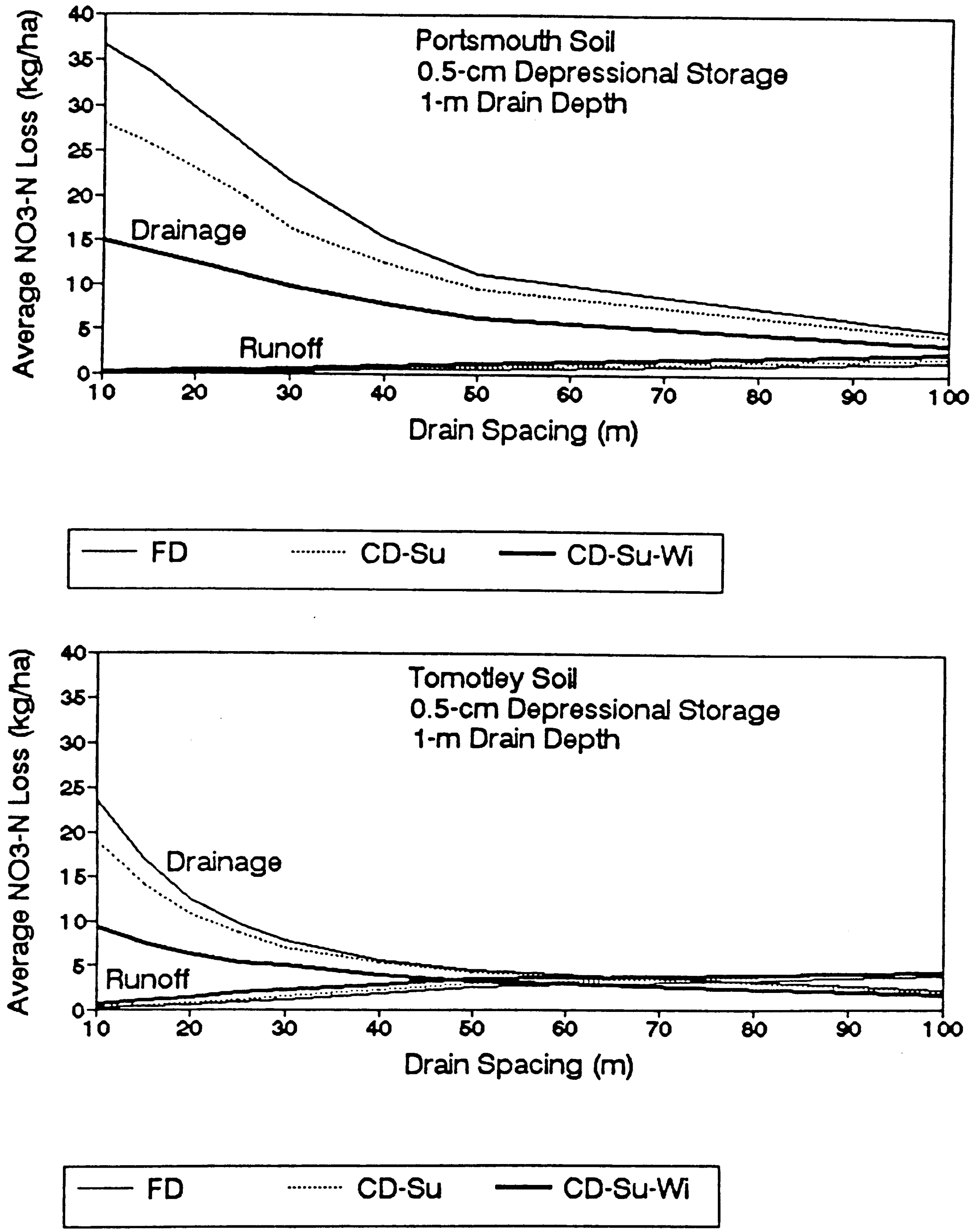


Figure 68 Predicted average annual nitrate-nitrogen losses in drainage and runoff as affected by system management, drain spacing and soil type. Results are for a system with a 1-m drain depth and good surface drainage. Notation: FD=free or conventional drainage, CD=controlled drainage, Su=summer, and Wi=winter).

Results of this study show that total NO_3-N losses (subsurface drainage plus surface runoff) can be substantially reduced with CD during the winter season. This can be explained by the climatological conditions in eastern North Carolina where drainage is usually greatest during the winter and early spring months when evapotranspiration is low.

Clearly, the ideal drainage design and management combination is one that will optimize profits and minimize environmental impacts. The results from economic analyses indicate that the maximum profit for the Tomotley soil would be obtained with a conventional drainage system with a 20-m drain spacing, 1.25-m drain depth, and 2.5-cm depressional storage (Fig. 64). In the case of the Portsmouth soil, a conventional drainage system with 2.5-cm depressional storage, 40-m spacing and 1.25-m drain depth would maximize profit from the crop (Fig. 62). However, these systems would not be optimum from the water quality perspective. The total nitrate-nitrogen losses associated with the drainage systems producing maximum profit are 24.2 and 31.5 kg/ha/yr for the Tomotley and Portsmouth soils, respectively (Appendix 5).

Figures 69 and 70 show the effect of drain spacing and system management on net profit and total loss of NO_3-N for both soils. These results illustrate the benefit of simulation modeling and the complexity of designing drainage systems to meet both environmental and production objectives simultaneously. Although the maximum predicted profits were obtained for spacings of 20 and 40 m for the Tomotley and Portsmouth soils, respectively, smaller spacings are more typical in real situations because drain spacing recommendations are usually based on conservative designs. These conservative systems are, therefore, more expensive than necessary, but they satisfy the production objectives as indicated by crop yields (Appendix 5) even though profits may be somewhat reduced (Fig. 69-70). Results in Figures 69-70 show clearly that NO_3-N losses can be decreased by reducing drainage intensities as much as possible. Thus NO_3-N losses to the environment can be reduced by fitting the drainage system design to the soil such that the drainage intensity is no greater than required (i.e., drain spacings as wide as possible and drain depths as shallow as possible).

Results in Figures 69-70 indicate that NO_3-N losses to the environment could be substantially reduced by reducing the drainage intensity below the level required for maximum profits from grain sales. That is, if the environmental objective is of equal or greater importance than profits from the agricultural crops, the drainage systems can be designed and managed to reduce NO_3-N losses while still providing an acceptable profit from the crop. For example, increasing the drain spacing from 40 to 50 m for the Portsmouth soil with a 1.25 m drain depth would reduce

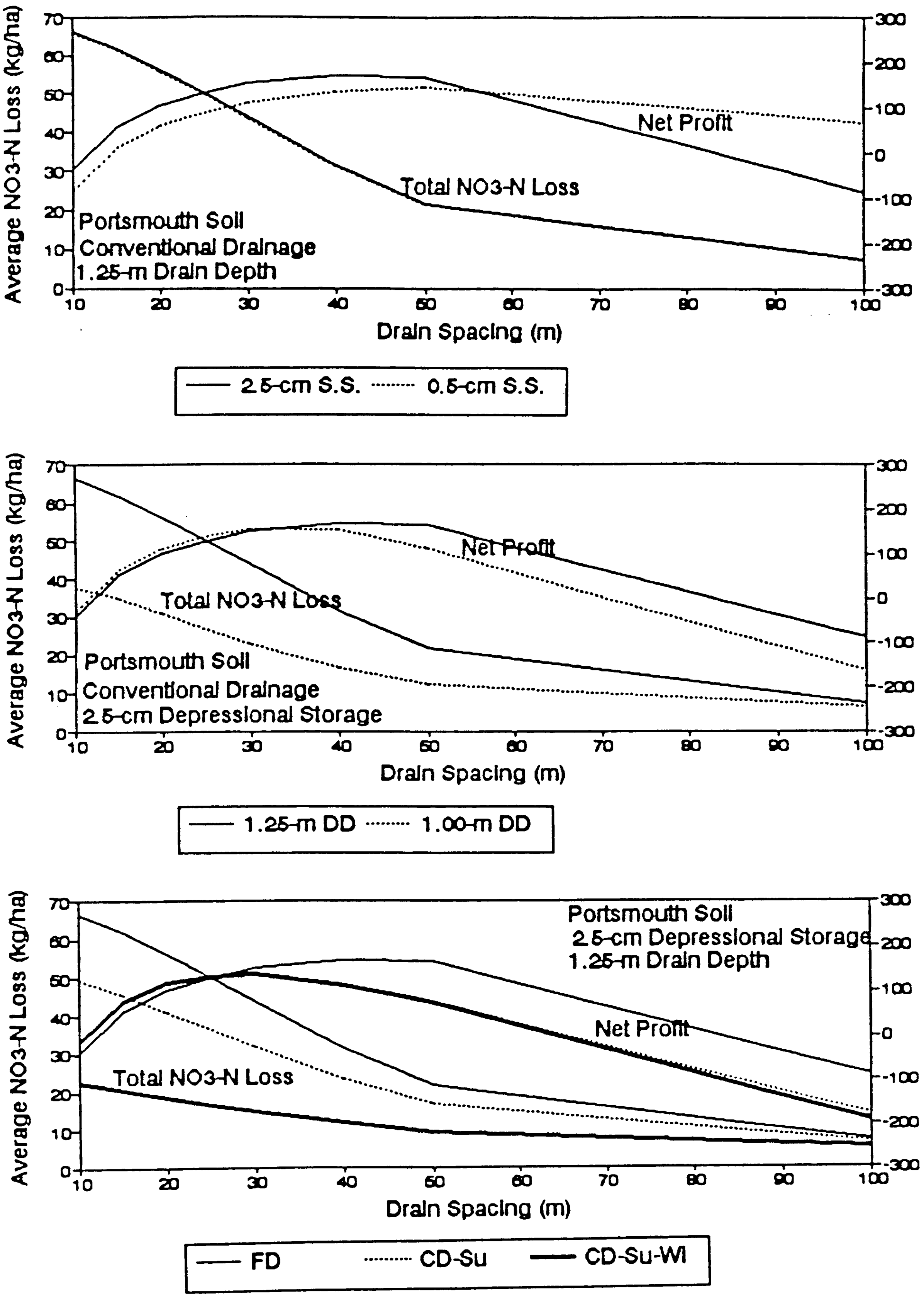


Figure 69 Predicted annual profit and total NO_3-N losses for a Portsmouth soil as affected by system management, and drain depth and spacing. Notation: CD=controlled drainage, FD=free drainage, Su=summer, and Wi=winter).

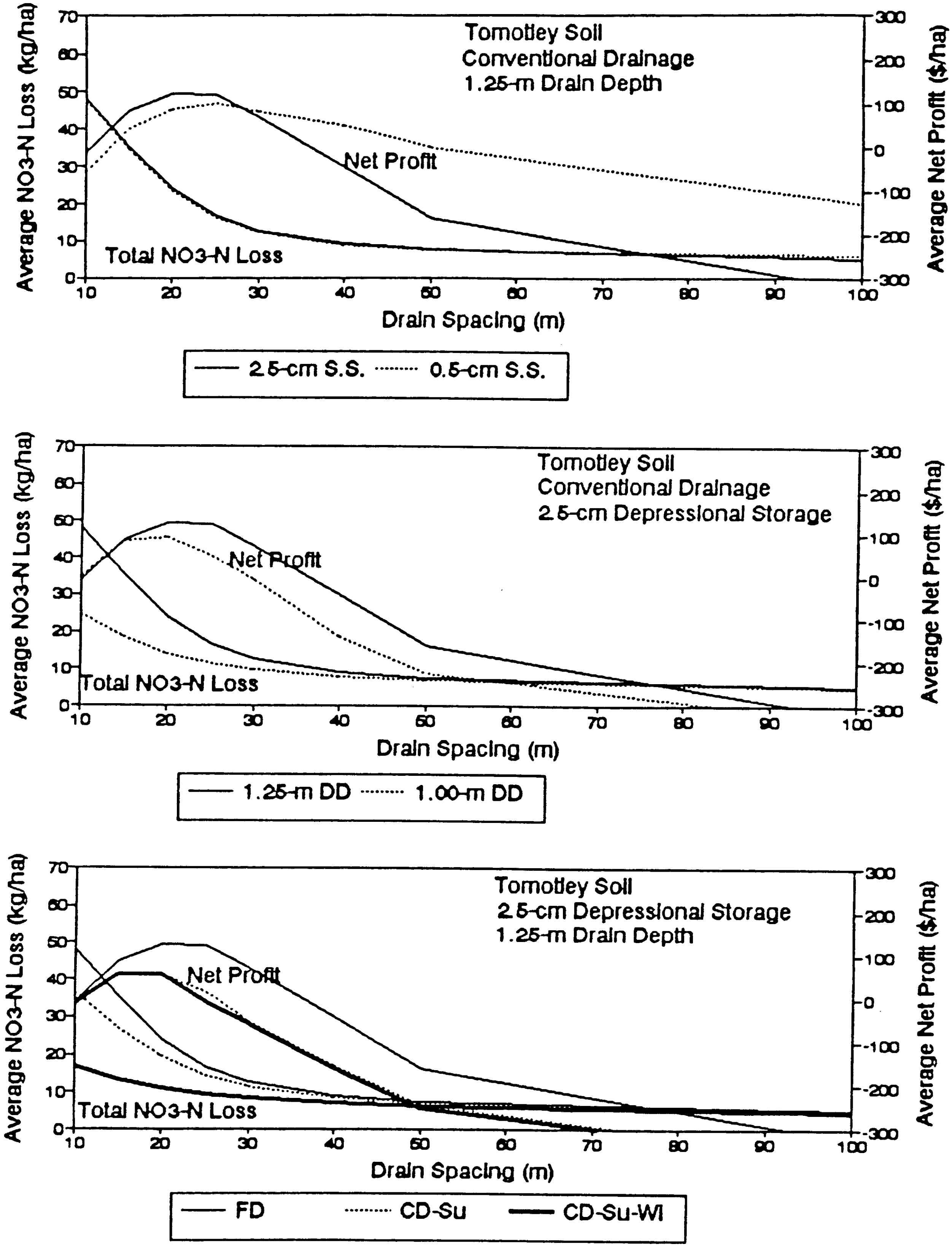


Figure 70 Predicted annual profit and total NO_3-N losses for a Tomotley soil as affected by system management, and drain depth and spacing. Notation: CD=controlled drainage, FD=free drainage, Su=summer, and Wi=winter).

total NO_3-N losses by 31%, from 31.5 to 21.6 kg/ha while reducing profits by only $2.90/ha (Fig. 69). In the case of the Tomotley soil with conventional drainage, with a 2.5-cm depressional storage and 1.25-m drain depth, increasing the drain spacing from 20 to 25 m would decrease total NO_3-N losses by 31%, from 24.2 to 16.8 kg/ha (Fig. 70) and reduce average profits by $3.70/ha. The risk of large losses in yields and profits during wet years would be increased, but the reduction in NO_3-N losses to surface waters may be of greater value.

The nitrogen results presented in Fig. 69-70 show that a substantial reduction in NO_3-N losses could be achieved by decreasing the drain depth of 1.25 m. If a 1.0 m drain depth is used, the projected reduction in total NO_3-N losses would be 48% and 43% for the Portsmouth and Tomotley soils, respectively. This would result in a reduction in profit of about $14/ha for the Portsmouth soil and $36/ha for the Tomotley soil (Appendix 5), but this may be warranted by the significant reduction in NO_3-N losses. That is, from a societal point of view, it may become less expensive to pay greater prices for grain compared to treating the water to remove excessive NO_3-N and, therefore, mitigate detrimental environmental impacts. Another way of decreasing total NO_3-N losses is by improving the surface conditions, but such decrease is not substantial compared to the associated decrease in profit (Fig. 69-70).

Simulated results indicate that using controlled drainage could reduce total nitrate-nitrogen losses, with another sacrifice in profits, however. If controlled drainage is used in the summer only, total NO_3-N losses can be decreased by 25% for the Portsmouth soil (to 23.5 kg/ha) and by 20% for the Tomotley soil (to 19.4 kg/ha), as compared to the conventionally drained system (Fig. 69-70). The decrease in profit associated with this water management modification is substantial for both soils ($54/ha and $70/ha for the Portsmouth and Tomotley soils, respectively). If controlled drainage is implemented during both the winter and summer seasons, total NO_3-N losses can be decreased by 62% (to 12 kg/ha) for the Portsmouth soil and by 54% (to 11.1 kg/ha) for the Tomotley soil. Because the use of CD in the winter, if properly managed, may not affect the yields of the summer crop greatly (Appendix 5), the decrease in profit associated with this water management scheme (CD in summer and winter) is the same as that of the CD-in-summer scenario. This suggests that controlled drainage in the winter alone may not affect profits, but may substantially decrease NO_3-N losses, and, thus, may meet both the production and environmental objectives.

The simulation results have demonstrated the applicability of *DRAINMOD-N* for quantifying effects of drainage design and management combinations on profits from agricultural crops and on losses of NO_3-N to the environment for a specific crop, soil and climatic conditions. Thus the model can be used to guide design and management decisions for satisfying both productivity and environmental objectives and assessing the costs and benefits of alternative choices to each set of objectives.

SUMMARY AND CONCLUSIONS

The environmental impacts of agricultural drainage have become a critical issue in many areas. There is a need to design and manage drainage and related water table control systems to satisfy both production and water quality objectives. Simulation models are a powerful tool to evaluate the effects of different drainage design and management combinations on drainage water quality. One such a model, *DRAINMOD-N*, was used to study long-term effects of drainage system design and management on two poorly drained eastern North Carolina soils.

Hydrologic results indicate that, for any equivalent design-management combination, greater subsurface drainage and lower surface runoff are associated with the Portsmouth soil due to its greater lateral conductivity, as compared to the Tomotley soil. Increasing the drain spacing and/or decreasing the drain depth reduces subsurface drainage while it increases surface runoff. Improving surface drainage causes an increase in surface runoff and a decrease in subsurface drainage. Controlled drainage (CD) is associated with a reduction in subsurface drainage and an increase in surface runoff.

Nitrogen results show that, in general, net mineralization rates and drainage losses are greater for the Portsmouth soil than for the Tomotley soil. Likewise, greater denitrification rates and runoff losses are associated in general with the Tomotley soil. Simulated results also indicate that increasing the drain spacing reduces NO_3-N drainage losses and net mineralization, but it increases NO_3-N runoff losses and denitrification for both soils. Increasing the drain depth increases drainage losses and net mineralization, and it decreases runoff losses and denitrification. Improving surface drainage decreases drainage losses and denitrification but increases runoff losses. Controlled drainage is associated with a reduction in drainage losses and an increase in denitrification and runoff losses.

The ideal drainage design and management combination is one that will optimize profits and minimize environmental impacts. Results from economic analyses indicate that the maximum profit for the Tomotley soil would be obtained with a conventional drainage system with a 20-m drain spacing, 1.25-m drain depth, and 2.5-cm depressional storage. In the case of the Portsmouth soil, a conventional drainage system with a 2.5-cm depressional storage, 40-m spacing, and 1.25-m drain depth would maximize profit from the crop.

Simulated results indicate that NO_3-N losses to the environment could be substantially reduced by reducing the drainage intensity below the level required for maximum profits from grain sales. That is, if the environmental objective is of equal or greater importance than profits from the agricultural crops, the drainage systems can be designed and managed to reduce NO_3-N losses while still providing an acceptable profit from the crop.

The simulation results have demonstrated the applicability of *DRAINMOD-N* for quantifying effects of drainage design and management combinations on profits from agricultural crops and on losses of NO_3-N to the environment for a specific crop, soil and climatic conditions. Thus the model can be used to guide design and management decisions for satisfying both productivity and environmental objectives and assessing the costs and benefits of alternative choices to each set of objectives.

DRAINMOD-N should be further field tested as discussed in the conclusions section of the previous chapter. After that is done the model should be used to study the interaction between fertilizer rates (amount and timing) and water table management strategies. Results of this study can then be used to develop improved design and management guidelines for poorly drained North Carolina Coastal Plain soils.

ALDICARB TRANSPORT IN A DRAINED COASTAL PLAIN SOIL *

The purpose of this chapter is to present results of a field experiment to determine the effect of water table control practices on the fate of the pesticide aldicarb in poorly drained soils in the coastal plain of North Carolina. The research site has subsurface drains that were maintained in conventional drainage, controlled drainage and subirrigation. Aldicarb concentrations in the soil, ground water, tile drainage and surface runoff were measured over a six month period in nine sampling rounds. Surface and subsurface drainage was measured and total aldicarb losses in the tile outflow and surface runoff were determined. The half life for aldicarb at this site was approximated.

Aldicarb (2-methyl-2-(methylthio)propionaldehyde *O*-methylcarbamoyloxime) was developed in 1962 by Union Carbide (now Rhone-Poulenc, Inc.) as a systemic insecticide, acaricide and nematicide for use in agriculture and silviculture (Weiden et al. 1965). Aldicarb (Temik®) is typically formulated in granules containing 15% active ingredient (AI) and degrades rapidly and irreversibly (Lightfoot et al. 1987). Two of the metabolites, sulfoxide and sulfone, have properties similar to aldicarb. All three compounds are extremely soluble in water, weakly sorbed to organic matter and highly toxic (Hornsby, et al. 1983). All aldicarb concentrations reported herein are the sum of the aldicarb, sulfoxide and sulfone concentrations.

Aldicarb is used widely throughout the world on fruits, vegetables, nuts, cotton, tobacco and ornamentals. In 1979 aldicarb residues were detected in drinking water wells on Long Island, New York (Zaki et al. 1982). To protect the public health, the EPA currently has a health advisory level of 3 ppb for aldicarb, 2 ppb for sulfone and 4 ppb for sulfoxide in drinking water.

Since 1979, over 88,000 soil and water samples have been collected in 35 states to study the fate of aldicarb (Jones 1989). The data base for aldicarb movement and degradation in the unsaturated zone is larger than that for any other pesticide (Jones 1989). These intensive investigations of the fate of aldicarb have been conducted to assess the environmental impact that aldicarb will have on the many and varied locations where it is used.

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* The contents of this chapter are summerized in the paper, Munster, C.L, R.W. Skaggs, J.E. Parsons, R.O. Evans, J.W. Gilliam and E.W. Harmsen. 1995. Aldicarb transport in drained coastal plain soil. J. Irrigation and Drainage Engineering 121(6):378-384.

RESULTS AND DISCUSSION

<u>Conventional Drainage, Plot 3.</u> The water level in the drain outlet tank was always below the drain for the conventional drainage treatment. Outflow from the center drain was measured at 21 mm along with 36 mm of surface runoff (Figure 71). The midpoint water table elevation remained at or above the drain (1.0 m) until 90 days after application when an extended dry period occurred (Figure 72).

As shown in Table 19, aldicarb persisted in the soil at the 0.00 to 0.15 m depth until day 225, 47 days after application. Aldicarb was not detected in the soil below the 0.46 to 0.61 m depth. However the initial concentration on day 1 was approximately four times the concentrations in the controlled drainage and subirrigation plots for unknown reasons. The high soil concentration (471 ng/g) in the 0.15 to 0.30 sample on day 178 (the day of application) may be due to cross contamination.

Very few of the samples from the piezometer nest near the center drain contained aldicarb (Table 20) and the concentrations seem to be without pattern. However, samples from the midpoint piezometer nest (Table 21) exhibited a consistent decline in aldicarb concentrations with depth and time. The erratic pattern in the piezometer nest near the drain was due to temporal variation in the water table and water movement near the drains. In the conventional drainage mode, the water table near the drain was lowered to the drains. The shallow piezometers went dry and a soil water sample could not be obtained to determine aldicarb concentrations (Table 20, Julian days 184 and 215). The next large rainfall event caused the water table to rise to the shallow piezometers (Table 20, Julian days 198 and 225) so that aldicarb concentrations could be determined. These concentrations indicate that aldicarb retained in the soil may be quickly transported vertically downward near the drains in the conventional drainage mode during infiltration events.

The aldicarb concentrations in the drain outflow (Table 22) support the above hypothesis. Aldicarb concentrations as high as 35 ppb were detected in the tile outflow soon after the large rainfall event on day 198.

Aldicarb concentrations were detected in two surface runoff samples from days 225 and 239 (Table 22). However, total aldicarb losses in the tile outflow and surface runoff (Figure 73) were 0.02 % and 0.02 % of the aldicarb applied, respectively, for the conventional drainage mode.

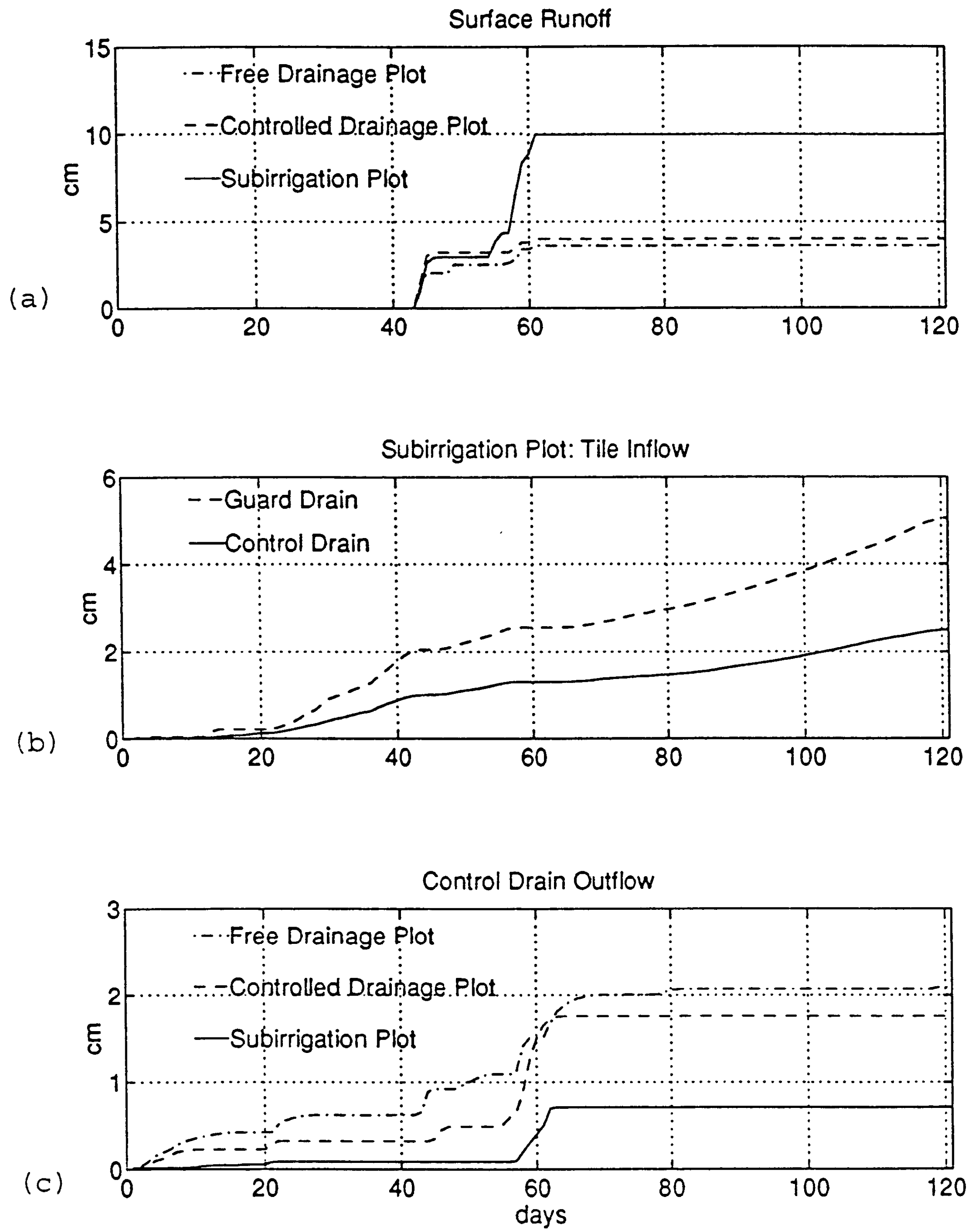
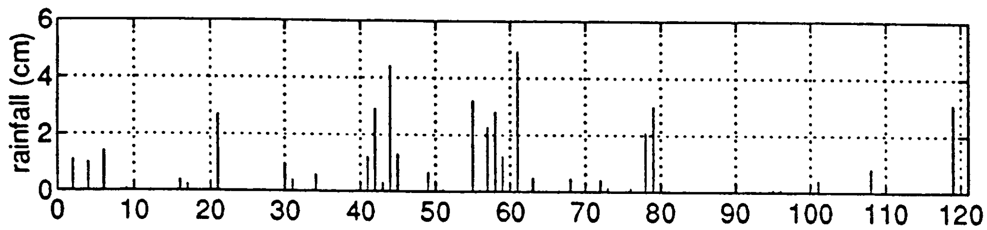
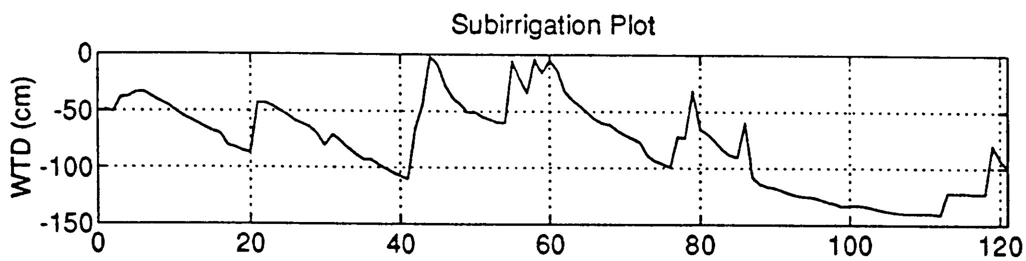


Figure 71 Surface runoff (a), subirrigation inflow (b), and drain outflow (c) for free drainage, controlled drainage, subirrigation plots.

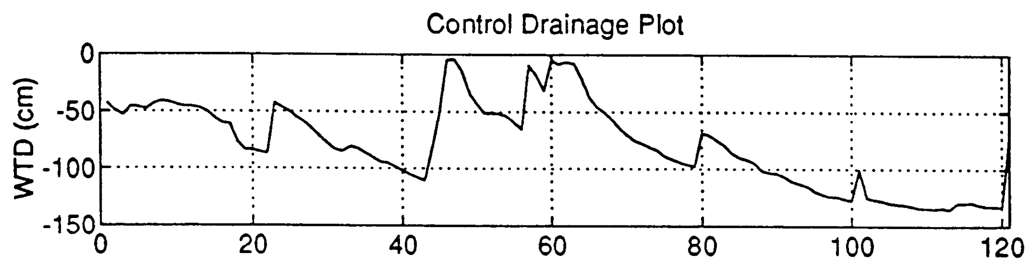
(a)



(b)



(c)



(d)

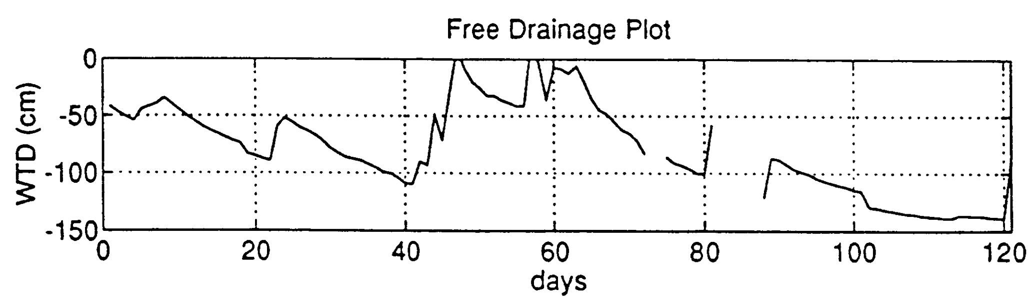


Figure 72 Rainfall record (a) and midpoint water table elevations for subirrigation (b), controlled drainage (c) and free drainage (d).

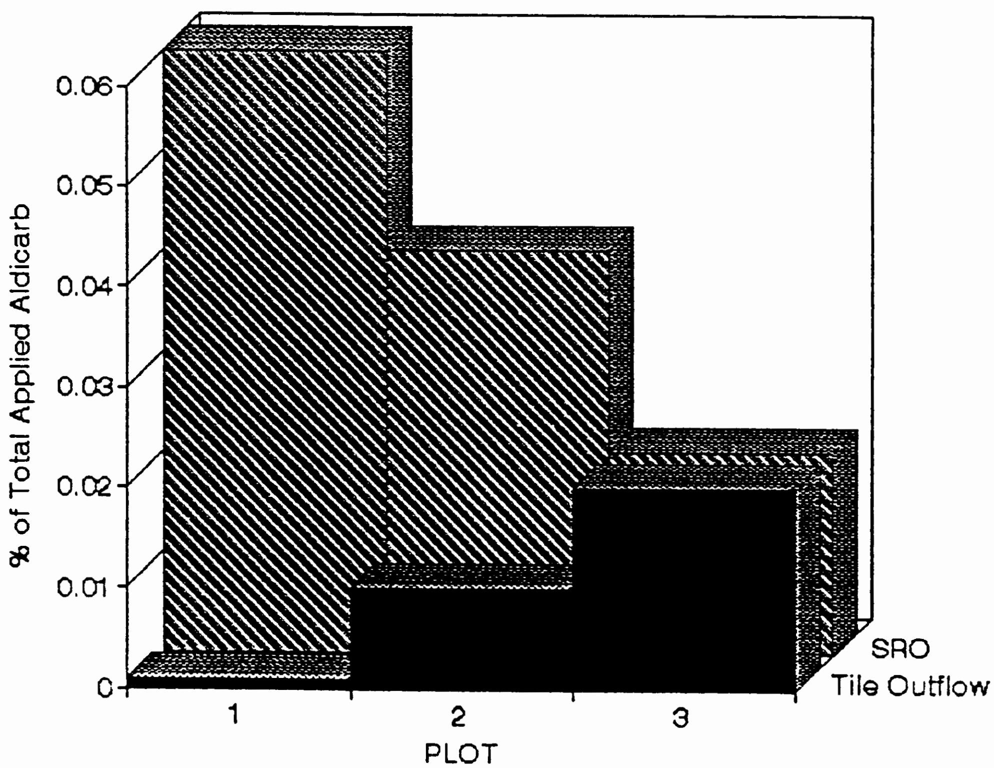


Figure 73 Total aldicarb lost as a percentage of the amount applied in the tile outflow and surface runoff (SRO) from subirrigation (plot 1), controlled drainage (plot 2), and free drainage (plot 3).

Table 19: Aldicarb concentrations (ng/g dry soil) in the free drainage plot (plot 3) in the soil samples.

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	SAMPLE DEPTH (M) 0.00 - 0.15	0.15 - 0.30	0.30 - 0.46	0.46 - 0.61	0.61 - 0.76
1	178	2018.0	471.0	---	---	---
2	184	461.0	41.0	17.0	---	---
3	198	140.0	4.0	7.0	---	---
4	215	29.0	0.0	3.0	5.0	---
5	225	7.0	0.0	0.0	0.0	---
6	239	0.0	0.0	0.0	0.0	0.0
7	256	0.0	0.0	0.0	0.0	0.0
8	297	0.0	0.0	0.0	0.0	0.0
9	4	0.0	0.0	0.0	0.0	0.0

Table 20: Aldicarb concentrations ($\mu g/L$) in the free drainage plot (plot 3) in the center drain wells.

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	SCREEN DEPTH (M) 0.61	0.85	1.30	0 -1.2	1.77	2.42
1	178	0.0	0.0	0.0	0.0	0.0	0.0
2	184	---	8.0	0.0	19.0	0.0	0.0
3	198	42.0	0.0	0.0	0.0	0.0	0.0
4	215	---	---	0.0	---	0.0	0.0
5	225	5.0	0.0	0.0	36.0	0.0	0.0
6	239	0.0	0.0	0.0	0.0	0.0	0.0
7	256	---	0.0	0.0	0.0	0.0	0.0
8	297	---	---	0.0	0.0	0.0	0.0
9	4	0.0	0.0	0.0	0.0	0.0	0.0

Table 21: Aldicarb concentrations (μg/L) in the free drainage plot (plot 3) in the midpoint wells.

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	SCREEN DEPTH (M)					
		0.59	0.90	1.22	0 -1.0	1.74	2.22
1	178	0.0	0.0	0.0	0.0	0.0	0.0
2	184	0.0	7.0	2.0	14.0	10.0	0.0
3	198	0.0	0.0	0.0	8.0	0.0	0.0
4	215	---	---	1.0	---	0.0	0.0
5	225	6.0	0.0	0.0	2.0	0.0	0.0
6	239	0.0	0.0	0.0	1.0	0.0	0.0
7	256	---	0.0	0.0	0.0	0.0	0.0
8	297	---	---	0.0	0.0	0.0	0.0
9	4	0.0	0.0	0.0	0.0	0.0	0.0

Table 22: Aldicarb concentrations (μg/L) in the free drainage plot (plot 3) in the tile outflow.

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	CENTER TANK	GUARD TANK	SRO TANK
1	178	0	0	0
2	184	16	9	---
3	198	35	32	---
4	215	0	0	---
5	225	4	4	15
6	239	0	0	2
7	256	0	0	---
8	297	0	0	---
9	4	0	0	0

Controlled Drainage, Plot 2. Controls were set on the outlet tanks such that drainage water was not pumped from the outlet until it exceeded a set point. No additional water was pumped into the outlet in this controlled drainage treatment. Total measured outflow from the center drain was 18 mm with 40 mm of surface runoff (Figure 71). The measured water table midway between the drains is shown in Figure 72.

Aldicarb concentrations in the soil in plot two (Table 23) decreased to below detectable limits by day 225, 47 days after application. Aldicarb was not detected in the soil deeper than the 0.30 to 0.46 m samples.

Aldicarb was not consistently detected after day 198, 20 days after application, in the piezometer nests (Tables 24, 25 and 26). The drainage outflow from both the center and guard drains consistently had aldicarb concentrations from 6 to 23 ppb until after day 225 (Table 27). Aldicarb in the soil water near the drain, as indicated by concentrations in the piezometer nest, was lost in the drainage outflow.

Only one surface runoff sample contained aldicarb (Table 27). Surface runoff from the rainfall event that occurred 47 days after application (Julian day 225) had an aldicarb concentration of 25 ppb. Aldicarb losses in the tile outflow and surface runoff (Figure 73) were 0.01 % and 0.04 % of total aldicarb applied, respectively.

Subirrigation, Plot 1. Subirrigation was applied to plot one by maintaining the water at a set level above the drain outlets. The center drain subirrigated 25 mm while draining 7 mm during wet periods (Figure 71). During the 120 day field study, 100 mm of surface runoff was measured in plot one (Figure 71). The midpoint water table elevation is shown in Figure 72.

As shown in Table 28, aldicarb persisted in the soil at the 0.00 to 0.15 m depth until day 225, 47 days after application. Aldicarb was not detected in the soil below the 0.46 to 0.61 m depth.

Aldicarb was never detected below the 1.3 m depth in the piezometer nest samples (Tables 29 and 30). The concentrations in the midpoint nest were approximately twice the values in the samples taken from the nest near the drain. This is due to the effects of subirrigation. The center drain nest was located 0.30 m from the center drain and the aldicarb concentrations were diluted by subirrigation water. However, due to high head losses near the drain, subirrigation water was not uniformly distributed across the plot and the midpoint piezometers which were 11.4 m from the center drain, were less affected by subirrigation.

Table 23: Aldicarb concentrations (ng/g dry soil) in the controlled drainage plot (plot 2) in the soil samples.

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	SAMPLE DEPTH (M) 0.00 - 0.15	0.15 - 0.30	0.30 - 0.46	0.46 - 0.61	0.61 - 0.76
1	178	544.0	21.0	---	---	---
2	184	234.0	17.0	16.0	---	---
3	198	38.0	3.0	3.0	---	---
4	215	8.0	0.0	0.0	0.0	---
5	225	0.0	0.0	0.0	0.0	---
6	239	0.0	0.0	0.0	0.0	---
7	256	0.0	0.0	0.0	0.0	0.0
8	297	0.0	0.0	0.0	0.0	0.0
9	4	0.0	0.0	0.0	0.0	0.0

Table 24: Aldicarb concentrations (μg/L)in the controlled drainage plot (plot 2) in the midpoint wells.

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	SCREEN DEPTH (M) 0.60	0.82	1.06	0 -1.2	1.40	1.78	2.37
1	178	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	184	6.0	12.0	0.0	3.0	11.0	0.0	2.0
3	198	0.0	11.0	0.0	6.0	0.0	0.0	0.0
4	215	---	---	0.0	0.0	0.0	0.0	0.0
5	225	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	239	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	256	0.0	1.0	0.0	0.0	0.0	0.0	0.0
8	297	---	0.0	0.0	0.0	0.0	0.0	0.0
9	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 25: Aldicarb concentrations ($\mu g/L$) in the controlled drainage plot (plot 2) in the quarter point wells.

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	SCREEN DEPTH (M) 0.56	0.79	1.03	0 -1.1	1.55	1.85	2.34
1	178	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	184	0.0	8.0	0.0	3.0	11.0	0.0	2.0
3	198	2.0	13.0	0.0	0.0	6.0	0.0	23.0
4	215	---	---	0.0	0.0	0.0	0.0	0.0
5	225	0.0	2.0	0.0	0.0	0.0	2.0	0.0
6	239	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	256	0.0	1.0	0.0	0.0	0.0	5.0	0.0
8	297	---	0.0	0.0	0.0	0.0	0.0	0.0
9	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 26: Aldicarb concentrations ($\mu g/L$) in the controlled drainage plot (plot 2) in the center drain wells.

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	SCREEN DEPTH (M) 0.55	0.80	1.09	0 -1.1	1.36	1.80	2.31
1	178	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	184	1.0	0.0	0.0	0.0	0.0	0.0	2.0
3	198	4.0	7.0	0.0	0.0	0.0	0.0	3.0
4	215	---	---	0.0	0.0	0.0	0.0	0.0
5	225	0.0	2.0	0.0	0.0	0.0	0.0	0.0
6	239	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	256	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	297	---	0.0	0.0	0.0	0.0	0.0	0.0
9	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 27: Aldicarb concentrations ($\mu g/L$) in the controlled drainage plot (plot 2) in the tile outflow.

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	CENTER TANK	GUARD TANK	SRO TANK
1	178	0	0	0
2	184	14	9	---
3	198	14	7	0
4	215	23	0	---
5	225	6	6	27
6	239	0	0	0
7	256	0	0	0
8	297	0	0	---
9	4	0	0	---

Table 28: Aldicarb concentrations (ng/g dry soil) in the subirrigation plot (plot 1) in the soil samples.

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	SAMPLE DEPTH (M)				
		0.00 - 0.15	0.15 - 0.30	0.30 - 0.46	0.46 - 0.61	0.61 - 0.76
1	178	553.0	5.0	---	---	---
2	184	163.0	9.0	52.0	---	---
3	198	57.0	1.0	6.0	---	---
4	215	30.0	0.0	4.0	1.0	---
5	225	19.0	0.0	0.0	0.0	---
6	239	0.0	0.0	0.0	0.0	---
7	256	0.0	0.0	0.0	0.0	0.0
8	297	0.0	0.0	0.0	0.0	0.0
9	4	0.0	0.0	0.0	0.0	0.0

Table 29: Aldicarb concentrations ($\mu g/L$) in the subirrigation plot (plot 1) in the midpoint wells.

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	SCREEN DEPTH (M) 0.56	0.76	1.17	0 -1.3	1.87	2.54
1	178	0.0	0.0	0.0	0.0	0.0	0.0
2	184	15.0	0.0	0.0	2.0	0.0	0.0
3	198	8.0	0.0	0.0	9.0	0.0	0.0
4	215	---	---	0.0	5.0	0.0	0.0
5	225	0.0	0.0	0.0	15.0	0.0	0.0
6	239	0.0	0.0	0.0	3.0	0.0	0.0
7	256	---	0.0	0.0	0.0	0.0	0.0
8	297	---	---	0.0	0.0	0.0	0.0
9	4	0.0	0.0	0.0	0.0	0.0	0.0

Table 30: Aldicarb concentrations ($\mu g/L$) in the subirrigation plot (plot 1) in the center drain wells

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	SCREEN DEPTH (M) 0.59	0.87	1.17	0 -1.3	2.00	2.37
1	178	0.0	0.0	0.0	0.0	0.0	0.0
2	184	0.0	1.0	0.0	0.0	0.0	0.0
3	198	5.0	5.0	0.0	8.0	0.0	0.0
4	215	---	---	0.0	0.0	0.0	0.0
5	225	0.0	0.0	0.0	2.0	0.0	0.0
6	239	0.0	0.0	0.0	0.0	0.0	0.0
7	256	---	0.0	0.0	0.0	0.0	0.0
8	297	---	0.0	0.0	0.0	0.0	0.0
9	4	0.0	0.0	0.0	0.0	0.0	0.0

Aldicarb occurred in the drain outflow once at a level of 2 ppb (Table 31). The quantity of aldicarb in the drain outflow was less than 0.001 % of total applied aldicarb (Figure 73).

Two rainfall events produced high concentrations of aldicarb in the surface runoff samples obtained 47 and 61 days (Julian days 225 and 239) after application (Table 31). The aldicarb concentration of 26 ppb in the surface runoff sample from day 225 is very similar to the concentration found in the surface runoff sample from plot 2 (25 ppb) on the same day. The amount of aldicarb in the surface runoff was approximately 0.06 % of total applied aldicarb (Figure 73).

<u>Ditch, Shallow Irrigation Well and Deep Irrigation Well.</u> Water samples were taken from the drainage ditch and the shallow and deep irrigation wells each sampling round. Aldicarb was never detected in either of the irrigation wells (Table 32). The drainage ditch contained aldicarb concentrations of 2 ppb on day 184 (6 days after application) and 7 ppb on day 225 (47 days after application).

<u>Aldicarb Degradation</u>. A summary of the degradation of aldicarb to the sulfoxide and sulfone metabolites detected in soil samples is shown in Table 33. The soil samples taken on the day of application (day 1) were obtained approximately two hours after application. As shown in Table 34, 86% of the aldicarb detected degraded to the metabolite sulfoxide. The sulfoxide then degraded to the metabolite sulfone.

The half life for aldicarb (aldicarb, sulfoxide and sulfone) was estimated using analysis data from the drain outflow and soil and water samples taken six days after application in the controlled drainage plot. The center drain outflow contained an aldicarb concentration of 14 ng/ml (Table 27). This concentration was assumed to exist in the saturated zone from the water table (0.60 m) to the maximum depth that aldicarb was detected (1.40 m) as shown in Table 24. The average soil concentration detected in the soil samples was 89 ng/g (Table 23). This concentration was assumed to exist from the soil surface to the water table.

Using the above soil and water concentrations and the average porosity of the soil layers from 0.60 m to 1.40 m, and the average bulk density of the soil from 0.60 m to the surface, the total mass of aldicarb within a unit width (0.01 m) cross section of the soil profile was determined. The amount of aldicarb lost from the plot was also determined using tile outflow data.

The cross section extended from the center drain to the midpoint between the adjacent guard drain. When the calculated mass of aldicarb was compared to the mass applied to this unit cross section, 70% of the applied aldicarb was remaining on the sixth day after application.

Table 31: Aldicarb concentrations ($\mu g/L$) in the subirrigation plot (plot 1) in the tile drainage.

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	CENTER TANK	GUARD TANK	SRO TANK
1	178	0.0	0.0	0.0
2	184	0.0	2.0	
3	198	0.0	0.0	0.0
4	215	---	---	---
5	225	---	---	26.0
6	239	0.0	0.0	2.0
7	256	0.0	0.0	---
8	297	---	---	---
9	4	0.0	0.0	---

Table 32: Aldicarb concentrations ($\mu g/L$) in the drainage ditch and irrigation wells.

SAMPLE ROUND NO.	SAMPLE DATE (JULIAN DAY)	DITCH	SHALLOW IRR.WELL	DEEP IRR. WELL
1	178	0.0	0.0	0.0
2	184	2.0	0.0	0.0
3	198	0.0	0.0	0.0
4	215	0.0	0.0	0.0
5	225	7.0	0.0	0.0
6	239	0.0	0.0	0.0
7	256	0.0	0.0	0.0
8	297	0.0	0.0	0.0
9	4	0.0	0.0	0.0

Table 33: The percent of aldicarb and the metabolites sulfoxide and sulfone detected in all soil samples taken 1, 6, 20 and 37 days after application.

Days After Application	Aldicarb (%)	Sulfoxide (%)	Sulfone (%)
1	14	86	0
6	0	81	19
20	0	39	61
37	0	18	82

A decay constant (k) of 0.06 was calculated by solving the radioactive decay equation:

$$A = A_0 e^{-kt} \tag{19}$$

where:

t = time (days) = 6

A_0 = initial concentration = 1

A = concentration at time t = 0.70.

The half life for aldicarb was calculated to be 11.5 days using the radioactive decay equation where:

k = decay constant = 0.06

A_0 = initial concentration = 1

A = concentration at time t = 0.50.

SUMMARY AND DISCUSSION

Aldicarb dissipated from the soil in all three plots by 61 days after application. Most of the aldicarb detected in the soil was found in the 0.00 to 0.15 m samples. Aldicarb was detected in the soil at a maximum depth of 0.46 m.

In each plot, the aldicarb concentrations in the midpoint well samples were consistently higher than the piezometer nest near the drain. For the subirrigation plot, this is due to a combination of dilution due to subirrigation water and aldicarb transport from near the drain with tile outflow when there was drainage. For the controlled drainage and conventional drainage plots, aldicarb transport in the vicinity of the drain with tile outflow is the sole cause. Aldicarb was not consistently detected in the well water samples after Julian day 239, 61 days after application.

The conventional drainage plot produced the largest volume of tile outflow with the highest aldicarb concentrations. This combination resulted in conventional drainage having the highest percentage of aldicarb lost from tile outflow, followed by controlled drainage and then subirrigation (Figure 73). However, the amount of aldicarb lost through the subsurface drains for all three management modes is extremely small when compared to the total amount of aldicarb applied (Figure 73). Aldicarb was not detected in the tile outflow after Julian day 225, 47 days after application.

Aldicarb concentrations in the surface runoff were similar in all three plots. However the volume of surface runoff was highest for the subirrigation plot and lowest for the conventional drainage plot. The subirrigation plot maintained the highest water table while the conventional drainage plot had the lowest water table. Therefore, the soil profile in subirrigation had the least amount of storage for infiltration and the soil profile in conventional drainage had the most storage. Accordingly, more surface runoff and aldicarb was lost in the subirrigation mode than in the controlled drainage or conventional drainage modes (Figure 73). Although the amount of aldicarb lost through surface runoff was higher than tile outflow, the total percentage of aldicarb lost through surface runoff is extremely low when compared to the total percentage applied (Figure 73). Aldicarb was not detected in the surface runoff after Julian day 239, 61 days after application.

Aldicarb degraded quickly in each plot. Calculations based on a mass balance for aldicarb resulted in an estimated half life of 11.5 days.

SIMULATING ALDICARB TRANSPORT IN A DRAINED FIELD *

Two-dimensional finite difference models were first developed to solve the Richards Equation for saturated and unsaturated flow in porous media by Remson et al. (1967), Rubin (1968), Amerman (1969), Taylor and Luthin (1969), Cooley (1971) and Brandt et al. (1971). Typically these early solutions were used to approximate flow to wells, ditch drainage, irrigation, infiltration and lateral flow on sloping lands. Later, advances in numerical solutions were applied to two-dimensional finite difference models by Amerman (1976) and Hornung and Messing (1980 and 1983).

The United States Geological Survey (USGS) computer model VS2DT (Variably Saturated Two Dimensional Transport) is a two dimensional finite difference program that couples the solution of the Richard's equation with the solution of the advection-dispersion equation for chemical transport (Lappala et al., 1987 and Healy, 1990). This model includes options for simulating first order decay, adsorption and ion exchange.

The VS2DT program was modified to include boundary conditions imposed by tile drainage and subirrigation. The model was also modified to include transport of multiple chemicals. This modified version of VS2DT was used to simulate the movement of the pesticide aldicarb (Temik®) in the soil, groundwater and surface runoff at a field research site in eastern North Carolina. Water management treatments considered were conventional drainage, controlled drainage and subirrigation.

Model predictions were evaluated by comparison with field measurements of water table elevation, tile outflow, surface runoff and subirrigation. Predicted transport and fate of aldicarb simulations were compared to water quality measurements obtained from the tile outflow and monitoring wells.

THE COMPUTER MODEL

A modified version of the USGS computer model, VS2DT, dated April, 1990, was used to simulate groundwater flow and aldicarb movement at the Plymouth research site. Finite difference methods were used in this model to simulate both saturated and unsaturated flow and chemical transport in two dimensions.

The original fortran code consisted of a primary program file with 23 supporting subroutines. Seven subroutines were added to the model to facilitate the input and output of data and to simulate subsurface drainage and subirrigation.

* The contents of this chapter are published in the paper, Munster, C.L., R.W. Skaggs, J.E. Parsons, R.O. Evans, J.W. Gilliam, and M.A. Breve. 1994. Simulating aldicarb transport in a drained field. TRANSACTIONS of the ASAE 37(6):1817-1824.

The flow domain was approximated by 900 nodes in a grid of 30 nodes by 30 nodes. The spatial derivatives of the governing partial differential equations are approximated by the central difference method. A fully implicit backward scheme was used to approximate the time derivatives. The matrix of finite difference equations was solved with a strongly implicit procedure.

Field data required by the model, such as rainfall, potential evapotranspiration and root depth, were input on a daily basis. The initial time step increment was 10^{-7} day and was increased by a factor of 2.1 when a stable solution was achieved and reduced by a factor of 0.2 when nonstable conditions persisted.

Transport for each time step was simulated after solution of the ground water equations was achieved. The governing advection dispersion equation was solved numerically by using finite difference techniques. The VS2DT program has the option to use either backward or centered approximations to solve both the space and time derivatives . Source and/or sink program options include first order decay, equilibrium adsorption and ion exchange. Equilibrium adsorption can be approximated by either Freundlich or Langmuir isotherms. The matrix of finite difference transport equations are solved by using the strongly implicit procedure. The program code was modified to simulate the transport of multiple chemicals. However, for this study, aldicarb and its toxic degradation compounds sulfoxide and sulfone, were transported as a single compound.

THE GOVERNING EQUATIONS

Ground Water Flow. The movement of water through the soil was approximated with the Richard's equation for saturated and unsaturated flow. The governing equation for groundwater flow may be written as (Lappala et al., 1987):

$$v[\rho(C_m + sS_s)]\frac{\partial H}{\partial t} = \sum_{k=1}^{m} \rho K(h)\frac{\partial H}{\partial n_k}A_k + \rho q v \qquad \textbf{(20)}$$

where:

v = volume
ρ = liquid density
s = saturation
t = time
q = source/sink (v/t)
K = hydraulic conductivity
h = pressure head
H = total hydraulic head
m = number of faces of the volume
A_k = the area of the k'^{th} face
n = spatial direction
$C_m = \partial\theta / \partial h$
$S_s = \rho g(\alpha_c + \phi\beta_c)$

where:

ϕ = porosity
$\theta = \phi\ s$
g = gravity
$\alpha_c = \partial\phi\ /\ \partial P$
P = average compression pressure
$\beta_c = (1/\rho)(\partial\rho/\partial P)$

Chemical Transport. Solute transport through the soil and groundwater was simulated by the advection-dispersion equation (Bear, 1979):

$$\frac{\partial(\theta c)}{\partial t} = \nabla\cdot\ \theta\ \overline{\overline{D_h}}\cdot\nabla c\ -\ \nabla\cdot\ \theta\ \overline{v}c\ +\ SS \qquad \textbf{(21)}$$

where

θ = volumetric water content
c = concentration of chemical (mass per unit volume of water)
t = time
D_h = hydrodynamic dispersion tensor
v = fluid velocity vector
SS = source / sink terms.

BOUNDARY CONDITIONS

Ground Water Flow. Each research plot had three subsurface drain lines spaced 22.9 m apart. The center control drain was bounded on either side by guard drains. The three subsurface drains within a research plot were maintained in the same water table management mode. Each water table management treatment theoretically created a symmetric water table profile, with a groundwater divide midway between each guard drain and the control drain (Figure 74).

The boundary conditions for the cross section shown in Figure 74 are as follows:

AB = no flow boundary
BC = no flow boundary
CD = no flow boundary
DE = constant head, or no flow boundary
EF = no flow boundary
AF = constant head, or known flux boundary

Chemical Transport. Aldicarb was incorporated directly into the soil on day 178 as a granular formulation at a rate of 0.94 kg/ha (active ingredient). The chemical concentration in the soil water in the surface nodes was increased to account for the amount of aldicarb applied. This assumes that there is sufficient soil moisture available to release the chemical into solution. All aldicarb concentrations reported are the sum of aldicarb, sulfoxide and sulfone concentrations.

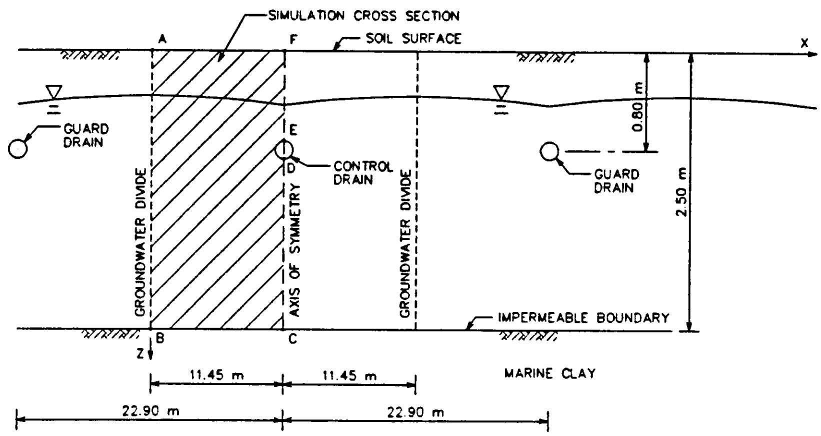


Figure 74: Schematic of flow domain simulated.

The chemical concentration in outflow was assumed identical to the concentration in the nodes adjacent to the boundary where the outflow occurs. For inflow, the chemical concentration must be specified. For transpiration, the chemical concentration of plant uptake was assumed equal to the concentration in the soil water in the root zone. No solute was assumed lost through soil evaporation.

SIMULATION INPUTS

Ground Water Flow. The soil profile was divided into eight soil layers. VS2DT requires seven soil property inputs for each soil layer (Table 34): the anisotropic ratio for saturated hydraulic conductivity (vertical/horizontal), the saturated horizontal hydraulic conductivity ($K_{sat\ horiz}$), the specific storage (S_s), the porosity (ϕ), the bubbling pressure (h_b), the residual volumetric moisture content (mc) and the pore size distribution index (λ). The last four parameters are inputs for the Brooks and Corey (1964) equations for functional relationships between soil water content, pressure head and unsaturated hydraulic conductivity. All values were determined experimentally from field and laboratory tests except for specific storage, which was estimated from data in the literature.

Chemical Transport. Seven soil and chemical variables were used in the chemical transport solution for each soil layer (Table 35). The variables are longitudinal dispersivity (α_l), transverse dispersivity (α_t), molecular diffusion (D_m), decay rate, bulk density (ρ_b), Freundlich adsorption constant (K_f) and the Freundlich exponent (n).

The longitudinal and transverse dispersivity values were calibrated (Harmsen et al., 1991) with nitrogen data from the Plymouth research sites. The bulk density and organic content for each soil layer were determined in the laboratory and the decay rate was calibrated by using the field data. All other chemical

Table 34: VS2DT inputs for soil properties.

SOIL LAYER	RATIO (V/H)	HORIZ K_{SAT} (CM/DAY)	SPECIFIC STORAGE (1/CM)	POROSITY	h_b (CM)	RESIDUAL MOISTURE CONTENT	λ
1	1.0	7.0	1.0E-9	0.45	-5.0	0.12	0.07
2	1.0	20.0	1.0E-9	0.40	-5.0	0.12	0.07
3	0.1	70.0	1.0E-9	0.34	-5.0	0.13	0.06
4	0.1	180.0	1.0E-9	0.34	-5.0	0.13	0.06
5	1.0	5.0	1.0E-9	0.30	-5.0	0.13	0.06
6	1.0	1.5	1.0E-9	0.32	-5.0	0.13	0.06
7	1.0	30.0	1.0E-9	0.32	-5.0	0.10	0.10
8	1.0	375.0	1.0E-9	0.32	-5.0	0.10	0.10

Table 35: VS2DT inputs for chemical transport.

SOIL LAYER	α_l (cm)	α_t (cm)	D_m (cm^2/day)	DECAY (1/day)	ρ_b (g/cm^3)	K_f	n
1	100	20	1.0E-6	0.10	1.1	0.0	1.30
2	150	30	1.0E-6	0.10	1.4	0.0	1.30
3	100	20	1.0E-6	0.10	1.5	0.0	1.30
4	150	30	1.0E-6	0.10	1.5	0.0	1.30
5	50	10	1.0E-6	0.10	1.5	0.0	1.30
6	50	10	1.0E-6	0.10	1.5	0.0	1.30
7	100	20	1.0E-6	0.10	1.6	0.0	1.30
8	100	20	1.0E-6	0.10	1.6	0.0	1.30

transport variables were estimated from data in the literature.Adsorption of aldicarb to the soil particles was set to zero (K_f=0) because of low attraction of aldicarb to organic matter (K_{oc}<30).

SIMULATION ANALYSIS

Ground Water Flow. The groundwater flow was simulated for each experimental plot for a 120 day period which started on day 178 (June 27) of 1990, the day aldicarb was applied to the experimental plots.

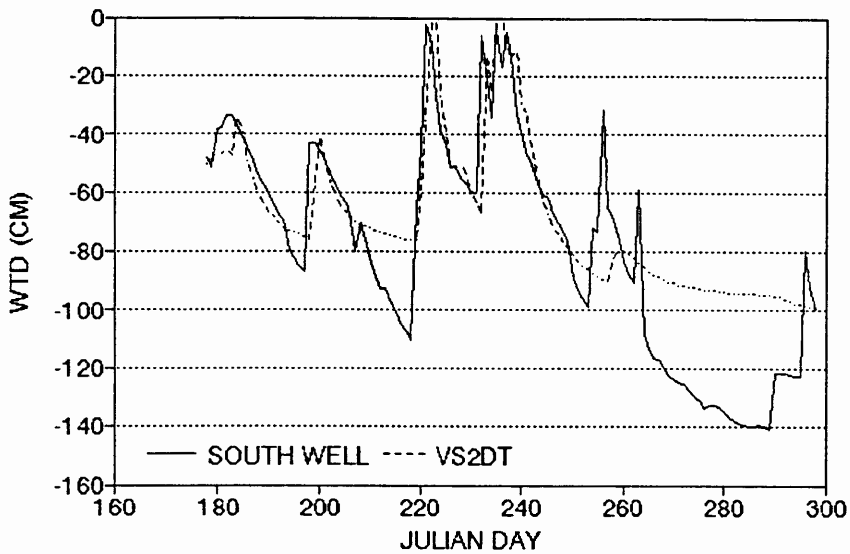


Figure 75: Measured and simulated midpoint water table depth in plot one under subirrigation.

All simulation input variables were determined either experimentally or from the literature. No variables were 'calibrated' or adjusted to improve agreement between measured and simulated results. The measured and simulated depth to the water table at the midpoint between the control and guard drains are shown in Figure 75 for plot 1, Figure 76 for plot 2 and Figure 77 for plot 3.

In the subirrigated plot, Figure 75, the simulated water table deviates from the measured water table during extended dry periods (days 220 and 280). The simulated profile never declines below the 1.0 m depth while the measured profile reaches the 1.4 m depth. The most likely cause for this discrepancy is high head losses in the vicinity of the drain tube. This resulted in over estimation of the volume of water subirrigated. A total of 25 mm of subirrigated water was measured whereas 65 mm was simulated. The excess volume of subirrigation water prevented the simulated water table profile from falling below 1.0 m.

In plot 2 with controlled drainage, the only significant deviation between the simulated and the measured water table profile occurred on day 256 (Figure 76). The 30 mm rainfall on day 256 caused the water table to rise 0.4 m in the field while the model predicted very little water table change. This deviation was probably caused by over estimation of evapotranspiration prior to the event. This caused the simulated soil water condition in the profile to be drier than the actual, so that sufficient storage was available for the infiltration water without substantial rise of the water table.

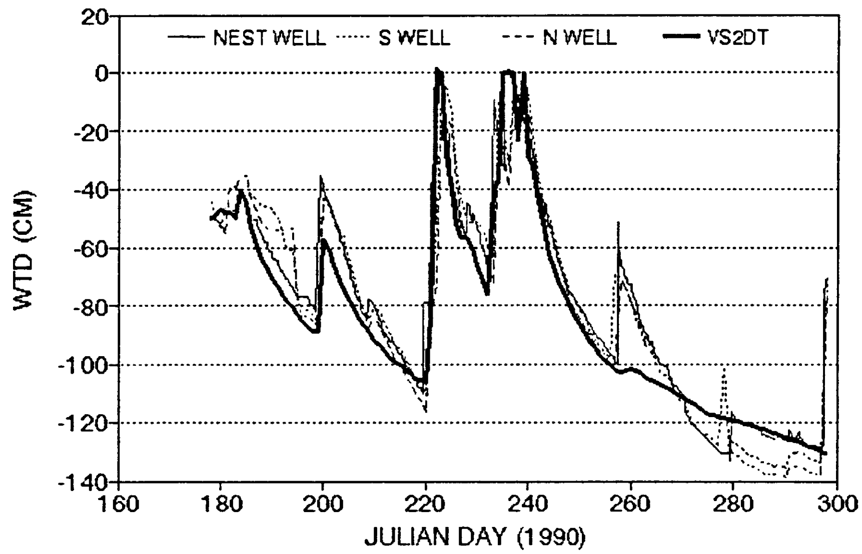


Figure 76: Measured and simulated midpoint water table depth in plot two under controlled drainage.

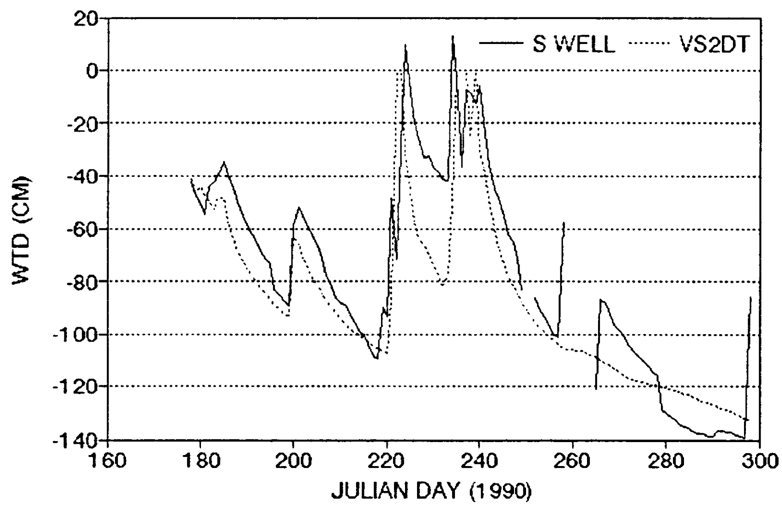


Figure 77: Measured and simulated midpoint water table depth in plot three under conventional drainage.

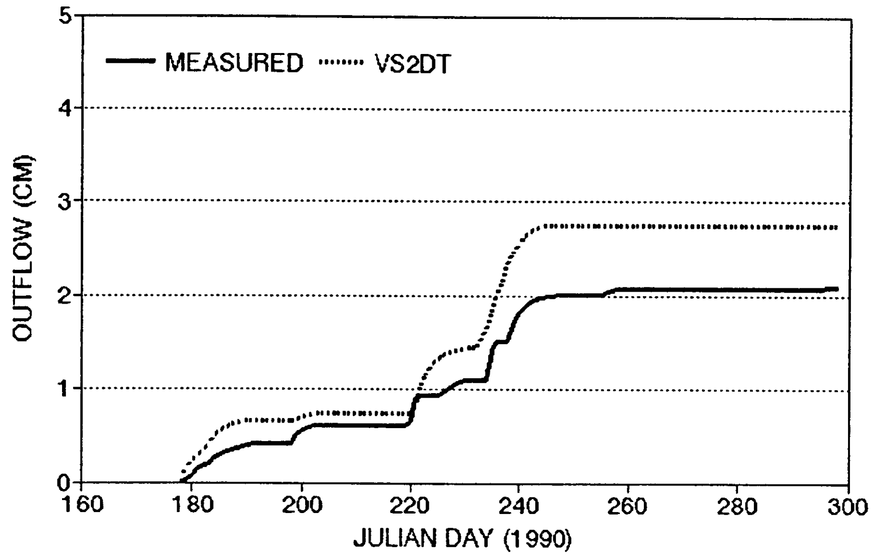


Figure 78: Measured and simulated control drain outflow in plot three under conventional drainage.

In plot 3 with free drainage, the measured profile deviated from the simulated profile on day 232 (Figure 77). The slow drop of the measured water table may be attributed to excessive ponding in the vicinity of the monitoring well. As shown in Figure 77, the ponding on days 221 and 238 was as high as 0.1 m above the surface, indicating that the well was located in a depression. In addition, on day 242, when the measured water table rose to within 0.05 m of the surface with no ponding, the water table quickly dropped 1.0 m as predicted by the simulation.

The measured and simulated tile drainage for experiment plot 3 is shown in Figure 78. For the two wet periods on days 221 and 235 the simulated outflow is higher than the measured outflow. However, the cumulative difference between measured and simulated is less than 7.5 mm for the entire simulation period.

Chemical Transport. The analysis of the soil and water samples from the field study indicated that aldicarb had essentially disappeared from all three research plots by 61 days after application (Munster, 1992). Therefore aldicarb transport and fate were simulated from day 1 (June 27, 1990), the day of application, to day 61 (August 26), for each experimental plot.

Average Absolute Deviation. The average absolute deviation (AAD) of the measured (M) and simulated (P) concentrations was calculated for each plot for each sampling round (N). The AAD statistic is calculated as follows:

$$AAD=\frac{\sum_{i=1}^{N}|M_i-P_i|}{N} \quad \textbf{(22)}$$

Since some of the soil concentrations are an order of magnitude higher than the water concentrations, AAD statistics were calculated for both soil and water concentrations.

These values quantify the average deviation between the measured and calculated aldicarb concentrations. The maximum AAD for the water samples is 8 μg/l, which indicates close agreement between measured and simulated values.

Since the measured soil concentrations are much higher than the water concentrations, the AAD for the soil samples are also higher. Plot 3, which had the highest measured concentrations also had the highest AAD statistics. The AAD statistics for plots 1 and 2 are similar. For the samples obtained on days 37 and 47, the measured soil concentrations approach the water sample values and the corresponding soil AAD values are close to the water AAD values.

In general, the model provided excellent agreement between measured and simulated aldicarb concentrations in the ground water and soil, as shown by the AAD values in Table 36.

<u>Transport Simulation Results for Plot 1, Subirrigation</u>. Transport simulation results for plot one (subirrigation) are compared to measured concentrations on days 6, 20, 37 and 47 in Figures 79-82. Measured concentrations in μg/l are shown next to the well screens with simulated concentrations shown in parenthesis.

Table 36: Average absolute deviation (AAD) of measured and simulated aldicarb concentrations.

DAY	PLOT 1 WELLS AAD (PPB)	PLOT 1 SOIL AAD (PPB)	PLOT 2 WELLS AAD (PPB)	PLOT 2 SOIL AAD (PPB)	PLOT 3 WELLS AAD (PPB)	PLOT 3 SOIL AAD (PPB)
6	2	31	6	46	8	125
20	2	15	6	12	4	41
37	0	8	0	3	0	8
47	1	7	1	1	1	2

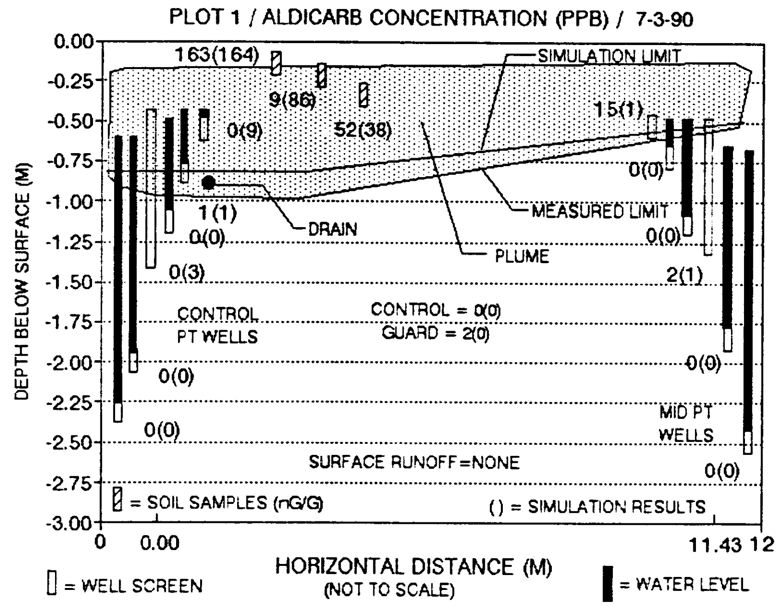


Figure 79: Measured and simulated aldicarb plumes 6 days (day 184) after application in plot one under subirrigation.

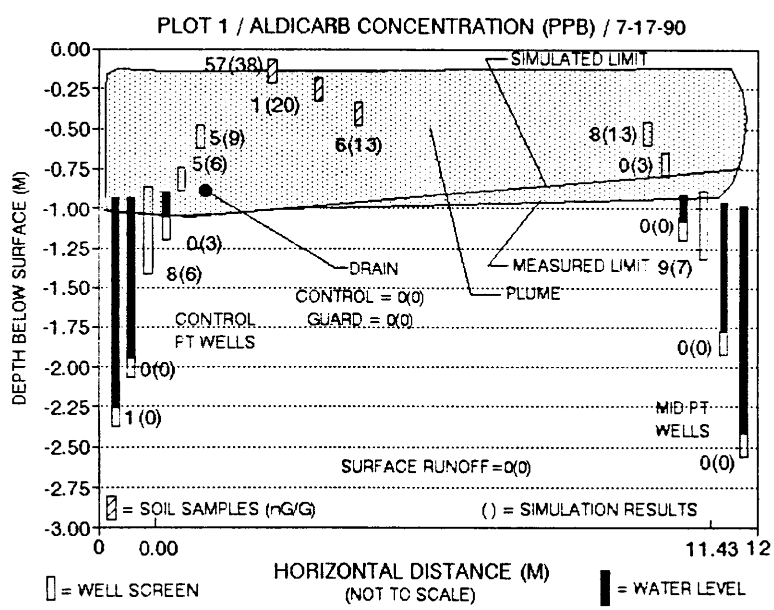


Figure 80: Measured and simulated aldicarb plumes 20 days (day 198) after application in plot one under subirrigation.

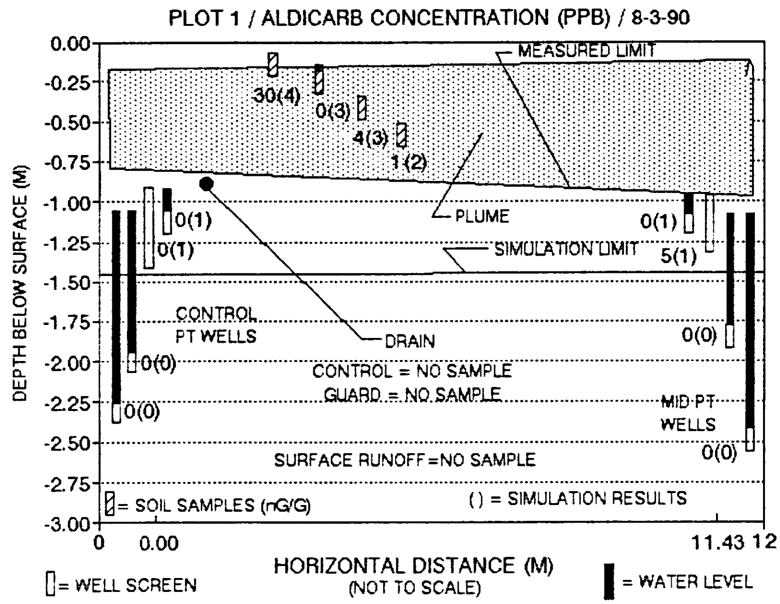


Figure 81: Measured and simulated aldicarb plumes 37 days (day 215) after application in plot one under subirrigation.

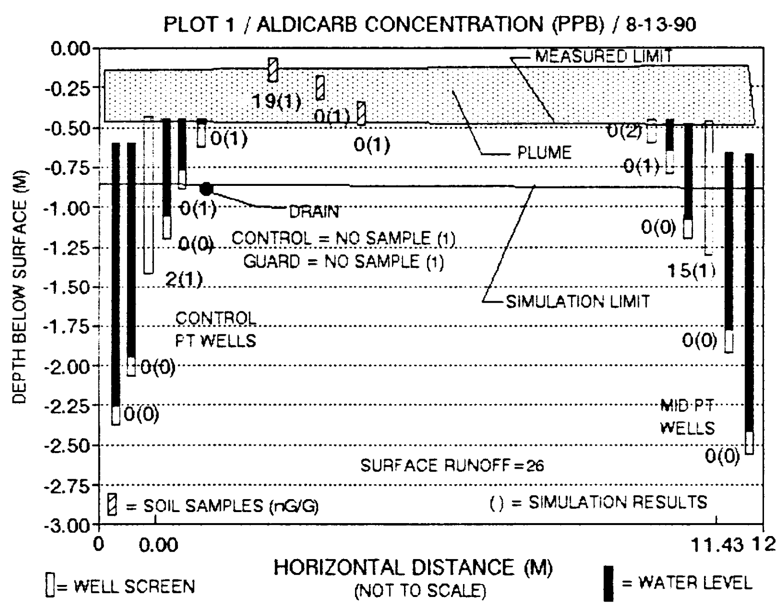


Figure 82: Measured and simulated aldicarb plumes 47 days (day 225) after application in plot one under subirrigation.

On day six, the measured plume limit was just above the drain while the simulated plume had reached the drain. On day 20 the simulated and measured plumes were almost identical. On day 37, the simulated plume continued to move downward from its position at day 20, while the measured plume receded. On day 47, both the measured and simulated plumes receded from the day 37 depths. Aldicarb disappeared completely from the flow domain in the computer simulation by day 57 and was not detected in the field measurements on day 61.

Since plot one was maintained in the subirrigation mode throughout the simulation period, very little tile drainage occurred during the simulation period. Total aldicarb loss in the tile outflow and surface runoff was <0.001% and 0.06% of the total applied aldicarb, respectively. Total simulated aldicarb loss in drainage outflow was <0.0001% of the total applied aldicarb.

Plot one had the best agreement between the measured and simulated aldicarb concentrations in the ground water and soil with maximum AAD values of 2 ppb and 31 ppb values, respectively (Table 36).

Transport Simulation Results for Plot 2, Controlled Drainage. The measured and simulated aldicarb concentrations in plot two for days 6, 20, 37 and 47 are shown in Figures 83-86. On day 6, the measured plume extended to a depth of 1.75 m, while the simulated plume extends to the drain tile, at a depth of 0.80 m. Transport of aldicarb to the deeper depths was caused by preferential flow. The concentration in the measured tile outflow (14 $\mu g/l$) is more than three times higher than the simulated concentration (4 $\mu g/l$).

On day 20 the water table had dropped to the level of the drain and both simulated and measured plumes receded slightly. The measured concentration in the drainage outflow was unchanged from the previous sampling period while the simulated plume no longer extended to the drain.

On day 37, with the water table below the drain, the limits of the measured and simulated plumes were similar. By day 47 the measured plume had receded while the simulated plume remained near the same location as on day 37. With approximately 100 mm of rainfall since the previous sampling round, the water table had risen above the drainage tile. Both the measured and simulated drainage outflow contained low concentrations of aldicarb. Simulated aldicarb concentrations were less than 1 $\mu g/l$ in the entire flow domain by day 58, while aldicarb was not detected in the field samples on day 61. Total aldicarb loss in the tile outflow and surface runoff was 0.01% and 0.04% of the total applied aldicarb, respectively. Total simulated aldicarb loss in drainage outflow was <0.001% of the total applied aldicarb.

Plot two had excellent agreement between the measured and simulated aldicarb concentrations in the ground water with a

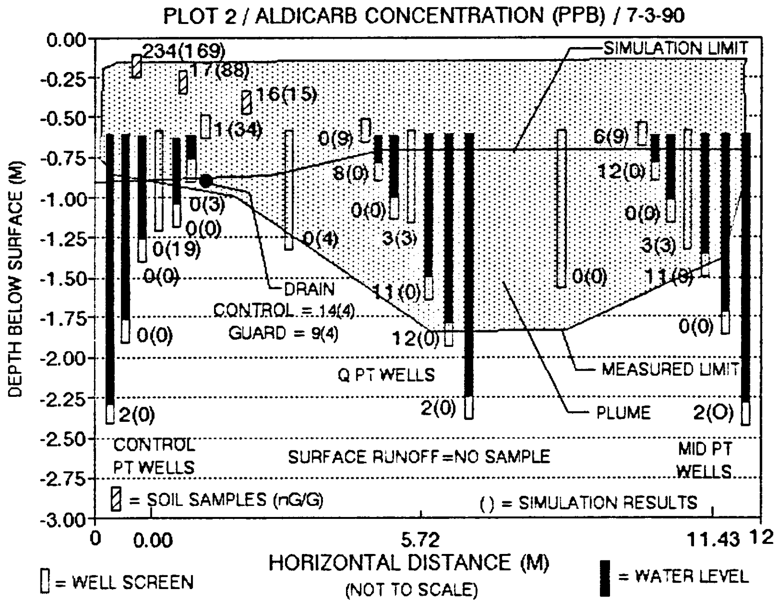


Figure 83: Measured and simulated aldicarb plumes 6 days (day 184) after application in plot two under controlled drainage.

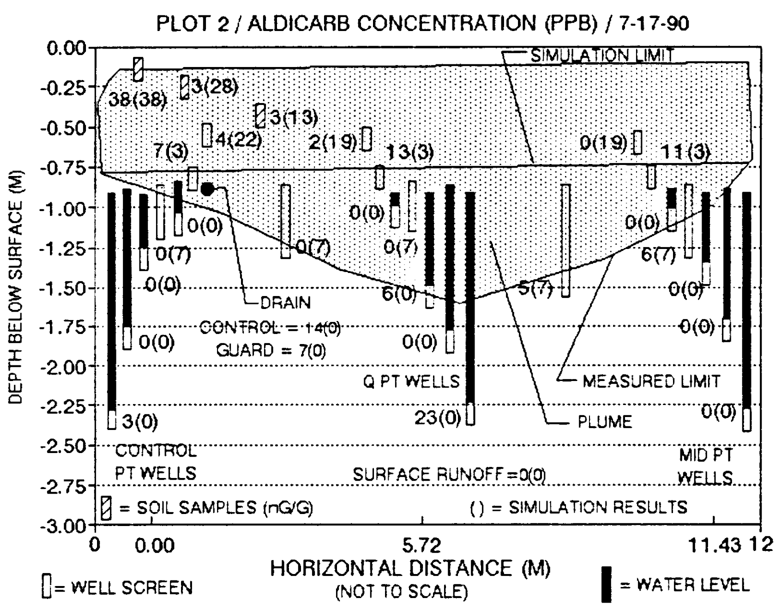


Figure 84: Measured and simulated aldicarb plumes 20 days (day 198) after application in plot two under controlled drainage.

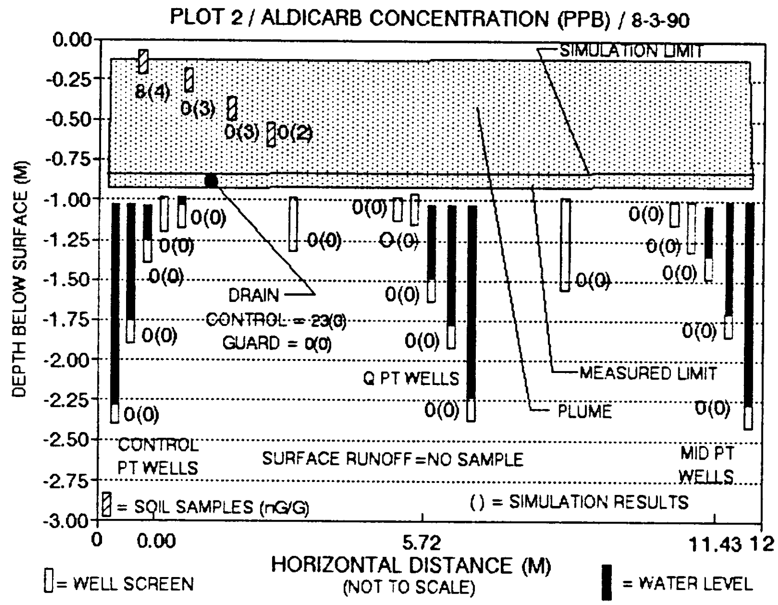


Figure 85: Measured and simulated aldicarb plumes 37 days (day 215) after application in plot two under controlled drainage.

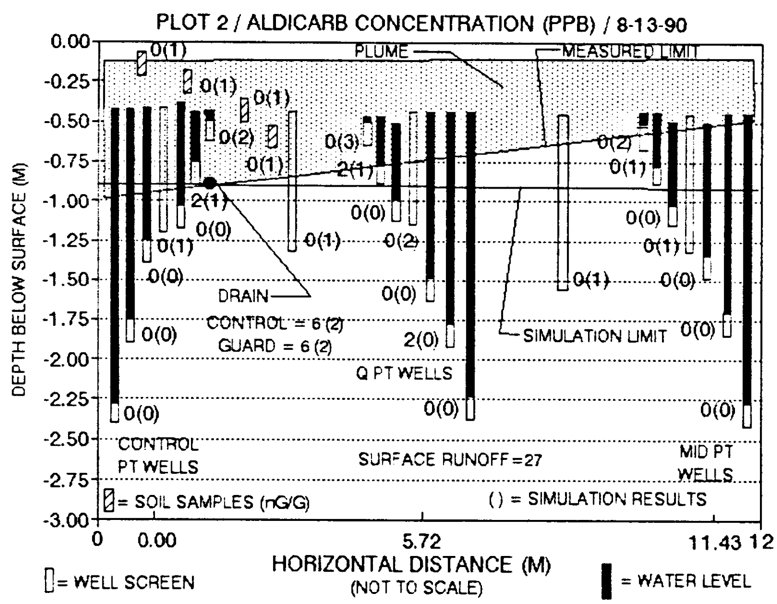


Figure 86: Measured and simulated aldicarb plumes 47 days (day 225) after application in plot two under controlled drainage.

maximum AAD value of 4 μg/l (Table 36). The maximum AAD soil value was 46 μg/kg on day 6 (Table 36).

Transport Simulation Results for Plot 3, Conventional Drainage. The transport simulation results are compared to the field data on days 6, 20, 37 and 47 in Figures 87-90. The field data for day 6 indicated that the aldicarb plume extended to a depth of 1.75 m. Whereas the simulated plume was no deeper than 0.60 m below the surface. We assumed that flow through macropores was the reason for aldicarb movement to the deeper horizons. Flow from the control drain had a concentration of 16 ppb, while the simulated plume had not reached the drains by day 6.

By day 20 the measured plume had started to recede while the simulated plume continued to move down. The sampling period on day 37 was conducted after an extended dry period with the water table 0.40 m below the drain. The plume limits were almost the same as on day 20. The simulated plume still had not reached the drains.

Between days 37 and 47, approximately 100 mm of rain caused the water table to rise above the drains. The predicted and measured plume limits were very similar for day 47. The simulated aldicarb concentrations were less than 1 μg/l everywhere in the flow domain by day 58 and was not detected in the field samples on day 61. Aldicarb loss in the tile outflow and surface runoff was 0.02% and 0.02% of the total applied aldicarb, respectively. Total simulated aldicarb loss in drainage outflow was <0.001% of the total applied aldicarb.

Plot three had good agreement between the measured and simulated aldicarb concentrations in the ground water with a maximum AAD value of 8 μg/l (Table 36). The maximum AAD soil value was 125 μg/kg on day 6 (Table 36). The measured concentration in the soil samples on day one from plot three were approximately four times higher than the concentrations measured in plots one and two. Thus the maximum AAD soil value in plot three was high.

SUMMARY AND CONCLUSIONS

The USGS computer model, VS2DT, was modified to simulate pesticide transport in fields with subsurface drains under conventional drainage, controlled drainage and subirrigation conditions. These modifications were validated by comparing measured and simulated values for drainage and subirrigation volumes, water table elevations and water quality data.

The modified VS2DT model accurately predicted surface and subsurface flow rates as well as water table response to rainfall events. The model also provided excellent simulations of chemical transport in the saturated and unsaturated soil profile as well as concentrations in the tile outflow. However, small concentrations of aldicarb were detected in the field much deeper than simulated plume limits. Preferential flow transport, which was measured in the field, was not predicted by the model.

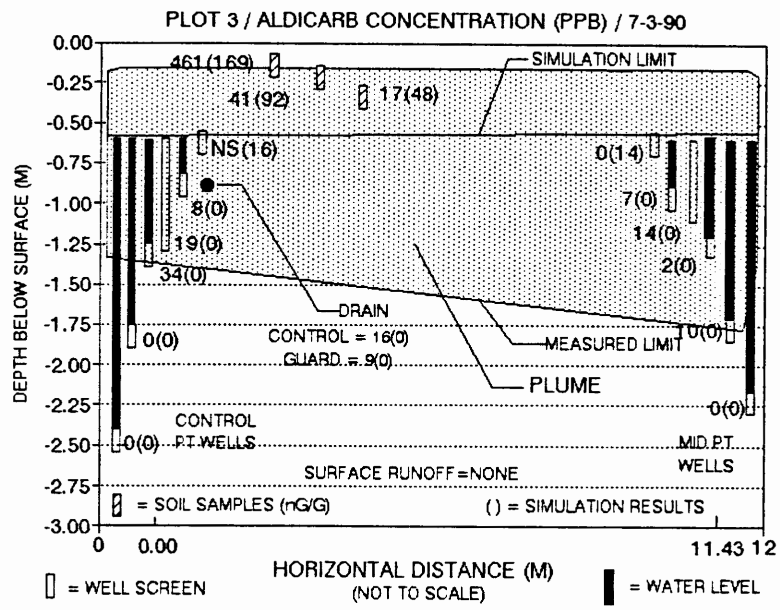


Figure 87: Measured and simulated aldicarb plumes 6 days (day 184) after application in plot three under conventional drainage.

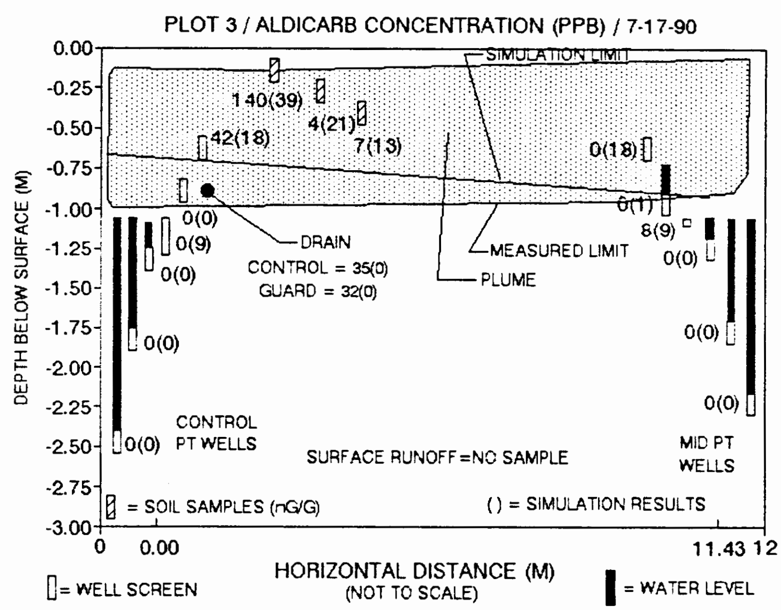


Figure 88: Measured and simulated aldicarb plumes 20 days (day 198) after application in plot three under conventional drainage.

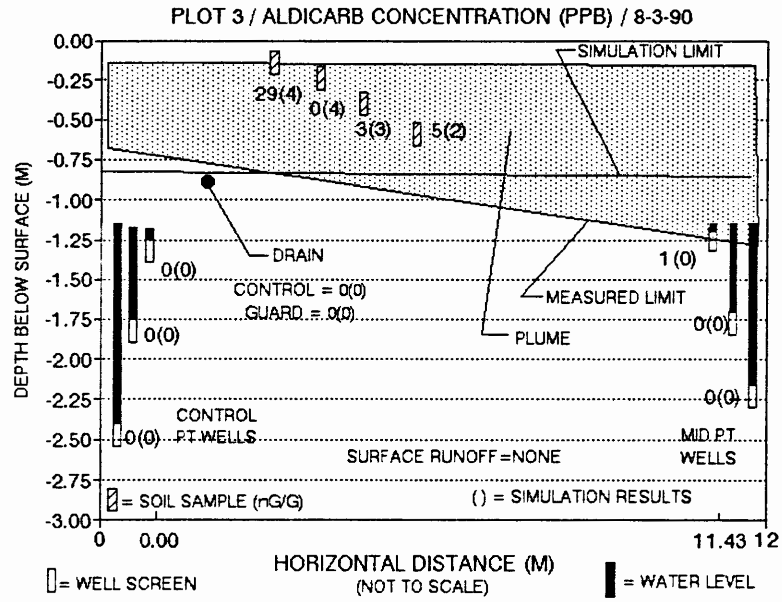


Figure 89: Measured and simulated aldicarb plumes 37 days (day 215) after application in plot three under conventional drainage.

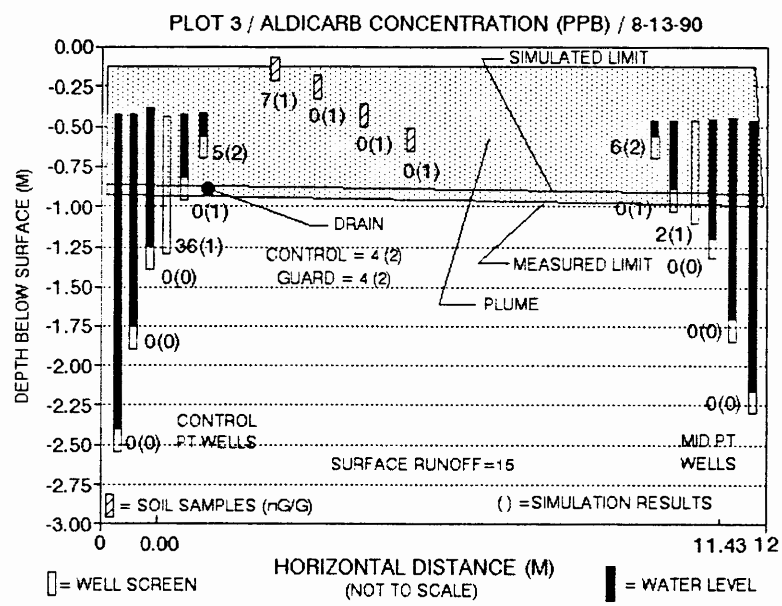


Figure 90: Measured and simulated aldicarb plumes 47 days (day 225) after application in plot three under conventional drainage.

In summary, the modified VS2DT model is an extremely useful tool that can be used to directly assess the effects of water table management on the transport of chemicals in fields with subsurface drainage. It is a researcher's model that will have valuable application in testing and developing simpler models written specifically for design and management.

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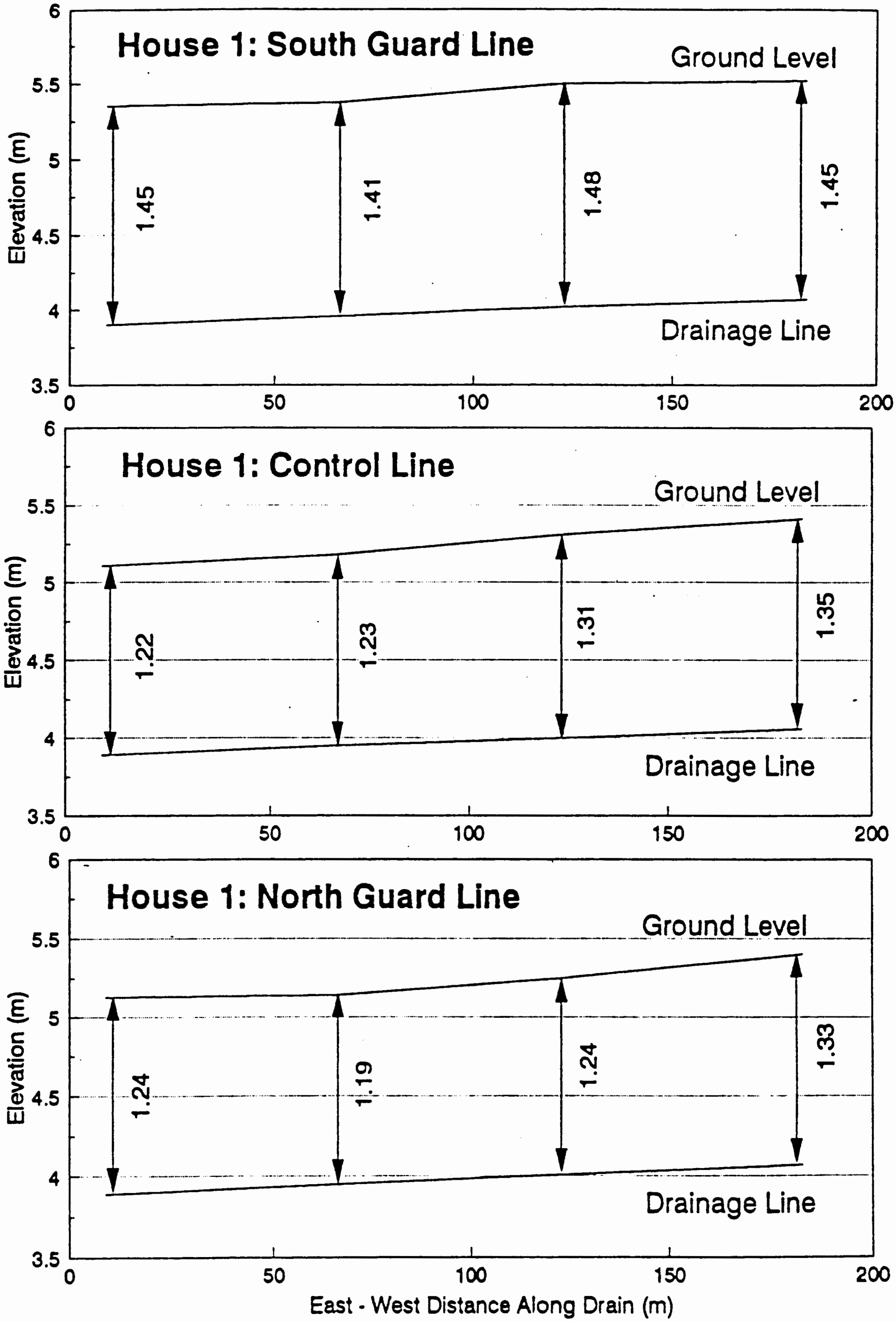
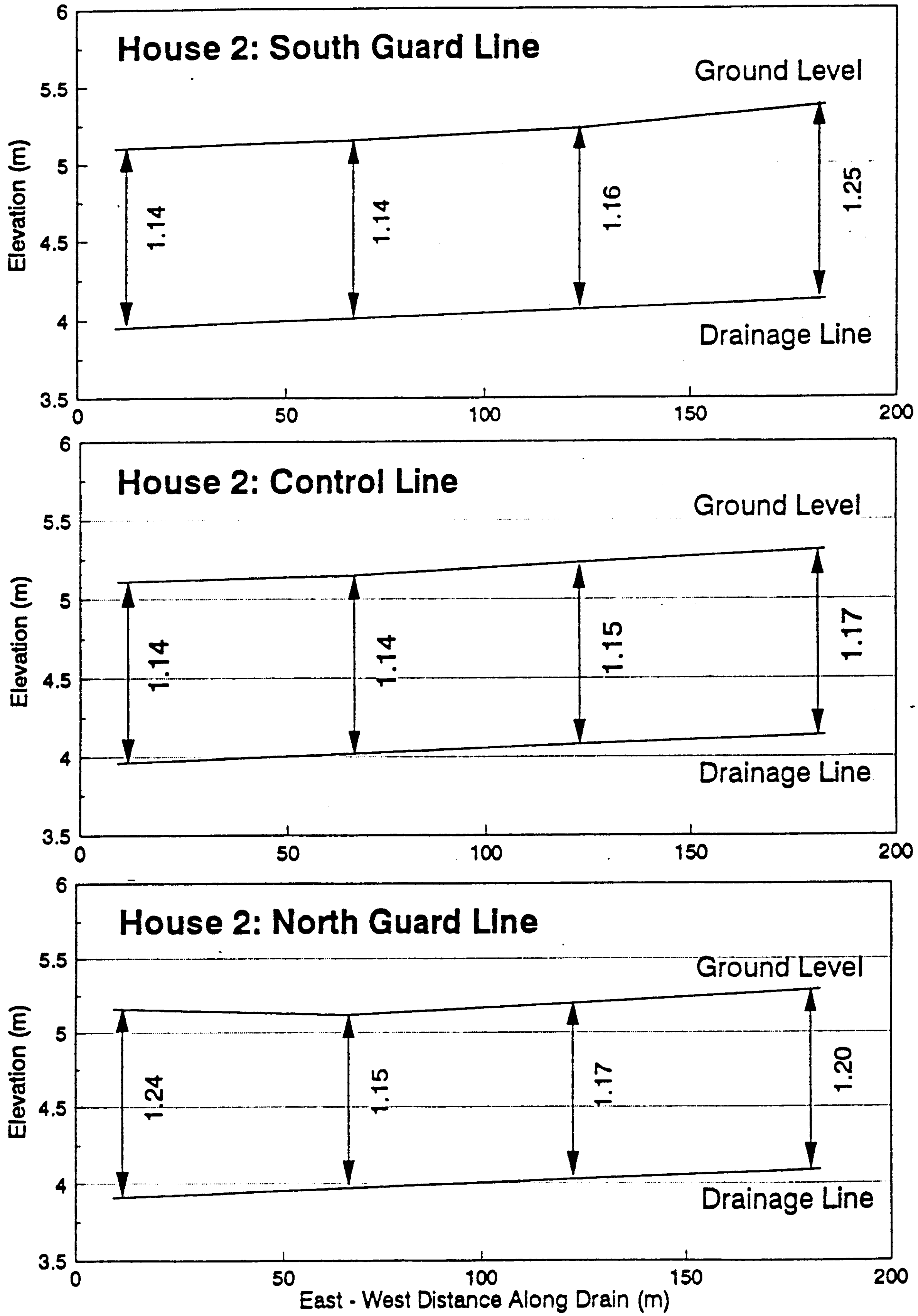
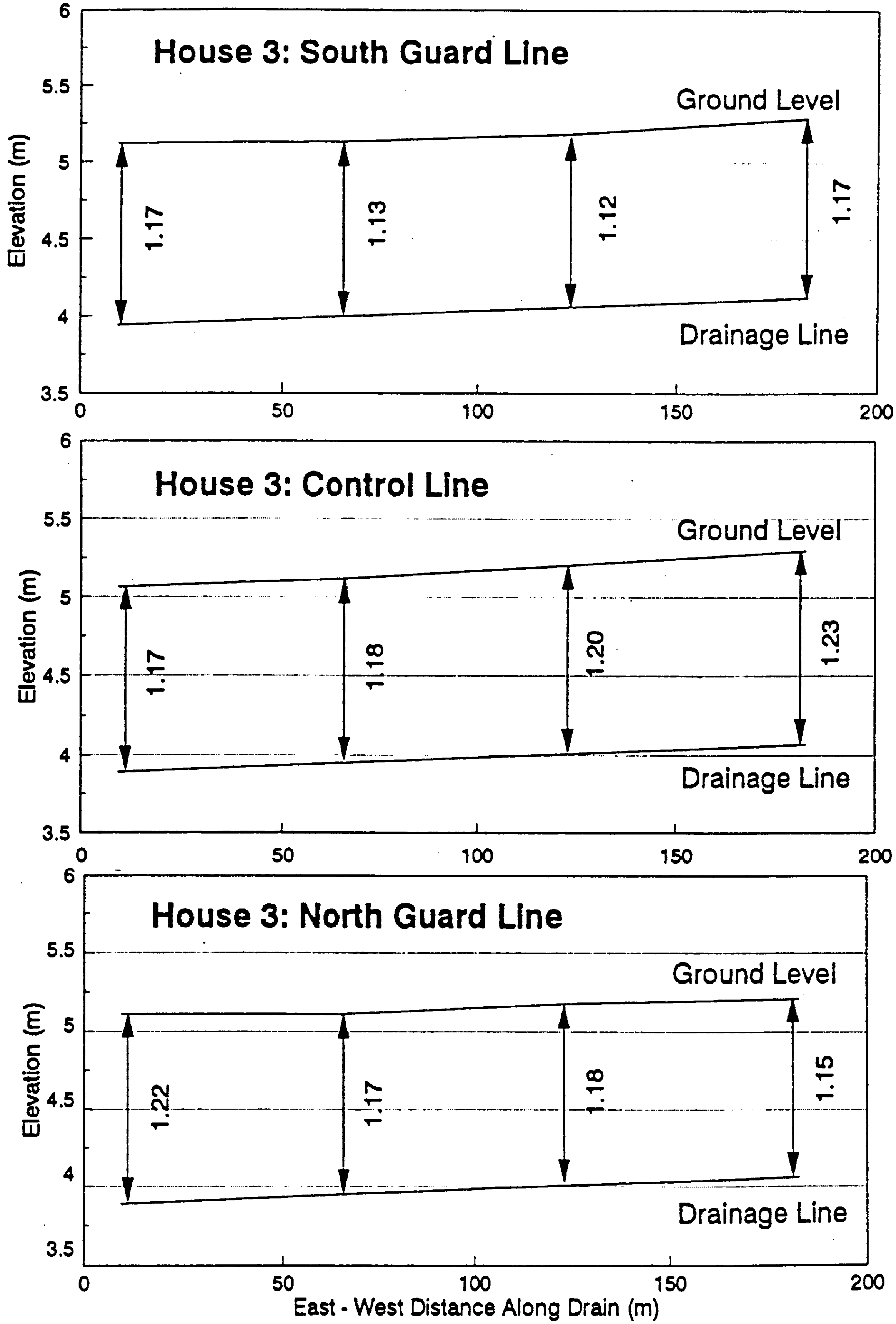
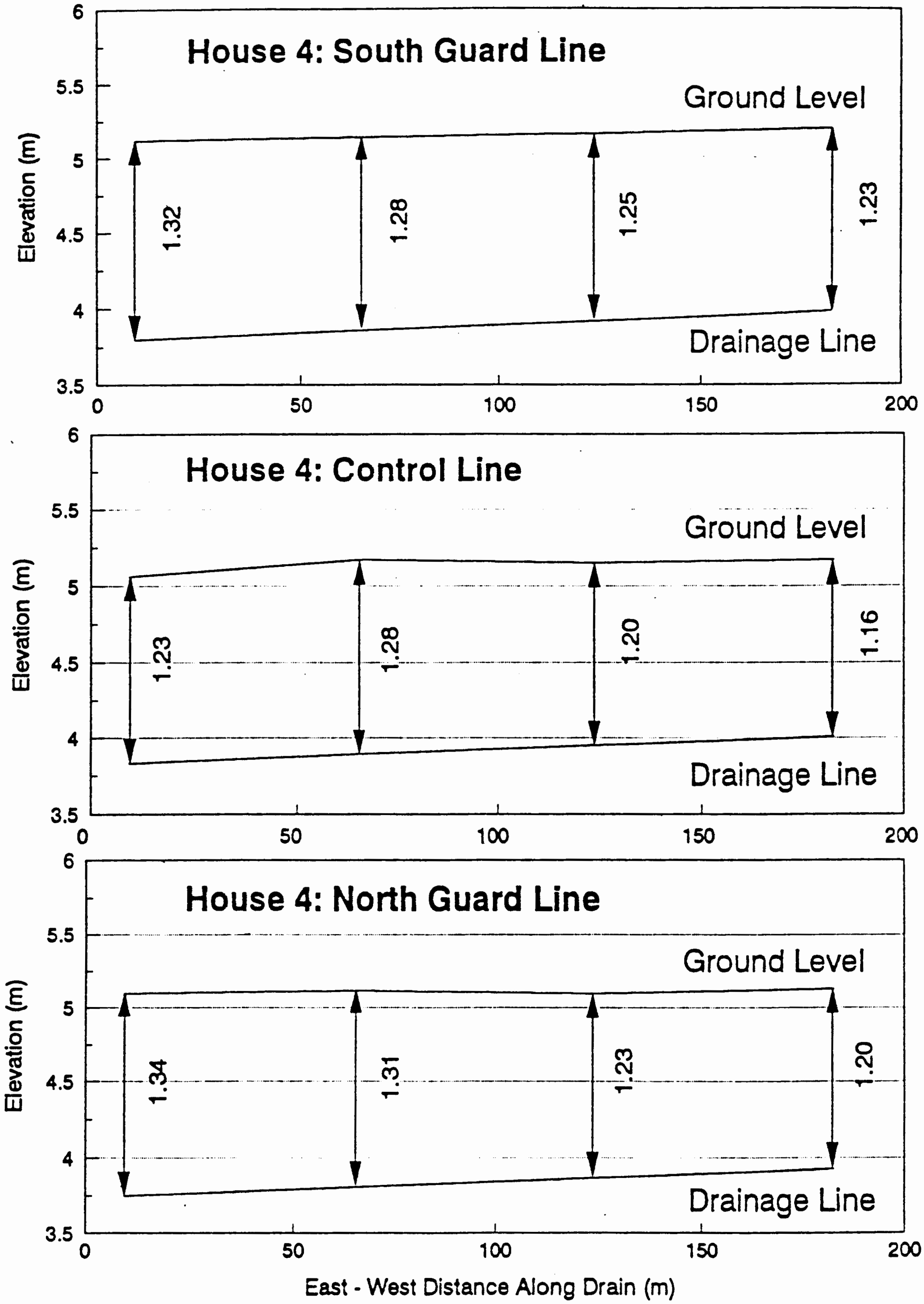
APPENDIX 1

Depths of drains in each experimental plot

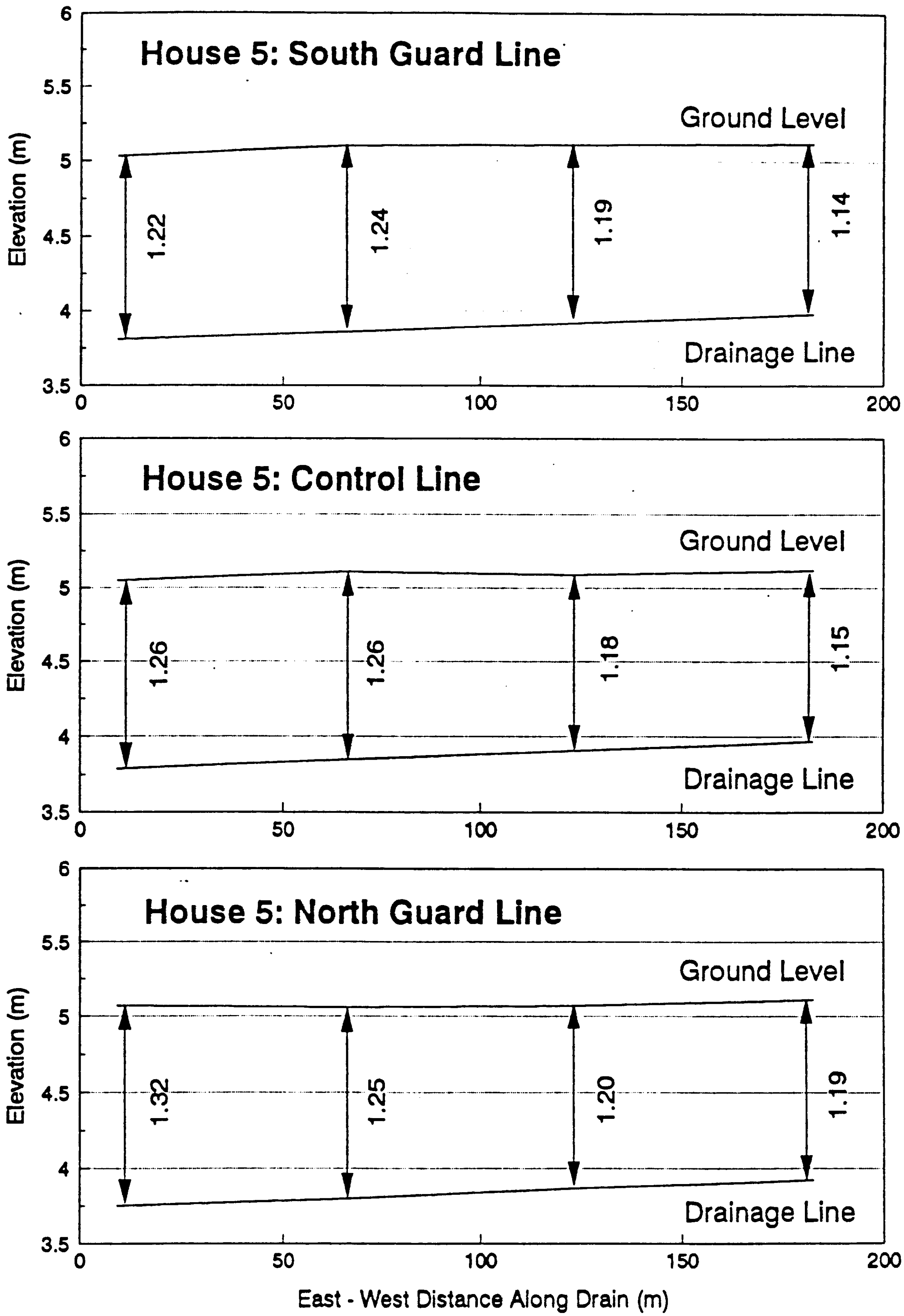

House 1: South Guard Line
Ground Level
Drainage Line
1.45
1.41
1.48
1.45
House 1: Control Line
Ground Level
Drainage Line
1.22
1.23
1.31
1.35
House 1: North Guard Line
Ground Level
Drainage Line
1.24
1.19
1.24
1.33
Elevation (m)
East - West Distance Along Drain (m)

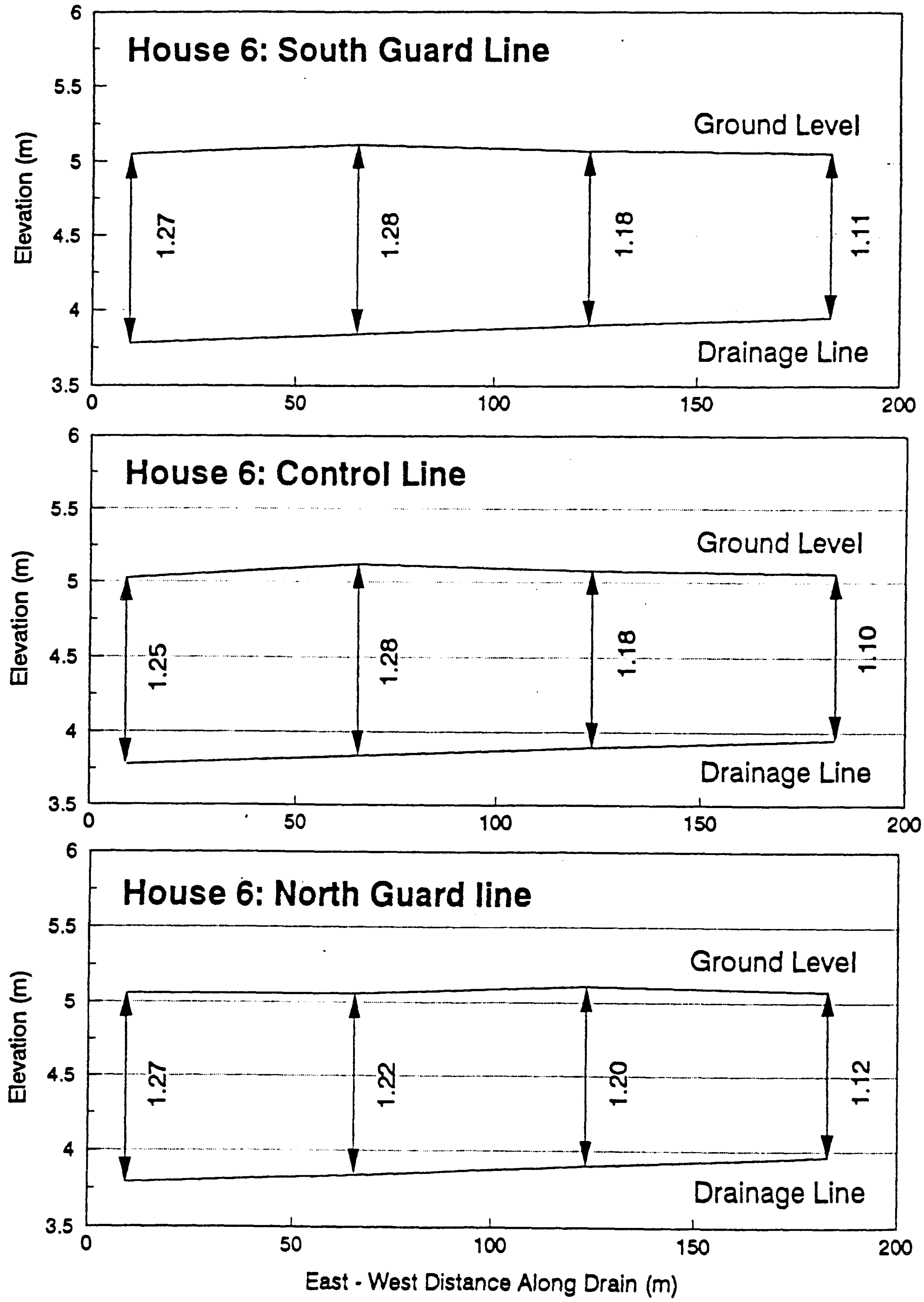

House 2: South Guard Line
Ground Level
Drainage Line
1.14
1.14
1.16
1.25
House 2: Control Line
Ground Level
Drainage Line
1.14
1.14
1.15
1.17
House 2: North Guard Line
Ground Level
Drainage Line
1.24
1.15
1.17
1.20
Elevation (m)
East - West Distance Along Drain (m)

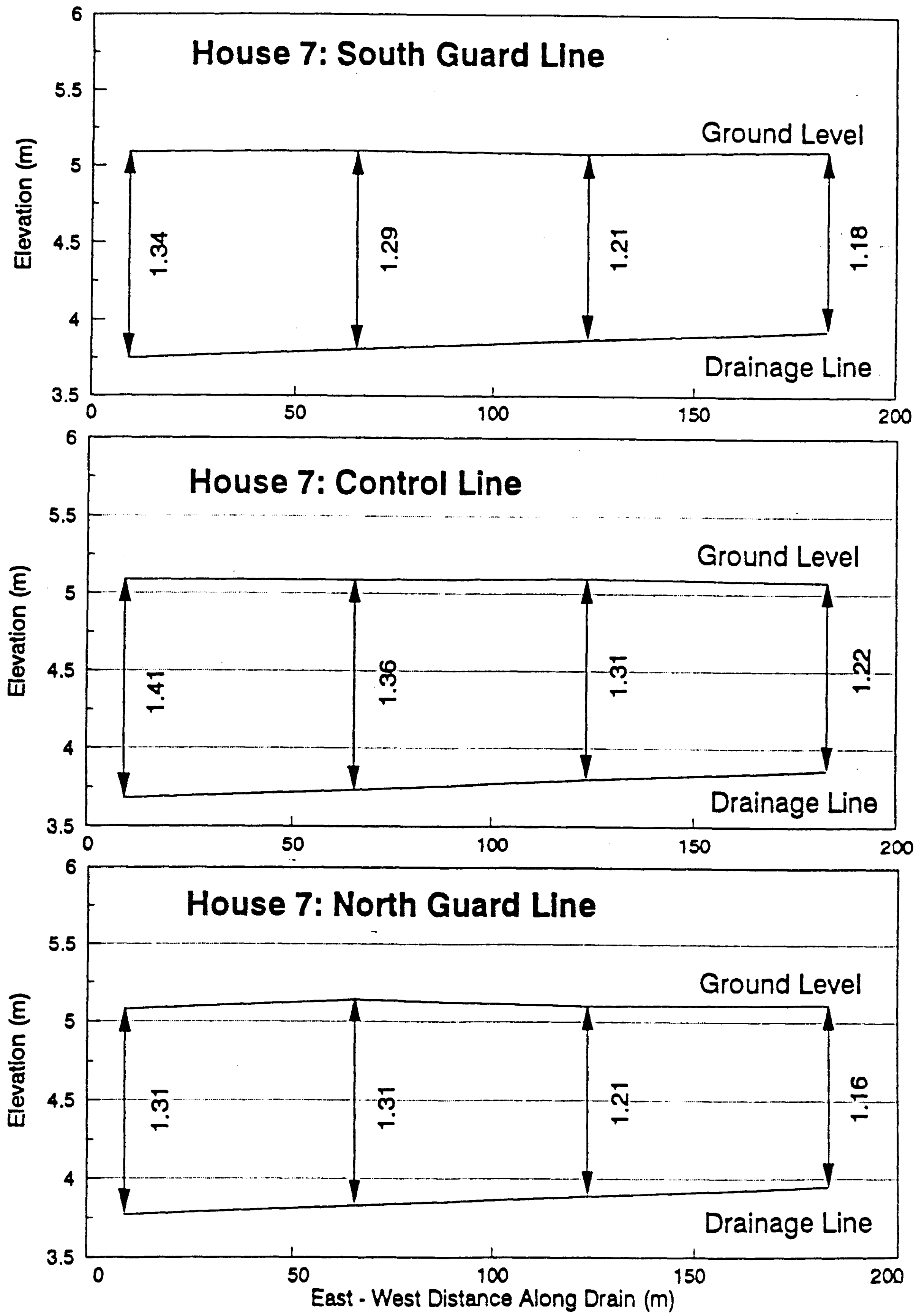

House 3: South Guard Line
Ground Level
Drainage Line
1.17
1.13
1.12
1.17
Elevation (m)
6
5.5
5
4.5
4
3.5
0
50
100
150
200
House 3: Control Line
Ground Level
Drainage Line
1.17
1.18
1.20
1.23
Elevation (m)
House 3: North Guard Line
Ground Level
Drainage Line
1.22
1.17
1.18
1.15
Elevation (m)
East - West Distance Along Drain (m)

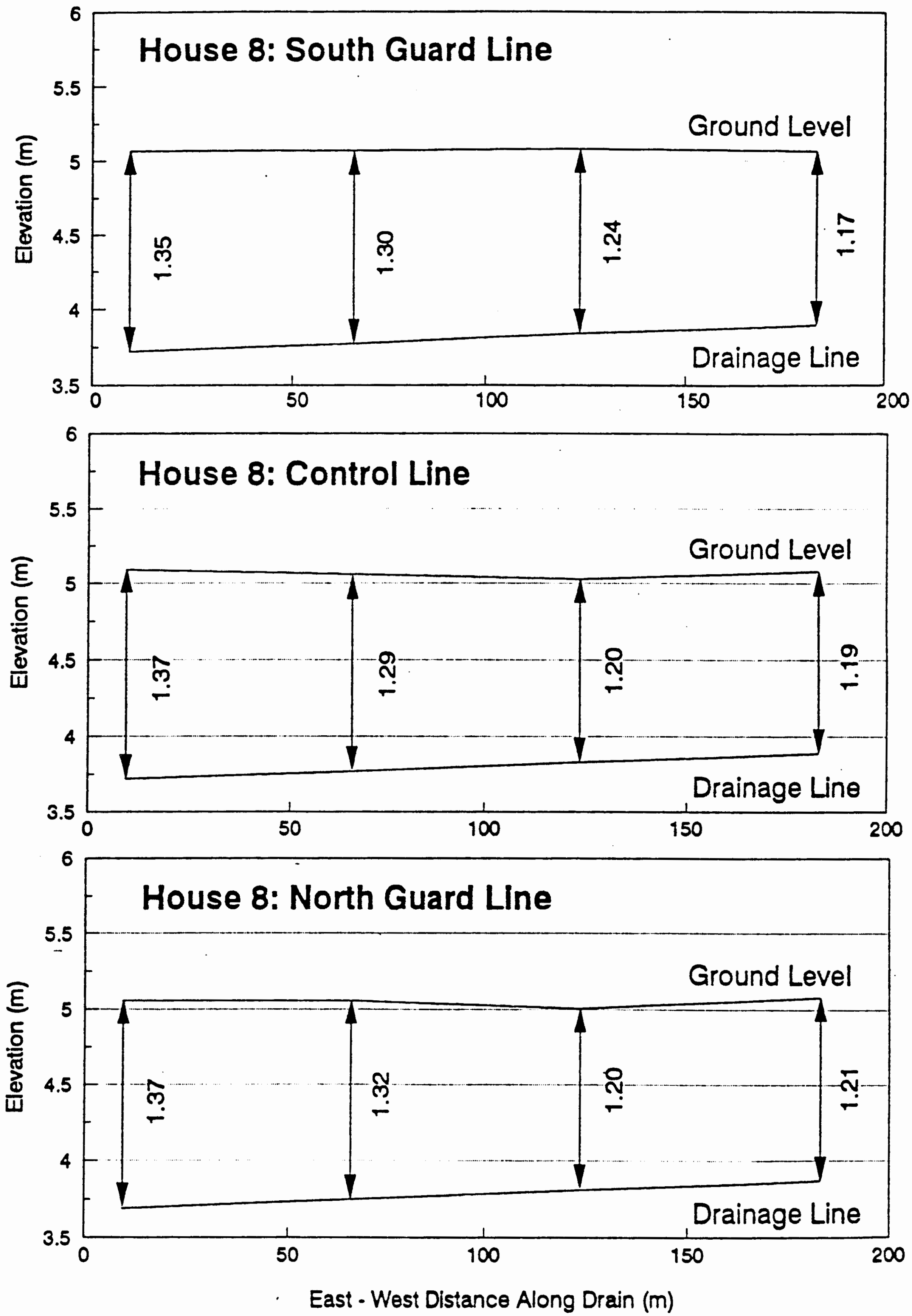


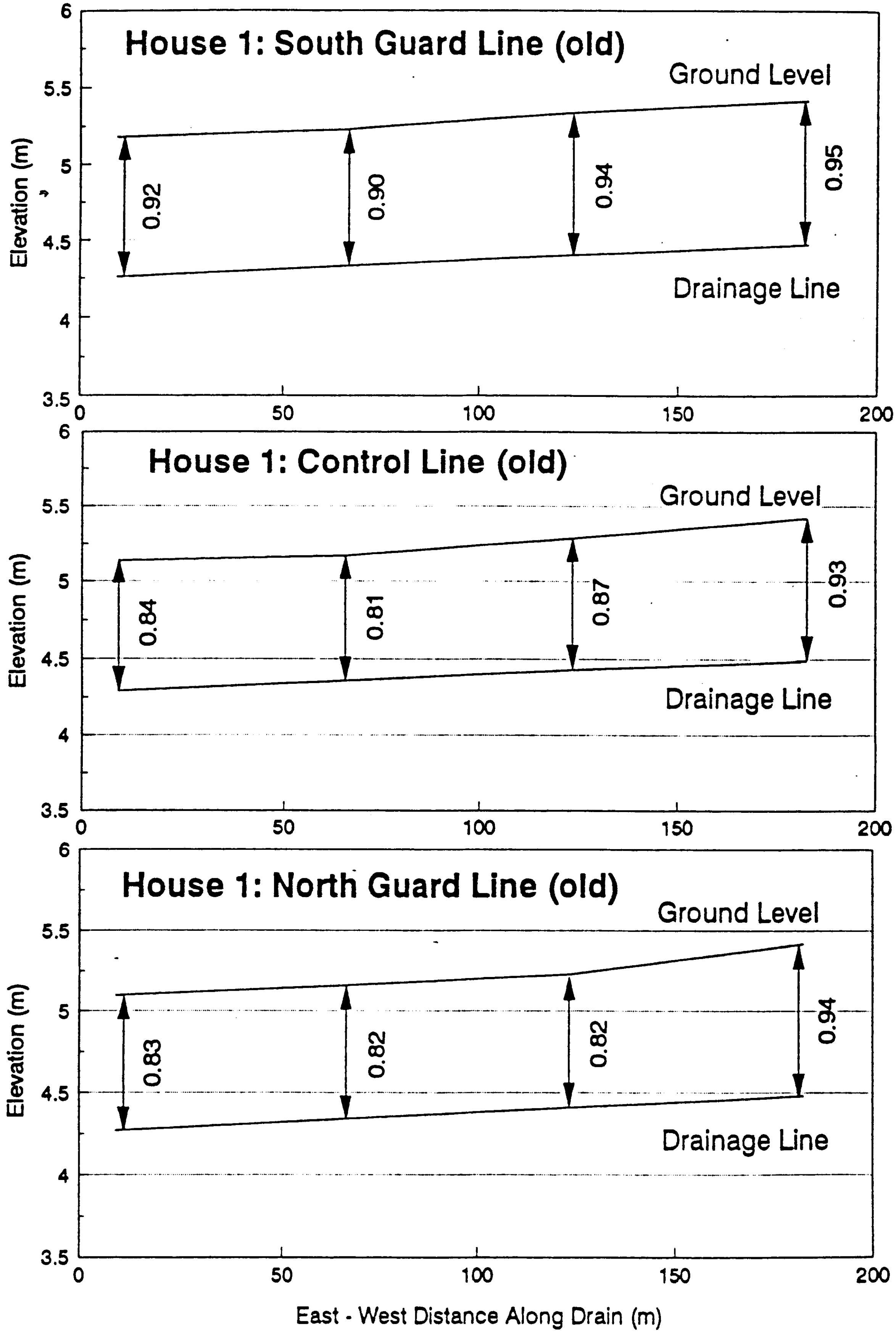
House 4: South Guard Line
Ground Level
Drainage Line
1.32
1.28
1.25
1.23
House 4: Control Line
Ground Level
Drainage Line
1.23
1.28
1.20
1.16
House 4: North Guard Line
Ground Level
Drainage Line
1.34
1.31
1.23
1.20
Elevation (m)
East - West Distance Along Drain (m)

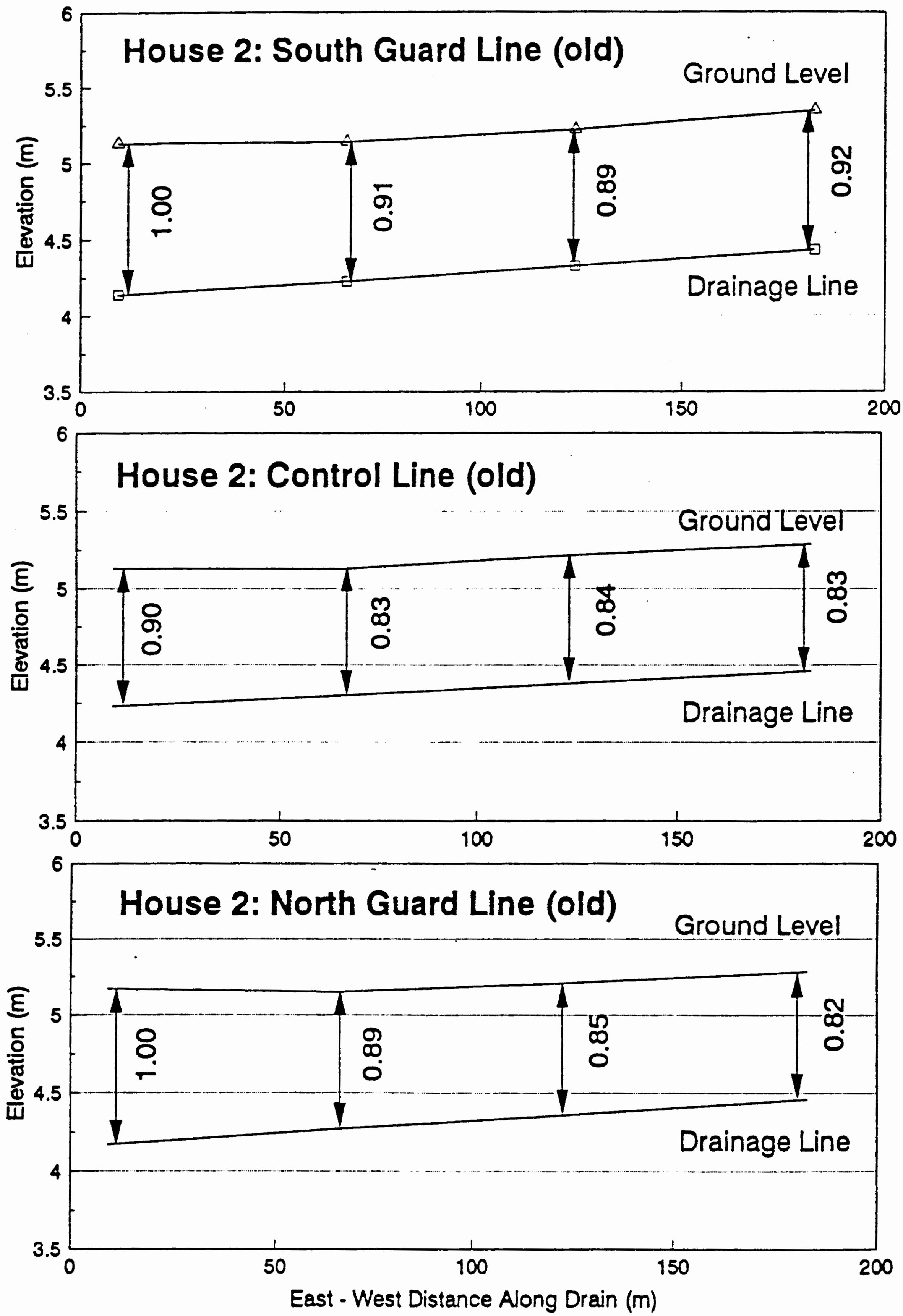

House 5: South Guard Line
Ground Level
Drainage Line
1.22
1.24
1.19
1.14
House 5: Control Line
Ground Level
Drainage Line
1.26
1.26
1.18
1.15
House 5: North Guard Line
Ground Level
Drainage Line
1.32
1.25
1.20
1.19
Elevation (m)
East - West Distance Along Drain (m)

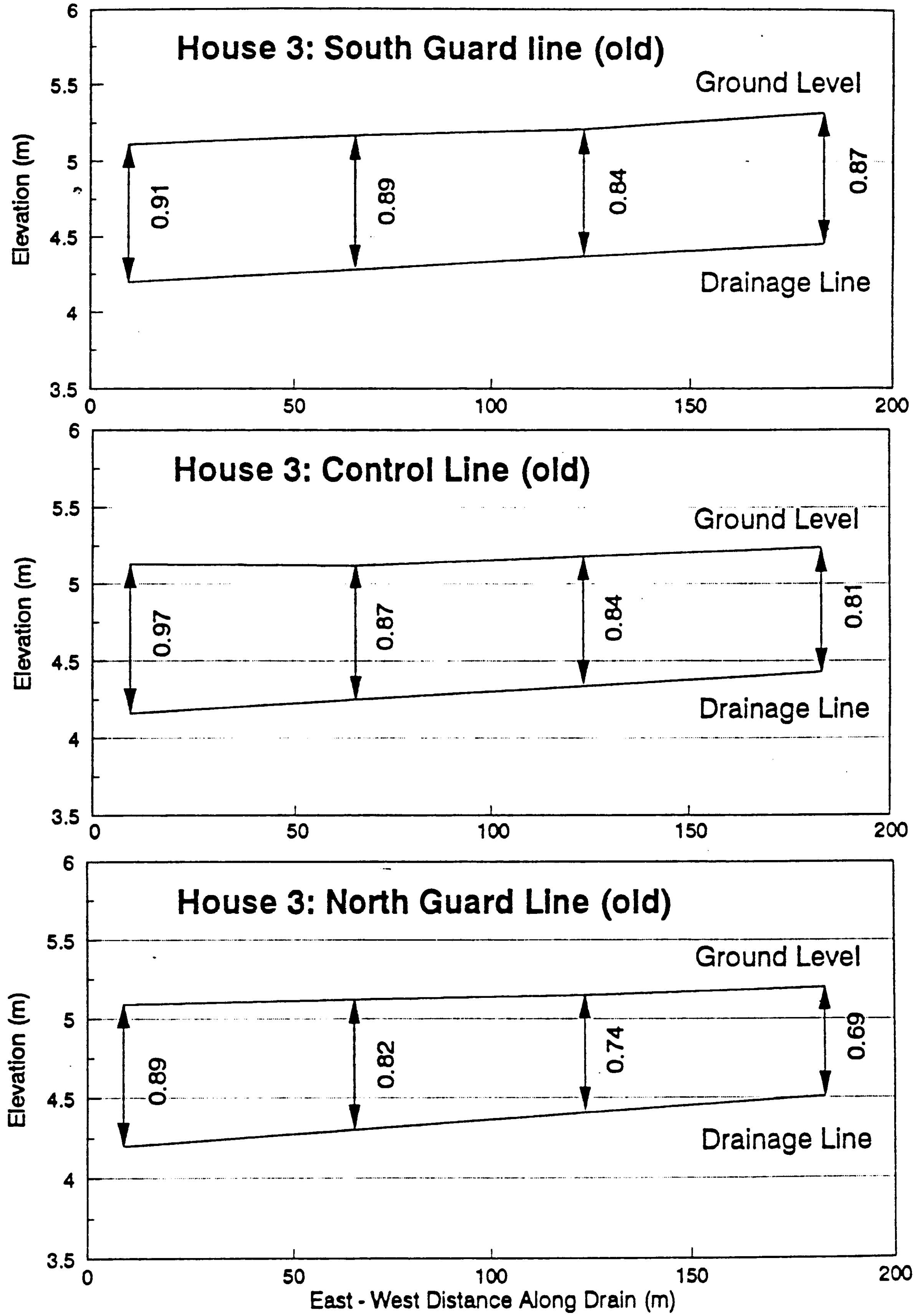

House 6: South Guard Line
Ground Level
Drainage Line
1.27
1.28
1.18
1.11
House 6: Control Line
Ground Level
Drainage Line
1.25
1.28
1.18
1.10
House 6: North Guard line
Ground Level
Drainage Line
1.27
1.22
1.20
1.12
Elevation (m)
East - West Distance Along Drain (m)

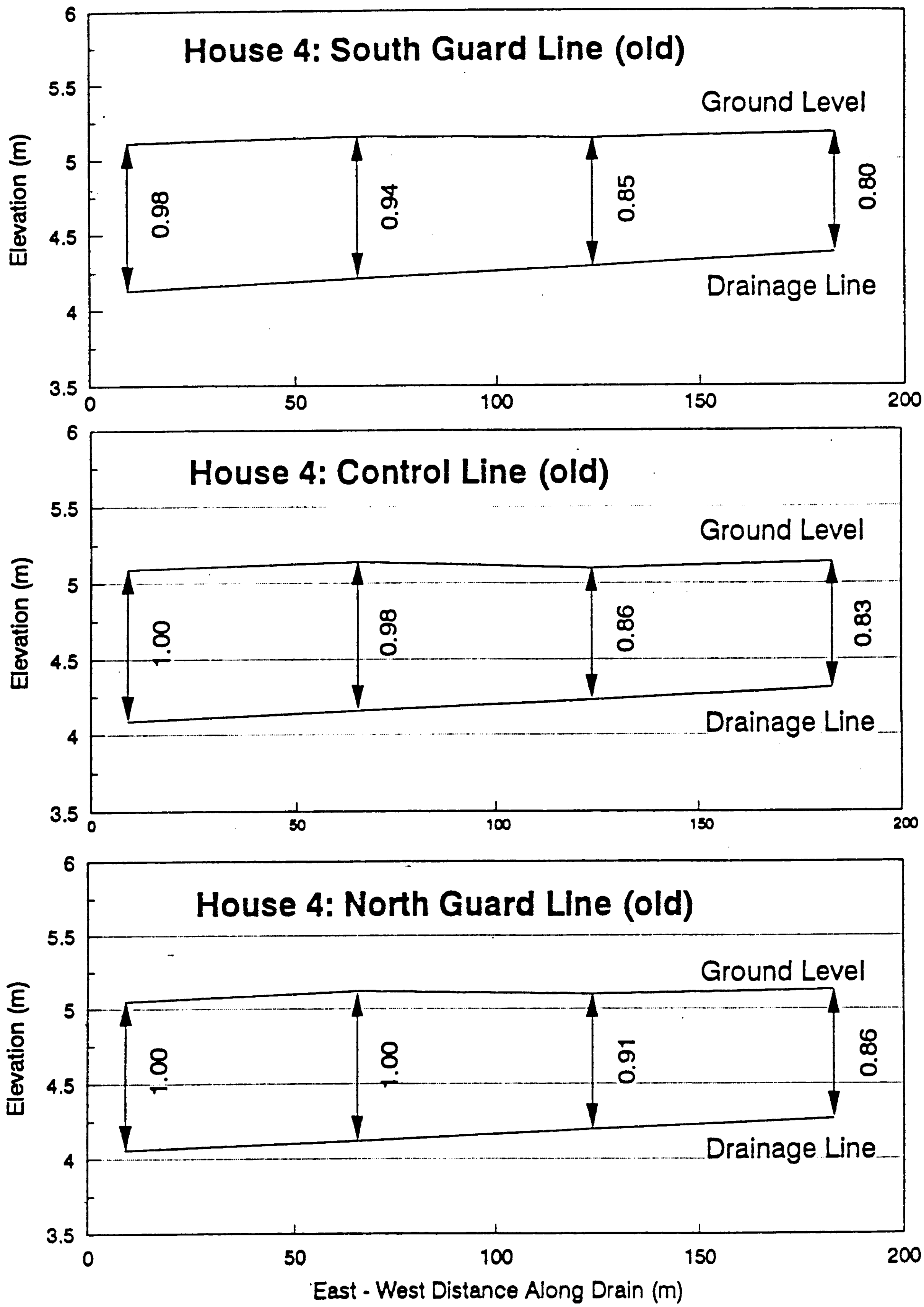

House 7: South Guard Line
Ground Level
Drainage Line
1.34
1.29
1.21
1.18
Elevation (m)
6
5.5
5
4.5
4
3.5
0
50
100
150
200
House 7: Control Line
Ground Level
Drainage Line
1.41
1.36
1.31
1.22
Elevation (m)
House 7: North Guard Line
Ground Level
Drainage Line
1.31
1.31
1.21
1.16
Elevation (m)
East - West Distance Along Drain (m)

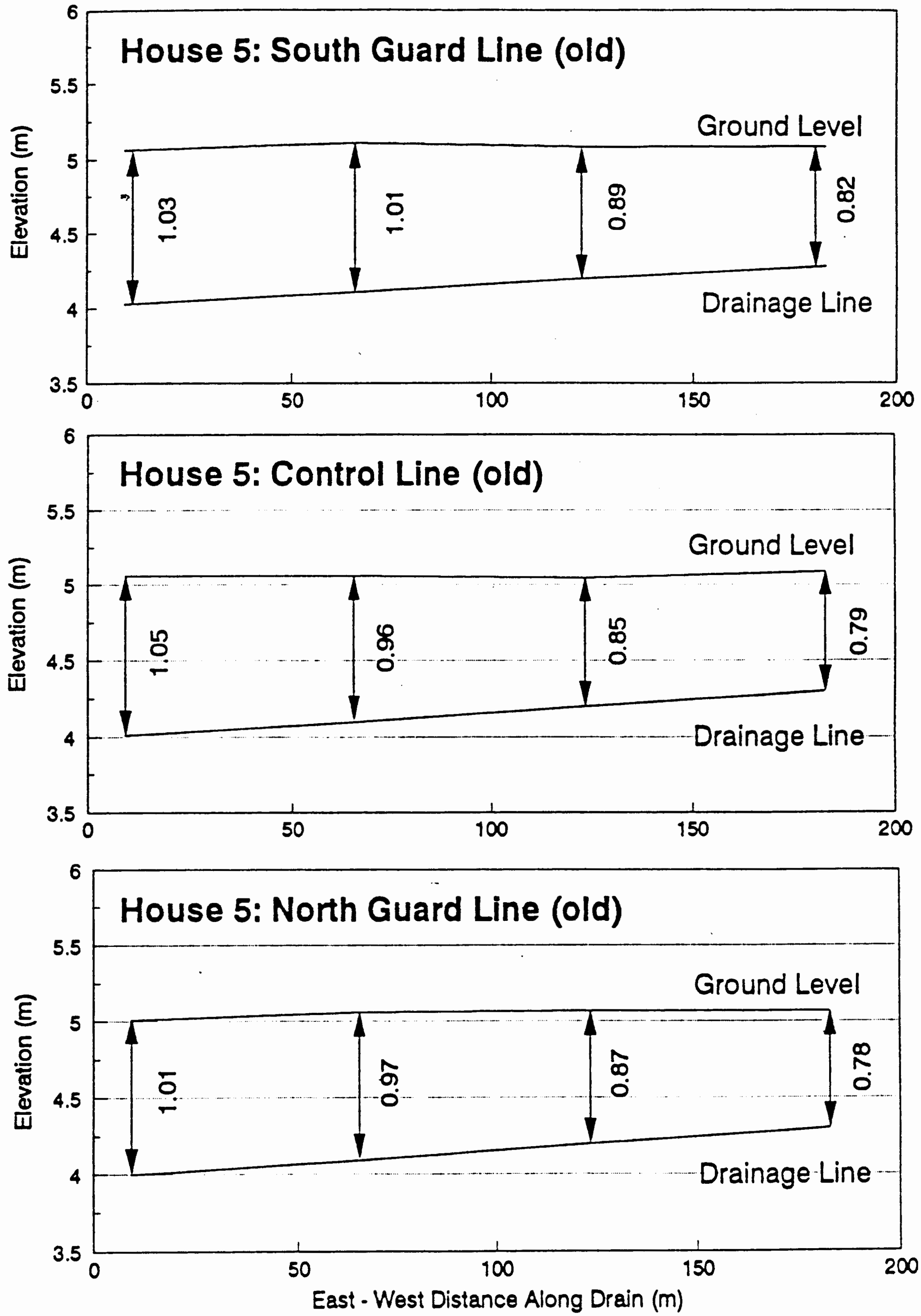

House 8: South Guard Line
Ground Level
Drainage Line
1.35
1.30
1.24
1.17
Elevation (m)
House 8: Control Line
1.37
1.29
1.20
1.19
House 8: North Guard Line
1.37
1.32
1.20
1.21
East - West Distance Along Drain (m)

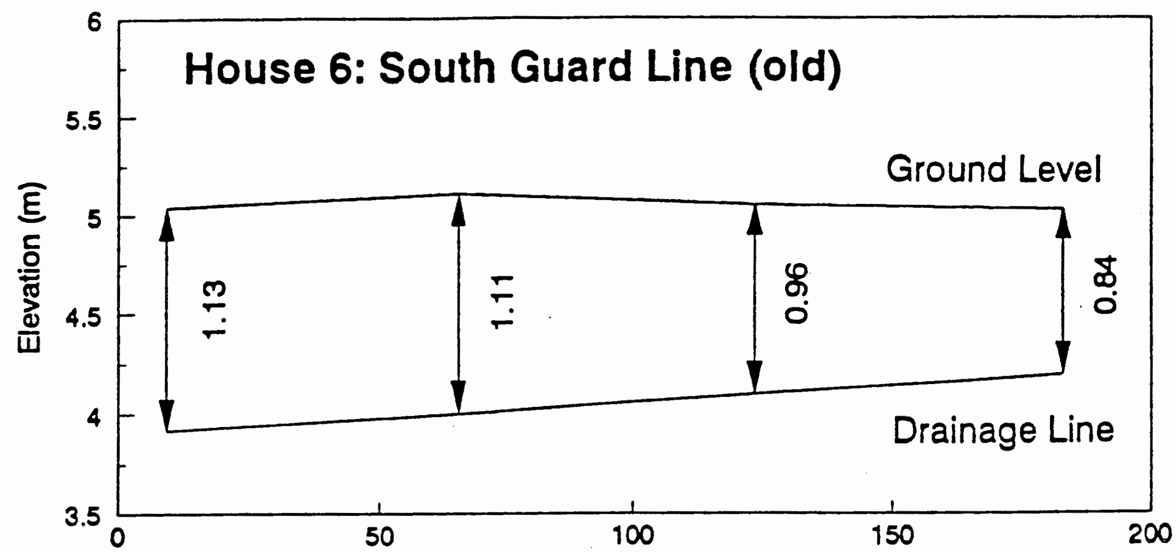

House 1: South Guard Line (old)
Ground Level
Drainage Line
0.92
0.90
0.94
0.95
House 1: Control Line (old)
Ground Level
Drainage Line
0.84
0.81
0.87
0.93
House 1: North Guard Line (old)
Ground Level
Drainage Line
0.83
0.82
0.82
0.94
Elevation (m)
6
5.5
5
4.5
4
3.5
0
50
100
150
200
East - West Distance Along Drain (m)

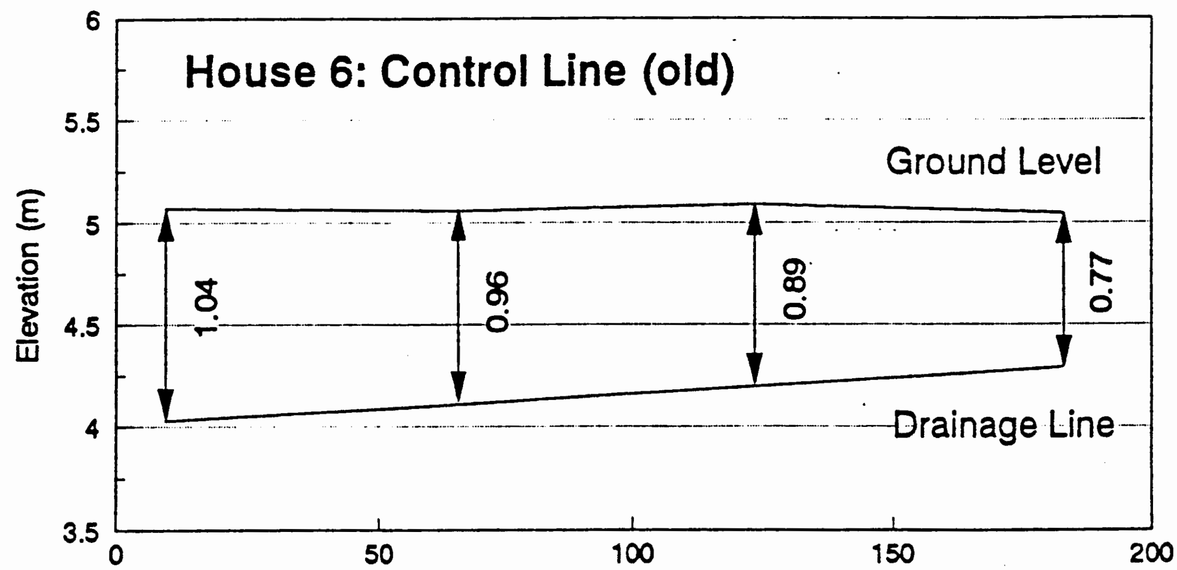

House 2: South Guard Line (old)
Ground Level
Drainage Line
1.00
0.91
0.89
0.92
Elevation (m)
House 2: Control Line (old)
Ground Level
Drainage Line
0.90
0.83
0.84
0.83
Elevation (m)
House 2: North Guard Line (old)
Ground Level
Drainage Line
1.00
0.89
0.85
0.82
Elevation (m)
East - West Distance Along Drain (m)

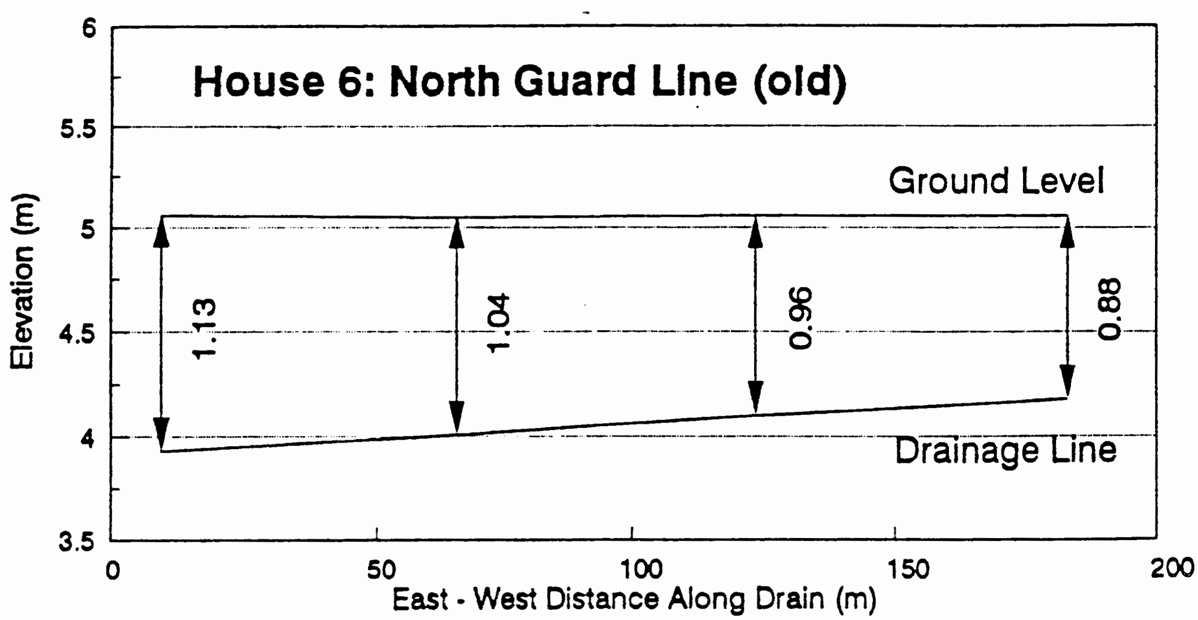

House 3: South Guard line (old)
Ground Level
Drainage Line
0.91
0.89
0.84
0.87
Elevation (m)
House 3: Control Line (old)
Ground Level
Drainage Line
0.97
0.87
0.84
0.81
Elevation (m)
House 3: North Guard Line (old)
Ground Level
Drainage Line
0.89
0.82
0.74
0.69
Elevation (m)
East - West Distance Along Drain (m)

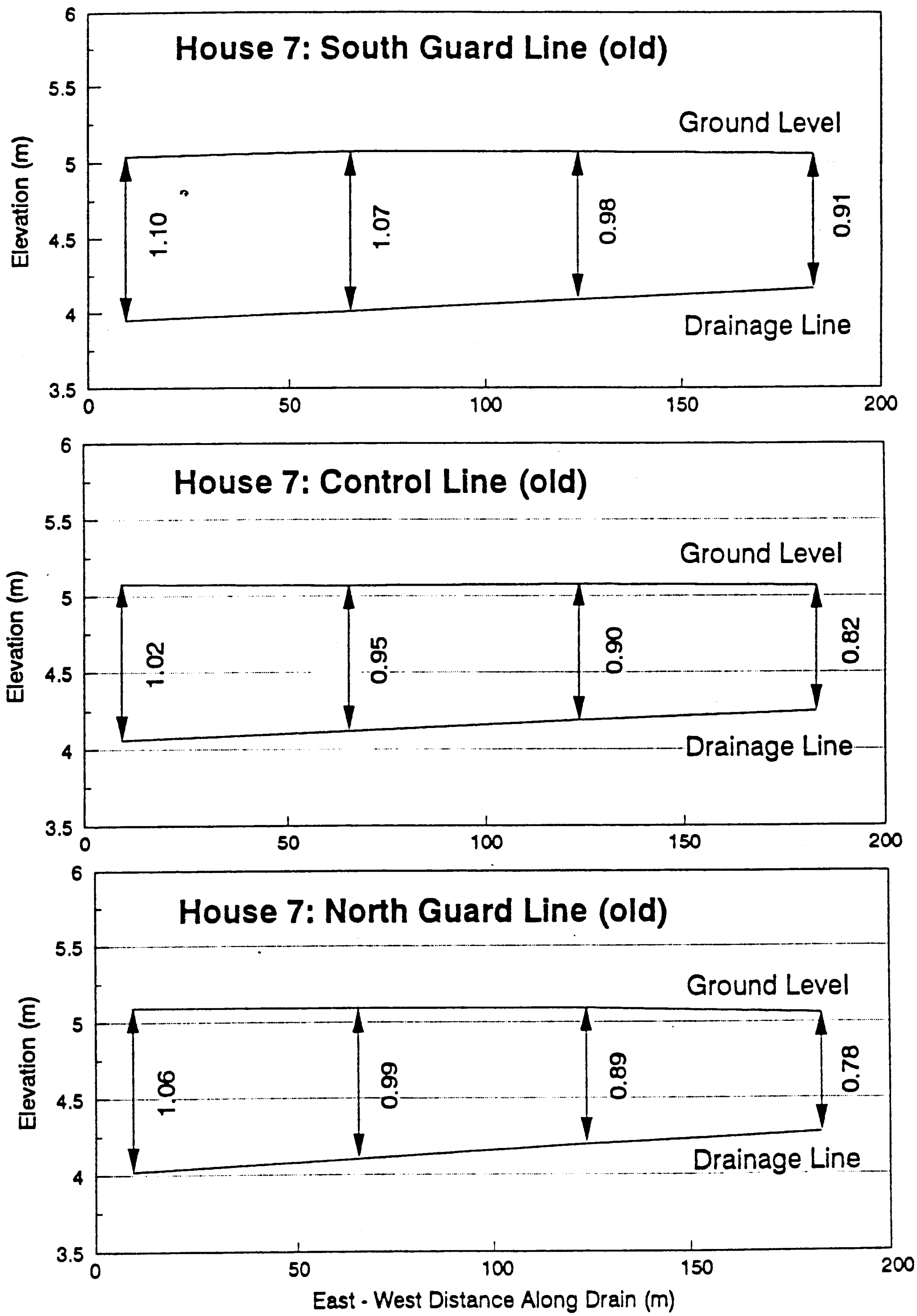

House 4: South Guard Line (old)
Ground Level
Drainage Line
0.98
0.94
0.85
0.80
House 4: Control Line (old)
Ground Level
Drainage Line
1.00
0.98
0.86
0.83
House 4: North Guard Line (old)
Ground Level
Drainage Line
1.00
1.00
0.91
0.86
Elevation (m)
6
5.5
5
4.5
4
3.5
0
50
100
150
200
East - West Distance Along Drain (m)

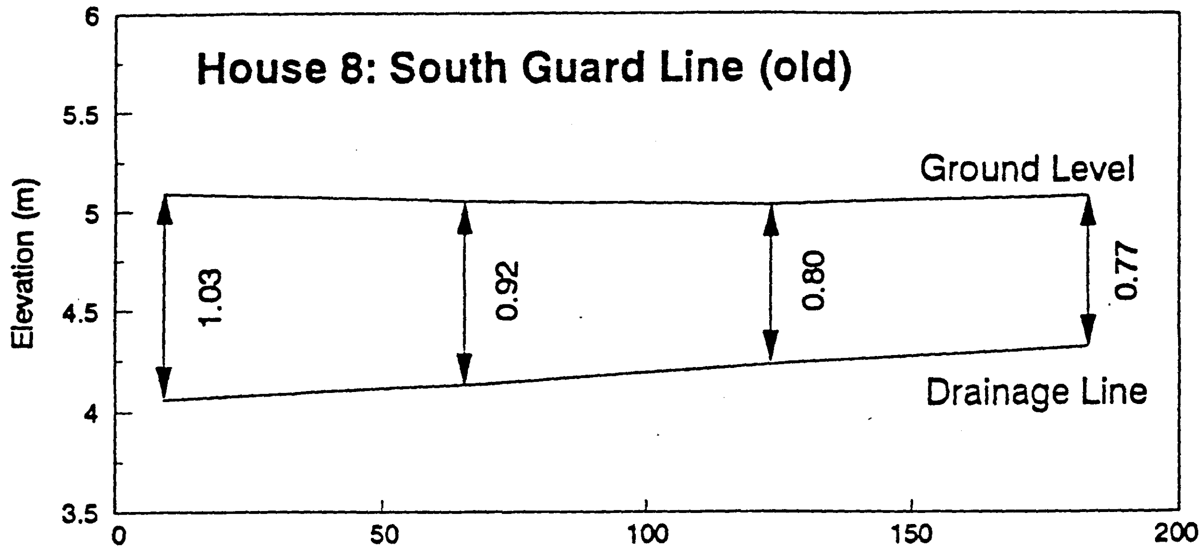

House 5: South Guard Line (old)
Ground Level
Drainage Line
1.03
1.01
0.89
0.82
House 5: Control Line (old)
Ground Level
Drainage Line
1.05
0.96
0.85
0.79
House 5: North Guard Line (old)
Ground Level
Drainage Line
1.01
0.97
0.87
0.78
Elevation (m)
East - West Distance Along Drain (m)

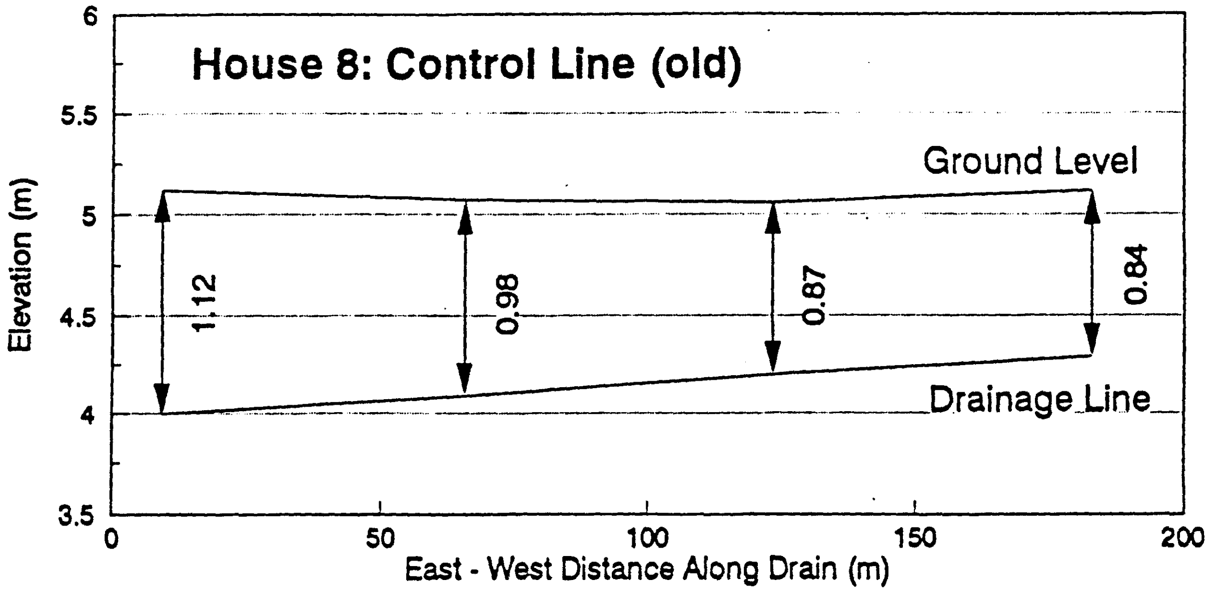

House 6: South Guard Line (old)
Ground Level
Drainage Line
1.13
1.11
0.96
0.84
Elevation (m)
6
5.5
5
4.5
4
3.5
0
50
100
150
200


House 6: Control Line (old)
Ground Level
Drainage Line
1.04
0.96
0.89
0.77
Elevation (m)
6
5.5
5
4.5
4
3.5
0
50
100
150
200


House 6: North Guard Line (old)
Ground Level
Drainage Line
1.13
1.04
0.96
0.88
Elevation (m)
6
5.5
5
4.5
4
3.5
0
50
100
150
200
East - West Distance Along Drain (m)


House 7: South Guard Line (old)
Ground Level
Drainage Line
1.10
1.07
0.98
0.91
House 7: Control Line (old)
Ground Level
Drainage Line
1.02
0.95
0.90
0.82
House 7: North Guard Line (old)
Ground Level
Drainage Line
1.06
0.99
0.89
0.78
Elevation (m)
East - West Distance Along Drain (m)


House 8: South Guard Line (old)
Ground Level
Drainage Line
1.03
0.92
0.80
0.77
Elevation (m)
6
5.5
5
4.5
4
3.5
0
50
100
150
200


House 8: Control Line (old)
Ground Level
Drainage Line
1.12
0.98
0.87
0.84
Elevation (m)
6
5.5
5
4.5
4
3.5
0
50
100
150
200
East - West Distance Along Drain (m)

APPENDIX 2

M.S. Thesis Abstracts for Joel E. Kimmelshue and Bryan A. Kliewer

ABSTRACT

KIMMELSHUE, JOEL EDWARD. Nitrogen mineralization of ^{15}N labelled corn residue as influenced by water management. (Under the direction of J. Wendell Gilliam).

Nearly 40 percent of North Carolina's crops are grown on poorly drained soils of the coastal plain. In North Carolina, high water table soils comprise nearly 2 million acres of agricultural land (Evans, et al., 1991). High water tables greatly influence crop residue decomposition due to anaerobic and cool conditions. Determination of the N mineralization potential of added residues in the lower coastal plain of North Carolina requires a better understanding of the influences of water table depth, soil characteristics, and climatic factors. An overwinter study was conducted to evaluate the effects of field and simulated water table depths on the mineralization potential of added ^{15}N labelled corn (Zea mays) residue as well as surface CO_2 evolution. Hauck (1973) stated that the overall objectives in performing ^{15}N mineralization studies are to predict changes in total soil organic matter content and quality under different systems of management and, more importantly, to determine whether total organic matter or fractions of particular ecological significance can be increased. Soda lime as a CO_2 absorbent is being used to determine relative differences in CO_2 evolution from soil with differing water table depths. Results reported by Edwards (1982) showed that, under static conditions, soda lime absorbs CO_2 more efficiently than alkali solutions such as KOH, and the soda lime technique is perhaps as accurate as any available for measuring absolute rates of CO_2 efflux.

The objective of this study is to determine relative differences of CO_2 evolution and ^{15}N mineralization over different water table depths following corn harvest. Four water table depth treatments of 0-, 15-, 30-, and 45-cm were incorporated in water table columns and 15-, 30-, 45-, and 60-cm depths for a companion field study using a flashboard riser system. Fifteen-centimeter diameter soil columns were extracted from a Portsmouth fine sandy loam, placed in PVC water table columns, and monitored in Raleigh, North Carolina, for CO_2 evolution and ^{15}N mineralization. Labelled plant residue was incorporated in the upper 15 cm in the enclosed PVC columns and soil micro samples taken for ^{15}N analysis. At the conclusion of the experiment, approximately 10 percent of the inorganic N came from the N added as plant residues even though it was only 1.1 percent of the total soil N. For water table depth treatments 30- and 45-cm, the amount of crop residue mineralized increased with water table depth treatment over time and the majority of inorganic N was found in the $^{15}NO3^{-}$-N fraction. The 0- and 15-cm water table depth treatments showed little $^{15}NO3^{-}$-N, but $^{15}NH4^{+}$-N accumulation increased by nearly 2.50 percent as determined by ^{15}N analysis. A general trend of increasing and decreasing CO_2 evolution with similar soil temperature fluctuations was observed.

ABSTRACT

KLIEWER, BRYAN ALBERT. Water Table Management Effects on Denitrification and Nitrous Oxide Evolution. Under the direction of Dr. J.W. Gilliam.

Previous research suggests that using controlled drainage to elevate the water table reduces nitrate (NO_3^-) contamination of surface water by enhancing denitrification. The acetylene (C_2H_2) inhibition technique was used to study denitrification and nitrous oxide (N_2O) evolution using Cape Fear loam (clayey, mixed, thermic Typic Umbraquult) cores subjected to different water table depths. Intermittent C_2H_2 exposure did not (a) affect soil inorganic nitrogen (N) distribution between ammonium (NH_4^+) and NO_3^-, (b) diminish inhibition of N_2O reduction during subsequent C_2H_2 exposure, or (c) induce C_2H_2 decomposition. Denitrification from 1 November 1993 through 21 April 1994 (172 days) was 404 kg N ha^{-1} for the 15-cm water table treatment, 269 for the 30-cm water table treatment, and 87 for the 45-cm water table treatment. Denitrification was greatest at the lowest monitored zone (36 to 54 cm) for each water table treatment. Denitrification accounted for 53 to 158 percent of the change in nitrate nitrogen (NO_3-N) content of the soil profile. Mineralization and nitrification in the unsaturated topsoil presumably allowed denitrification to exceed the change in NO_3-N content. Nitrate leaching was believed responsible for denitrification underestimating the change in NO_3-N content. Nitrous oxide evolution ranged from 4 to 119 g N_2O-N ha^{-1} day^{-1}, increasing as the water table approached the soil surface. Nitrous oxide evolution was positively correlated with mean soil temperature (10 cm depth) until $NO3^-$ limited denitrification. Total N_2O evolution from November 1 through April 21 was 9 kg N ha^{-1} for the 15-cm water table treatment, 4 for the 30-cm water table treatment, and 2 for the 45-cm water table treatment. Since steady state diffusion was not reached, estimates of N_2 evolution using N2O evolution in the presence of C_2H_2 were underestimated 12 fold. Drainage control level did not influence the magnitude of N_2O evolved per unit of N denitfified. Evolved N_2O-N represented only 2% of denitrification in the soil core (O to 54 cm) at each water table treatment. Drainage control to elevate the water table enhanced denitrification, reducing the potential for N transport with subsurface drainage to surface water.

APPENDIX 3

Rainfall, PET, and Root Depth For *DRAINMOD-N*

Date	Rainfall vs.	PET vs.	Root Depth (cm)
01-Nov-91	0.0	0.8	3.0
02-Nov-91	0.0	0.8	3.0
03-Nov-91	0.0	0.0	3.0
04-Nov-91	0.0	0.1	3.0
05-Nov-91	0.0	0.3	3.0
06-Nov-91	0.0	0.5	3.0
07-Nov-91	0.0	0.2	3.0
08-Nov-91	0.0	0.5	3.0
09-Nov-91	1.5	0.1	3.0
10-Nov-91	1.2	0.5	3.0
11-Nov-91	0.0	0.1	3.0
12-Nov-91	0.0	0.3	3.0
13-Nov-91	0.0	0.4	3.0
14-Nov-91	0.0	0.6	3.0
15-Nov-91	0.0	0.5	3.0
16-Nov-91	0.0	0.7	3.0
17-Nov-91	0.0	1.1	3.0
18-Nov-91	0.0	0.5	3.0
19-Nov-91	0.0	0.5	3.0
20-Nov-91	0.0	0.9	3.0
21-Nov-91	0.0	0.2	3.1
22-Nov-91	0.2	0.3	3.2
23-Nov-91	0.1	0.8	3.3
24-Nov-91	0.4	1.2	3.4
25-Nov-91	0.0	0.5	3.5
26-Nov-91	0.0	0.3	3.6
27-Nov-91	0.0	0.3	3.7
28-Nov-91	0.0	0.5	3.8
29-Nov-91	0.0	0.9	3.9
30-Nov-91	0.0	0.9	4.0
01-Dec-91	0.0	0.4	4.1
02-Dec-91	0.0	0.1	4.2
03-Dec-91	0.8	0.9	4.3

Date	Rainfall vs.	PET vs.	Root Depth (cm)
04-Dec-91	0.0	1.1	4.4
05-Dec-91	0.0	0.1	4.5
06-Dec-91	0.0	0.5	4.6
07-Dec-91	0.0	0.6	4.7
08-Dec-91	0.0	0.8	4.8
09-Dec-91	0.0	0.8	4.9
10-Dec-91	0.3	0.9	5.0
11-Dec-91	0.0	0.3	5.0
12-Dec-91	0.0	0.3	5.0
13-Dec-91	0.0	0.6	5.0
14-Dec-91	0.0	0.4	5.0
15-Dec-91	0.0	0.6	5.0
16-Dec-91	0.0	0.3	5.0
17-Dec-91	0.0	0.8	5.0
18-Dec-91	0.0	0.5	5.0
19-Dec-91	0.0	0.1	5.0
20-Dec-91	0.0	0.3	5.0
21-Dec-91	0.0	0.3	5.0
22-Dec-91	0.0	0.4	5.0
23-Dec-91	0.1	0.8	5.0
24-Dec-91	1.7	0.5	5.0
25-Dec-91	0.0	0.1	5.0
26-Dec-91	0.0	0.2	5.0
27-Dec-91	1.3	0.0	5.0
28-Dec-91	1.2	0.1	5.0
29-Dec-91	1.6	0.3	5.0
30-Dec-91	0.0	0.3	5.0
31-Dec-91	0.0	0.1	5.0
01-Jan-92	0.0	0.3	5.0
02-Jan-92	0.1	0.1	5.2
03-Jan-92	1.8	0.1	5.4
04-Jan-92	1.0	0.0	5.7
05-Jan-92	0.2	0.1	5.9

Date	Rainfall vs.	PET vs.	Root Depth (cm)
06-Jan-92	0.0	0.1	6.1
07-Jan-92	0.0	0.3	6.3
08-Jan-92	0.0	0.3	6.6
09-Jan-92	0.0	0.1	6.8
10-Jan-92	0.2	0.1	7.0
11-Jan-92	0.0	0.5	7.1
12-Jan-92	0.0	0.5	7.2
13-Jan-92	0.3	0.1	7.3
14-Jan-92	0.6	2.0	7.3
15-Jan-92	0.0	0.2	7.4
16-Jan-92	0.0	0.5	7.5
17-Jan-92	0.0	0.6	7.6
18-Jan-92	0.0	0.4	7.7
19-Jan-92	0.0	0.2	7.8
20-Jan-92	0.0	0.5	7.9
21-Jan-92	0.0	0.7	7.9
22-Jan-92	0.0	0.4	8.0
23-Jan-92	1.4	0.1	8.1
24-Jan-92	0.0	1.4	8.2
25-Jan-92	0.0	0.5	8.3
26-Jan-92	0.0	0.5	8.4
27-Jan-92	0.1	0.4	8.5
28-Jan-92	2.2	0.1	8.5
29-Jan-92	0.0	0.2	8.6
30-Jan-92	0.1	0.2	8.7
31-Jan-92	0.0	0.4	8.8
01-Feb-92	0.0	0.4	8.9
02-Feb-92	0.0	0.5	9.0
03-Feb-92	0.0	0.5	9.1
04-Feb-92	0.0	1.0	9.1
05-Feb-92	0.0	0.6	9.2
06-Feb-92	0.0	0.5	9.3
07-Feb-92	0.0	0.8	9.4

Date	Rainfall vs.	PET vs.	Root Depth (cm)
08-Feb-92	0.0	0.1	9.5
09-Feb-92	0.0	0.5	9.6
10-Feb-92	0.0	0.4	9.7
11-Feb-92	0.0	0.1	9.7
12-Feb-92	0.0	0.5	9.8
13-Feb-92	0.9	0.1	9.9
14-Feb-92	0.3	0.5	10.0
15-Feb-92	0.1	0.6	10.1
16-Feb-92	0.0	1.4	10.3
17-Feb-92	0.0	0.6	10.4
18-Feb-92	0.1	0.1	10.5
19-Feb-92	0.4	0.2	10.7
20-Feb-92	0.0	1.1	10.8
21-Feb-92	0.0	1.1	10.9
22-Feb-92	0.0	1.1	11.1
23-Feb-92	0.4	0.0	11.2
24-Feb-92	0.0	0.2	11.3
25-Feb-92	0.6	0.2	11.5
26-Feb-92	0.5	0.2	11.6
27-Feb-92	0.0	0.8	11.7
28-Feb-92	0.0	1.3	11.8
29-Feb-92	0.0	2.0	12.0
01-Mar-92	0.0	1.3	12.1
02-Mar-92	0.0	1.5	12.2
03-Mar-92	0.0	1.3	12.4
04-Mar-92	0.0	0.1	12.5
05-Mar-92	0.0	0.0	12.6
06-Mar-92	0.0	1.3	12.8
07-Mar-92	0.4	0.8	12.9
08-Mar-92	0.4	1.0	13.0
09-Mar-92	0.0	1.2	13.2
10-Mar-92	0.2	1.2	13.3
11-Mar-92	0.1	1.6	13.4

Date	Rainfall vs.	PET vs.	Root Depth (cm)
12-Mar-92	0.0	0.8	13.6
13-Mar-92	0.0	0.5	13.7
14-Mar-92	0.0	0.8	13.8
15-Mar-92	0.0	0.7	14.0
16-Mar-92	0.0	0.9	14.1
17-Mar-92	0.0	1.7	14.2
18-Mar-92	0.0	1.1	14.3
19-Mar-92	0.6	1.8	14.5
20-Mar-92	0.0	0.1	14.6
21-Mar-92	0.0	1.0	14.7
22-Mar-92	0.0	1.0	14.9
23-Mar-92	1.1	0.7	15.0
24-Mar-92	0.1	1.0	15.2
25-Mar-92	0.0	1.3	15.5
26-Mar-92	2.1	0.1	15.7
27-Mar-92	0.1	0.8	16.0
28-Mar-92	0.0	1.3	16.2
29-Mar-92	0.0	1.3	16.4
30-Mar-92	0.3	0.8	16.7
31-Mar-92	0.0	0.3	16.9
01-Apr-92	0.1	1.2	17.1
02-Apr-92	0.2	1.0	17.4
03-Apr-92	0.0	1.1	17.6
04-Apr-92	0.3	0.6	17.9
05-Apr-92	0.0	1.1	18.1
06-Apr-92	0.0	1.5	18.3
07-Apr-92	0.0	1.4	18.6
08-Apr-92	0.0	1.5	18.8
09-Apr-92	0.0	1.8	19.1
10-Apr-92	0.0	1.8	19.3
11-Apr-92	0.0	1.6	19.5
12-Apr-92	0.0	0.4	19.8
13-Apr-92	0.0	1.5	20.0

Date	Rainfall vs.	PET vs.	Root Depth (cm)
14-Apr-92	0.0	0.4	19.8
15-Apr-92	0.0	1.1	19.7
16-Apr-92	0.5	1.1	19.5
17-Apr-92	0.0	1.7	19.4
18-Apr-92	0.0	1.8	19.2
19-Apr-92	0.0	1.5	19.0
20-Apr-92	0.0	1.2	18.9
21-Apr-92	0.0	1.1	18.7
22-Apr-92	2.9	1.0	18.6
23-Apr-92	0.0	2.0	18.4
24-Apr-92	0.0	2.3	18.2
25-Apr-92	0.2	0.6	18.1
26-Apr-92	0.1	0.2	17.9
27-Apr-92	0.0	0.7	17.7
28-Apr-92	0.0	1.0	17.6
29-Apr-92	0.0	1.7	17.4
30-Apr-92	0.0	1.5	17.3
01-May-92	0.0	1.4	17.1
02-May-92	0.0	2.3	16.9
03-May-92	0.0	1.7	16.8
04-May-92	0.0	1.7	16.6
05-May-92	0.5	0.1	16.5
06-May-92	0.1	0.1	16.3
07-May-92	0.8	0.2	16.1
08-May-92	2.4	0.7	16.0
09-May-92	0.0	1.8	15.8
10-May-92	0.0	1.5	15.7
11-May-92	0.0	1.8	15.5
12-May-92	0.0	0.5	15.3
13-May-92	0.0	1.4	15.2
14-May-92	0.0	1.6	15.0
15-May-92	0.0	1.6	14.8
16-May-92	0.0	1.4	14.6

Date	Rainfall vs.	PET vs.	Root Depth (cm)
17-May-92	0.0	1.2	14.4
18-May-92	2.1	1.4	14.2
19-May-92	0.2	0.3	14.0
20-May-92	0.2	0.1	13.8
21-May-92	0.0	2.3	13.7
22-May-92	0.0	2.1	13.5
23-May-92	0.0	2.2	13.3
24-May-92	0.0	2.3	13.1
25-May-92	0.0	0.5	12.9
26-May-92	1.3	0.2	12.7
27-May-92	0.1	0.6	12.5
28-May-92	0.0	1.7	12.3
29-May-92	0.4	0.3	12.1
30-May-92	3.6	0.4	11.9
31-May-92	0.0	1.4	11.7
01-Jun-92	0.0	1.5	11.5
02-Jun-92	0.0	1.6	11.3
03-Jun-92	0.0	1.6	11.2
04-Jun-92	0.3	0.3	11.0
05-Jun-92	3.5	0.8	10.8
06-Jun-92	0.0	2.0	10.6
07-Jun-92	0.0	2.0	10.4
08-Jun-92	0.0	2.1	10.2
09-Jun-92	2.8	0.1	10.0
10-Jun-92	0.0	1.5	9.2
11-Jun-92	0.0	1.6	8.4
12-Jun-92	0.0	0.6	7.7
13-Jun-92	0.0	1.2	6.9
14-Jun-92	0.0	1.0	6.1
15-Jun-92	0.0	1.7	5.3
16-Jun-92	0.0	1.2	4.6
17-Jun-92	0.0	1.9	3.8
18-Jun-92	0.0	2.1	3.0

Date	Rainfall vs. PET vs. Root Depth (cm)		
19-Jun-92	0.0	1.2	3.0
20-Jun-92	0.1	1.5	3.0
21-Jun-92	0.5	0.2	3.0
22-Jun-92	0.0	1.9	3.0
23-Jun-92	0.0	2.1	3.0
24-Jun-92	0.1	2.0	3.0
25-Jun-92	1.5	1.8	3.0
26-Jun-92	3.3	1.0	3.0
27-Jun-92	0.0	1.1	3.0
28-Jun-92	0.0	1.9	3.0
29-Jun-92	0.0	1.9	3.0
30-Jun-92	0.0	1.9	3.0
01-Jul-92	0.1	1.4	3.0
02-Jul-92	0.0	1.3	3.0
03-Jul-92	0.0	2.0	3.0
04-Jul-92	0.2	1.3	3.0
05-Jul-92	0.0	1.9	3.0
06-Jul-92	1.3	0.6	3.0
07-Jul-92	0.0	1.2	3.0
08-Jul-92	0.0	1.9	3.0
09-Jul-92	0.0	2.0	3.0
10-Jul-92	0.0	2.2	3.1
11-Jul-92	0.0	2.3	3.3
12-Jul-92	0.0	2.0	3.4
13-Jul-92	0.0	2.6	3.6
14-Jul-92	0.0	2.4	3.7
15-Jul-92	0.0	2.4	3.9
16-Jul-92	0.4	1.8	4.0
17-Jul-92	0.0	2.1	4.1
18-Jul-92	3.4	2.1	4.3
19-Jul-92	0.1	0.8	4.4
20-Jul-92	0.0	1.8	4.6
21-Jul-92	0.0	1.9	4.7

Date	Rainfall vs.	PET vs.	Root Depth (cm)
22-Jul-92	0.0	1.4	4.9
23-Jul-92	1.4	0.7	5.0
24-Jul-92	0.4	0.7	5.1
25-Jul-92	0.0	0.6	5.3
26-Jul-92	0.0	1.0	5.4
27-Jul-92	4.1	1.8	5.6
28-Jul-92	1.6	1.1	5.7
29-Jul-92	0.0	1.7	5.9
30-Jul-92	0.0	1.4	6.0
31-Jul-92	0.2	1.2	6.1
01-Aug-92	0.0	1.5	6.3
02-Aug-92	0.0	1.6	6.4
03-Aug-92	0.5	0.8	6.6
04-Aug-92	0.0	1.1	6.7
05-Aug-92	0.0	0.9	6.9
06-Aug-92	0.0	0.2	7.0
07-Aug-92	0.0	0.5	7.1
08-Aug-92	0.0	1.6	7.3
09-Aug-92	2.0	1.3	7.4
10-Aug-92	0.0	0.7	7.6
11-Aug-92	0.0	1.5	7.7
12-Aug-92	1.7	0.5	7.9
13-Aug-92	2.1	0.6	8.0
14-Aug-92	3.3	0.2	8.1
15-Aug-92	4.6	0.4	8.3
16-Aug-92	2.0	0.4	8.4
17-Aug-92	0.9	0.2	8.6
18-Aug-92	0.0	0.7	8.7
19-Aug-92	0.0	1.5	8.9
20-Aug-92	1.5	0.2	9.0
21-Aug-92	0.0	1.2	9.1
22-Aug-92	0.0	1.1	9.3
23-Aug-92	0.0	1.2	9.4

Date	Rainfall vs.	PET vs.	Root Depth (cm)
24-Aug-92	0.0	1.2	9.6
25-Aug-92	0.0	1.4	9.7
26-Aug-92	0.0	1.1	9.9
27-Aug-92	0.0	1.0	10.0
28-Aug-92	0.1	0.8	10.9
29-Aug-92	0.0	1.1	11.9
30-Aug-92	0.0	1.5	12.8
31-Aug-92	0.0	1.6	13.8
01-Sep-92	0.0	1.3	14.7
02-Sep-92	0.0	1.5	15.6
03-Sep-92	0.0	1.2	16.6
04-Sep-92	0.6	1.2	17.5
05-Sep-92	4.9	0.6	18.4
06-Sep-92	0.1	0.4	19.4
07-Sep-92	0.0	0.6	20.3
08-Sep-92	0.0	1.2	21.3
09-Sep-92	0.0	0.9	22.2
10-Sep-92	0.0	1.2	23.1
11-Sep-92	0.0	0.4	24.1
12-Sep-92	0.0	1.4	25.0
13-Sep-92	0.0	1.2	24.5
14-Sep-92	0.0	1.2	24.1
15-Sep-92	0.0	0.6	23.6
16-Sep-92	0.0	1.0	23.2
17-Sep-92	0.0	0.8	22.7
18-Sep-92	0.0	1.0	22.3
19-Sep-92	0.4	0.7	21.8
20-Sep-92	0.4	0.3	21.4
21-Sep-92	0.9	0.2	20.9
22-Sep-92	0.1	0.6	20.5
23-Sep-92	0.5	0.2	20.0
24-Sep-92	0.0	0.2	19.5
25-Sep-92	0.2	0.3	19.1

Rainfall vs. PET vs. Root Depth (cm)

Date			
26-Sep-92	0.0	0.4	18.6
27-Sep-92	0.0	0.7	18.2
28-Sep-92	2.2	0.1	17.7
29-Sep-92	0.1	0.8	17.3
30-Sep-92	0.0	0.9	16.8
01-Oct-92	0.0	0.7	16.4
02-Oct-92	0.0	0.9	15.9
03-Oct-92	0.0	0.9	15.5
04-Oct-92	3.1	0.1	15.0
05-Oct-92	0.3	0.3	14.7
06-Oct-92	0.0	0.7	14.4
07-Oct-92	0.0	0.8	14.1
08-Oct-92	0.2	1.1	13.9
09-Oct-92	0.2	0.1	13.6
10-Oct-92	0.0	0.3	13.3
11-Oct-92	0.2	0.1	13.0
12-Oct-92	0.1	0.8	12.7
13-Oct-92	0.0	0.9	12.4
14-Oct-92	0.0	1.0	12.1
15-Oct-92	0.0	0.9	11.9
16-Oct-92	0.0	0.4	11.6
17-Oct-92	0.0	0.5	11.3
18-Oct-92	0.0	0.5	11.0
19-Oct-92	0.0	0.7	10.7
20-Oct-92	0.0	0.7	10.4
21-Oct-92	0.0	0.7	10.1
22-Oct-92	0.0	0.7	9.9
23-Oct-92	0.0	0.6	9.6
24-Oct-92	0.0	0.9	9.3
25-Oct-92	0.0	1.0	9.0
26-Oct-92	0.0	0.9	8.7
27-Oct-92	0.0	0.8	8.4
28-Oct-92	0.0	0.5	8.1

Date	Rainfall vs.	PET vs.	Root Depth (cm)
29-Oct-92	0.0	0.5	7.9
30-Oct-92	0.0	0.4	7.6
31-Oct-92	1.2	0.1	7.3
01-Nov-92	0.0	0.2	7.0
02-Nov-92	0.0	0.5	6.7
03-Nov-92	0.8	0.4	6.4
04-Nov-92	0.1	0.2	6.1
05-Nov-92	1.6	0.3	5.9
06-Nov-92	0.1	0.2	5.6
07-Nov-92	0.0	0.1	5.3
08-Nov-92	0.0	0.4	5.0
09-Nov-92	0.0	0.6	4.7
10-Nov-92	0.0	0.6	4.4
11-Nov-92	0.0	0.6	4.1
12-Nov-92	0.7	0.5	3.9
13-Nov-92	0.5	1.3	3.6
14-Nov-92	0.0	0.4	3.3
15-Nov-92	0.0	0.5	3.0
16-Nov-92	0.0	0.5	3.0
17-Nov-92	0.0	0.6	3.0
18-Nov-92	0.0	0.5	3.0
19-Nov-92	0.0	0.4	3.0
20-Nov-92	0.0	0.2	3.0
21-Nov-92	0.0	1.1	3.0
22-Nov-92	0.0	0.6	3.0
23-Nov-92	0.0	1.4	3.0
24-Nov-92	0.9	0.1	3.0
25-Nov-92	0.6	0.3	3.0
26-Nov-92	2.4	0.3	3.0
27-Nov-92	3.2	0.1	3.0
28-Nov-92	0.0	0.3	3.0
29-Nov-92	0.0	0.2	3.0
30-Nov-92	0.0	0.3	3.0

Date	Rainfall vs. PET vs. Root Depth (cm)		
01-Dec-92	0.3	0.3	3.0
02-Dec-92	0.0	0.5	3.0
03-Dec-92	0.0	0.6	3.0
04-Dec-92	0.0	0.1	3.0
05-Dec-92	0.0	1.1	3.0
06-Dec-92	0.0	0.4	3.0
07-Dec-92	0.0	0.2	3.0
08-Dec-92	0.0	0.2	3.0
09-Dec-92	0.0	0.3	3.0
10-Dec-92	3.7	0.6	3.0
11-Dec-92	0.0	0.2	3.0
12-Dec-92	0.0	0.1	3.0
13-Dec-92	0.0	0.1	3.0
14-Dec-92	0.0	0.1	3.0
15-Dec-92	0.0	0.1	3.0
16-Dec-92	0.0	0.3	3.0
17-Dec-92	0.0	0.1	3.0
18-Dec-92	0.0	0.4	3.0
19-Dec-92	0.0	0.0	3.0
20-Dec-92	0.9	0.1	3.0
21-Dec-92	0.0	0.2	3.0
22-Dec-92	0.0	0.1	3.0
23-Dec-92	0.2	0.4	3.0
24-Dec-92	0.0	1.0	3.0
25-Dec-92	0.0	0.2	3.0
26-Dec-92	0.0	0.1	3.0
27-Dec-92	0.0	0.2	3.0
28-Dec-92	2.6	0.1	3.0
29-Dec-92	0.1	0.1	3.0
30-Dec-92	0.0	0.1	3.0
31-Dec-92	0.0	0.5	3.0

APPENDIX 4

Estimating field-scale hydraulic conductivity

ESTIMATING FIELD-SCALE HYDRAULIC CONDUCTIVITY

The procedure was based on the Hooghoudt equation:

$$q = \frac{4K_{sat_t}m^2 + 8K_{sat_b}d_e m}{L^2} \tag{1}$$

where q is the steady drainage flux [L T^{-1}], m the distance between the drain depth and the water table at the midpoint between drains [L], $Ksat_t$ the lateral hydraulic conductivity in the zone between the drain depth and the midpoint water table [L T^{-1}], $Ksat_b$ the lateral hydraulic conductivity in the zone between the drain and the impermeable layer [L T^{-1}], and d_e the equivalent depth to the impermeable layer [L].

Daily drainage events that occurred without rainfall (usually the days after a major rainfall event) and their corresponding midnight water table depths were selected from the 1991 and 1992 data sets. A quadratic regression analysis was performed on the drainage rate-water table data to develop an equation for each experimental plot that could generate q-m values for any depth. With such relationship, $Ksat_t$ can be approximated with the following equation:

$$K_{sat_t} = \frac{qL^2 - 8K_{sat_b}d_e m}{8m^2} \tag{2}$$

Equation 2 was solved for different scenarios, starting with those q-m associated with the bottom two layers (layers 4 and 5). For this, a $Ksat_b$ value of 3.75 m/d, previously reported by Munster (1992), for layer 5 was used to compute a $Ksat_t$, using an iteration procedure that varied $Ksat_t$ until convergence was obtained. The same procedure was sequentially repeated moving one layer up at a time. For instance, to estimate $Ksat_t$ for layer 3, the previously determined $Ksat_t$ for layer 4 was used as a $Ksat_b$ to solve Equation 2.

APPENDIX 5

DRAINMOD-N input and output data

Table B1. Soil water characteristic, volume drained and upward flux relationships for the Portsmouth and Tomotley sandy loams.

Portsmouth		Tomotley	
Water content (cm^3/cm^3)	Suction (cm)	Water content (cm^3/cm^3)	Suction (cm)
0.366	0	0.460	0
0.341	3	0.450	9
0.333	10	0.440	16
0.327	20	0.420	25
0.321	30	0.400	35
0.316	40	0.380	50
0.311	50	0.360	70
0.304	70	0.340	100
0.300	80	0.320	150
0.293	100	0.300	220
0.283	150	0.280	600
0.274	200	0.250	1000
0.256	300	0.200	2000
0.233	400		
0.209	500		
0.190	600		
0.179	700		
0.168	900		
0.165	1000		
0.150	1500		

Portsmouth			Tomotley		
WT depth (cm)	Volume drained (cm)	Upward flux (cm/hr)	WT depth (cm)	Volume drained (cm)	Upward flux (cm/hr)
0	0.000	1.0000	0	0.000	0.1000
10	0.186	0.5000	10	0.250	0.0800
20	0.488	0.2000	20	0.400	0.0600
30	0.833	0.0200	30	0.650	0.0500
40	1.230	0.0150	40	0.920	0.0400
50	1.690	0.0080	50	1.350	0.0200
60	2.200	0.0050	60	1.850	0.0063
80	3.624	0.0020	70	2.530	0.0025
100	5.362	0.0005	80	3.400	0.0016
120	7.251	0.0000	100	5.500	0.0011
140	9.234	0.0000	120	7.500	0.0005
160	11.313	0.0000	160	13.400	0.0000
180	13.507	0.0000	200	19.300	0.0000
200	15.818	0.0000	240	25.600	0.0000
220	18.152	0.0000	280	32.100	0.0000
240	20.487	0.0000	320	38.700	0.0000
250	21.654	0.0000	1000	100.000	0.0000
1000	100.000	0.0000			

Table B2. Estimated costs for corn production in eastern North Carolina (Anderson and Neuman, 1990).

Variable costs:	$/ha
Seed	50.16
Lime	24.65
Fertilizer, custom applied	72.79
Nitrogen, custom applied	73.73
Pre-emergence herbicides	36.59
Insecticides and nematocides	24.06
Tractor fuel and lube	15.37
Tractor repair	11.72
Machinery repair	43.13
Machinery fuel and lube	11.28
Interest on operating capital	87.15
Labor	40.20
Total variable costs:	491.08
Fixed costs:	$/ha
Machinery replacement, machinery interest, tax and insurance	65.12
Total fixed costs:	65.12
Total production costs:	556.76

Table B3. Estimated drainage costs for eastern North Carolina

Initial costs:	
Drain tubing	$2.62/m
Surface drainage	$247/ha
Control drainage structure	$1650/unit ($55/ha)
Annual maintenance costs:	
Subsurface drainage	2% of amortized cost
Surface drainage	$20/ha

Table B4. Predicted average annual relative corn yield for a Portsmouth soil with conventional drainage in eastern North Carolina.

Drain Spacing (m)	Drain Depth (m)	Relative Yield, % Good S.D	Relative Yield, % Poor S.D	Actual Yield, kg/ha Good S.D	Actual Yield, kg/ha Poor S.D	Gross Income, $/ha Good S.D	Gross Income, $/ha Poor S.D
10	0.75	83.5	82.3	8350	8230	835.0	823.0
15	0.75	83.4	82.0	8340	8200	834.0	820.0
20	0.75	82.8	81.4	8280	8140	828.0	814.0
25	0.75	81.6	79.9	8160	7990	816.0	799.0
30	0.75	79.8	76.8	7980	7680	798.0	768.0
40	0.75	75.1	68.7	7510	6870	751.0	687.0
50	0.75	71.7	61.0	7170	6100	717.0	610.0
100	0.75	59.2	33.4	5920	3340	592.0	334.0
10	1.00	81.4	81.0	8140	8100	814.0	810.0
15	1.00	81.6	81.2	8160	8120	816.0	812.0
20	1.00	81.8	81.2	8180	8120	818.0	812.0
25	1.00	82.1	81.1	8210	8110	821.0	811.0
30	1.00	82.0	80.8	8200	8080	820.0	808.0
40	1.00	80.9	78.3	8090	7830	809.0	783.0
50	1.00	77.4	72.7	7740	7270	774.0	727.0
100	1.00	61.8	42.2	6180	4220	618.0	422.0
10	1.25	79.9	80.0	7990	8000	799.0	800.0
15	1.25	80.0	80.0	8000	8000	800.0	800.0
20	1.25	80.1	80.0	8010	8000	801.0	800.0
25	1.25	80.2	80.1	8020	8010	802.0	801.0
30	1.25	80.4	80.2	8040	8020	804.0	802.0
40	1.25	80.6	79.7	8060	7970	806.0	797.0
50	1.25	80.3	78.0	8030	7800	803.0	780.0
100	1.25	69.8	49.8	6980	4980	698.0	498.0

Actual Yield is based on a potential yield of 10,000 kg/ha
Gross Income is based on a corn price of $0.10/kg

Table B5. Predicted average annual relative corn yield for a Portsmouth soil with controlled drainage in the summer in eastern North Carolina.

Drain Spacing (m)	Drain Depth (m)	Relative Yield, % Good S.D	Relative Yield, % Poor S.D	Actual Yield, kg/ha Good S.D	Actual Yield, kg/ha Poor S.D	Gross Income, $/ha Good S.D	Gross Income, $/ha Poor S.D
10	0.75	84.0	82.5	8400	8250	840.0	825.0
15	0.75	83.1	81.5	8310	8150	831.0	815.0
20	0.75	81.8	79.9	8180	7990	818.0	799.0
25	0.75	80.0	76.7	8000	7670	800.0	767.0
30	0.75	77.7	72.2	7770	7220	777.0	722.0
40	0.75	72.3	62.6	7230	6260	723.0	626.0
50	0.75	68.3	54.6	6830	5460	683.0	546.0
100	0.75	54.6	31.0	5460	3100	546.0	310.0
10	1.00	84.6	83.6	8460	8360	846.0	836.0
15	1.00	84.0	82.9	8400	8290	840.0	829.0
20	1.00	83.2	81.2	8320	8120	832.0	812.0
25	1.00	82.2	80.0	8220	8000	822.0	800.0
30	1.00	80.6	76.7	8060	7670	806.0	767.0
40	1.00	78.1	71.3	7810	7130	781.0	713.0
50	1.00	73.7	63.7	7370	6370	737.0	637.0
100	1.00	57.5	36.5	5750	3650	575.0	365.0
10	1.25	83.5	83.1	8350	8310	835.0	831.0
15	1.25	83.3	82.8	8330	8280	833.0	828.0
20	1.25	82.8	82.2	8280	8220	828.0	822.0
25	1.25	82.2	81.0	8220	8100	822.0	810.0
30	1.25	81.4	79.4	8140	7940	814.0	794.0
40	1.25	79.5	74.9	7950	7490	795.0	749.0
50	1.25	77.8	69.6	7780	6960	778.0	696.0
100	1.25	61.0	41.5	6100	4150	610.0	415.0

Actual Yield is based on a potential yield of 10,000 kg/ha
Gross Income is based on a corn price of $0.10/kg

Table B6. Predicted average annual relative corn yield for a Portsmouth soil with controlled drainage in the summer and winter in eastern North Carolina.

Drain Spacing (m)	Drain Depth (m)	Relative Yield, % Good S.D	Relative Yield, % Poor S.D	Actual Yield, kg/ha Good S.D	Actual Yield, kg/ha Poor S.D	Gross Income, $/ha Good S.D	Gross Income, $/ha Poor S.D
10	0.75	84.0	82.5	8400	8250	840.0	825.0
15	0.75	83.1	81.5	8310	8150	831.0	815.0
20	0.75	81.8	79.9	8180	7990	818.0	799.0
25	0.75	79.7	76.4	7970	7640	797.0	764.0
30	0.75	76.5	71.1	7650	7110	765.0	711.0
40	0.75	72.2	62.2	7220	6220	722.0	622.0
50	0.75	68.4	54.4	6840	5440	684.0	544.0
100	0.75	53.9	29.1	5390	2910	539.0	291.0
10	1.00	84.6	83.6	8460	8360	846.0	836.0
15	1.00	84.0	82.9	8400	8290	840.0	829.0
20	1.00	83.2	81.9	8320	8190	832.0	819.0
25	1.00	82.2	80.0	8220	8000	822.0	800.0
30	1.00	80.9	77.3	8090	7730	809.0	773.0
40	1.00	77.9	70.8	7790	7080	779.0	708.0
50	1.00	72.7	62.3	7270	6230	727.0	623.0
100	1.00	57.5	35.9	5750	3590	575.0	359.0
10	1.25	83.5	83.1	8350	8310	835.0	831.0
15	1.25	83.3	82.8	8330	8280	833.0	828.0
20	1.25	82.8	82.2	8280	8220	828.0	822.0
25	1.25	82.2	81.0	8220	8100	822.0	810.0
30	1.25	81.4	79.4	8140	7940	814.0	794.0
40	1.25	79.5	74.8	7950	7480	795.0	748.0
50	1.25	77.6	69.3	7760	6930	776.0	693.0
100	1.25	60.6	40.1	6060	4010	606.0	401.0

Actual Yield is based on a potential yield of 10,000 kg/ha
Gross Income is based on a corn price of $0.10/kg

Table B7. Economic analysis for the production of corn on a Portsmouth soil with conventional drainage in eastern North Carolina. Cost and income results are on a $/ha basis.

Drain Spacing (m)	Drain Depth (m)	Drain per ha (m)	Initial Drainage System Cost		Annual Drainage System Cost		Annual Drainage Maintenance Cost		Annual Production Cost	Total Annual Cost ($/ha)		Gross Income ($/ha)		Net Profit ($/ha)	
			Good S.D.	Poor S.D.	Good S.D.	Poor S.D.	Good S.D	Poor S.D.		Good S.D.	Poor S.D.	Good S.D	Poor S.D.	Good S.D	Poor S.D.
10	0.75	1000	2867.0	2620.0	304.1	277.9	25.6	5.6	556.8	886.4	840.2	835.0	823.0	-51.4	-17.2
15	0.75	667	1993.7	1746.7	211.5	185.3	23.7	3.7	556.8	792.0	745.8	834.0	820.0	42.0	74.2
20	0.75	500	1557.0	1310.0	165.2	139.0	22.8	2.8	556.8	744.7	698.5	828.0	814.0	83.3	115.5
25	0.75	400	1295.0	1048.0	137.4	111.2	22.2	2.2	556.8	716.4	670.2	816.0	799.0	99.6	128.8
30	0.75	333	1120.3	873.3	118.8	92.6	21.9	1.9	556.8	697.5	651.3	798.0	768.0	100.5	116.7
40	0.75	250	902.0	655.0	95.7	69.5	21.4	1.4	556.8	673.8	627.6	751.0	687.0	77.2	59.4
50	0.75	200	771.0	524.0	81.8	55.6	21.1	1.1	556.8	659.7	613.5	717.0	610.0	57.3	-3.5
100	0.75	100	509.0	262.0	54.0	27.8	20.6	0.6	556.8	631.3	585.1	592.0	334.0	-39.3	-251.1
10	1.00	1000	2867.0	2620.0	304.1	277.9	25.6	5.6	556.8	886.4	840.2	814.0	810.0	-72.4	-30.2
15	1.00	667	1993.7	1746.7	211.5	185.3	23.7	3.7	556.8	792.0	745.8	816.0	812.0	24.0	66.2
20	1.00	500	1557.0	1310.0	165.2	139.0	22.8	2.8	556.8	744.7	698.5	818.0	812.0	73.3	113.5
25	1.00	400	1295.0	1048.0	137.4	111.2	22.2	2.2	556.8	716.4	670.2	821.0	811.0	104.6	140.8
30	1.00	333	1120.3	873.3	118.8	92.6	21.9	1.9	556.8	697.5	651.3	820.0	808.0	122.5	156.7
40	1.00	250	902.0	655.0	95.7	69.5	21.4	1.4	556.8	673.8	627.6	809.0	783.0	135.2	155.4
50	1.00	200	771.0	524.0	81.8	55.6	21.1	1.1	556.8	659.7	613.5	774.0	727.0	114.3	113.5
100	1.00	100	509.0	262.0	54.0	27.8	20.6	0.6	556.8	631.3	585.1	618.0	422.0	-13.3	-163.1
					0.0										
10	1.25	1000	2867.0	2620.0	304.1	277.9	25.6	5.6	556.8	886.4	840.2	799.0	800.0	-87.4	-40.2
15	1.25	667	1993.7	1746.7	211.5	185.3	23.7	3.7	556.8	792.0	745.8	800.0	800.0	8.0	54.2
20	1.25	500	1557.0	1310.0	165.2	139.0	22.8	2.8	556.8	744.7	698.5	801.0	800.0	56.3	101.5
25	1.25	400	1295.0	1048.0	137.4	111.2	22.2	2.2	556.8	716.4	670.2	802.0	801.0	85.6	130.8
30	1.25	333	1120.3	873.3	118.8	92.6	21.9	1.9	556.8	697.5	651.3	804.0	802.0	106.5	150.7
40	1.25	250	902.0	655.0	95.7	69.5	21.4	1.4	556.8	673.8	627.6	806.0	797.0	132.2	169.4
50	1.25	200	771.0	524.0	81.8	55.6	21.1	1.1	556.8	659.7	613.5	803.0	780.0	143.3	166.5
100	1.25	100	509.0	262.0	54.0	27.8	20.6	0.6	556.8	631.3	585.1	698.0	498.0	66.7	-87.1

Table B8. Economic analysis for the production of corn on a Portsmouth soil with controlled drainage in the summer in eastern North Carolina. Cost and income results are on a \$/ha basis.

Drain Spacing (m)	Drain Depth (m)	Drain per ha (m)	Initial Drainage System Cost Good S.D.	Initial Drainage System Cost Poor S.D.	Control Structure Cost	Annual Drainage System Cost Good S.D.	Annual Drainage System Cost Poor S.D.	Annual Drainage Maintenance Cost Good S.D.	Annual Drainage Maintenance Cost Poor S.D.	Annual Production Cost	Total Annual Cost (\$/ha) Good S.D.	Total Annual Cost (\$/ha) Poor S.D.	Gross Income (\$/ha) Good S.D.	Gross Income (\$/ha) Poor S.D.	Net Profit (\$/ha) Good S.D.	Net Profit (\$/ha) Poor S.D.
10	0.75	1000	2867.0	2620.0	55.0	310.0	283.8	25.7	5.7	556.8	892.4	846.2	840.0	825.0	-52.4	-21.2
15	0.75	667	1993.7	1746.7	55.0	217.3	191.1	23.8	3.8	556.8	797.9	751.7	831.0	815.0	33.1	63.3
20	0.75	500	1557.0	1310.0	55.0	171.0	144.8	22.9	2.9	556.8	750.7	704.5	818.0	799.0	67.3	94.5
25	0.75	400	1295.0	1048.0	55.0	143.2	117.0	22.3	2.3	556.8	722.3	676.1	800.0	767.0	77.7	90.9
30	0.75	333	1120.3	873.3	55.0	124.7	98.5	22.0	2.0	556.8	703.4	657.2	777.0	722.0	73.6	64.8
40	0.75	250	902.0	655.0	55.0	101.5	75.3	21.5	1.5	556.8	679.8	633.6	723.0	626.0	43.2	-7.6
50	0.75	200	771.0	524.0	55.0	87.6	61.4	21.2	1.2	556.8	665.6	619.4	683.0	546.0	17.4	-73.4
100	0.75	100	509.0	262.0	55.0	59.8	33.6	20.7	0.7	556.8	637.3	591.1	546.0	310.0	-91.3	-281.1
10	1.00	1000	2867.0	2620.0	55.0	310.0	283.8	25.7	5.7	556.8	892.4	846.2	846.0	836.0	-46.4	-10.2
15	1.00	667	1993.7	1746.7	55.0	217.3	191.1	23.8	3.8	556.8	797.9	751.7	840.0	829.0	42.1	77.3
20	1.00	500	1557.0	1310.0	55.0	171.0	144.8	22.9	2.9	556.8	750.7	704.5	832.0	819.0	81.3	114.5
25	1.00	400	1295.0	1048.0	55.0	143.2	117.0	22.3	2.3	556.8	722.3	676.1	822.0	800.0	99.7	123.9
30	1.00	333	1120.3	873.3	55.0	124.7	98.5	22.0	2.0	556.8	703.4	657.2	806.0	767.0	102.6	109.8
40	1.00	250	902.0	655.0	55.0	101.5	75.3	21.5	1.5	556.8	679.8	633.6	781.0	713.0	101.2	79.4
50	1.00	200	771.0	524.0	55.0	87.6	61.4	21.2	1.2	556.8	665.6	619.4	737.0	637.0	71.4	17.6
100	1.00	100	509.0	262.0	55.0	59.8	33.6	20.7	0.7	556.8	637.3	591.1	575.0	365.0	-62.3	-226.1
10	1.25	1000	2867.0	2620.0	55.0	310.0	283.8	25.7	5.7	556.8	892.4	846.2	835.0	831.0	-57.4	-15.2
15	1.25	667	1993.7	1746.7	55.0	217.3	191.1	23.8	3.8	556.8	797.9	751.7	833.0	828.0	35.1	76.3
20	1.25	500	1557.0	1310.0	55.0	171.0	144.8	22.9	2.9	556.8	750.7	704.5	828.0	822.0	77.3	117.5
25	1.25	400	1295.0	1048.0	55.0	143.2	117.0	22.3	2.3	556.8	722.3	676.1	822.0	810.0	99.7	133.9
30	1.25	333	1120.3	873.3	55.0	124.7	98.5	22.0	2.0	556.8	703.4	657.2	814.0	794.0	110.6	136.8
40	1.25	250	902.0	655.0	55.0	101.5	75.3	21.5	1.5	556.8	679.8	633.6	795.0	749.0	115.2	115.4
50	1.25	200	771.0	524.0	55.0	87.6	61.4	21.2	1.2	556.8	665.6	619.4	778.0	696.0	112.4	76.6
100	1.25	100	509.0	262.0	55.0	59.8	33.6	20.7	0.7	556.8	637.3	591.1	610.0	415.0	-27.3	-176.1

Table B9. Economic analysis for the production of corn on a Portsmouth soil with controlled drainage in the summer and winter in eastern North Carolina. Cost and income results are on a $/ha basis.

Drain Spacing (m)	Drain Depth (m)	Drain per ha (m)	Initial Drainage System Cost Good S.D.	Initial Drainage System Cost Poor S.D.	Control Structure Cost	Annual Drainage System Cost Good S.D.	Annual Drainage System Cost Poor S.D.	Annual Drainage Maintenance Cost Good S.D.	Annual Drainage Maintenance Cost Poor S.D.	Annual Production Cost	Total Annual Cost ($/ha) Good S.D.	Total Annual Cost ($/ha) Poor S.D.	Gross Income ($/ha) Good S.D.	Gross Income ($/ha) Poor S.D.	Net Profit ($/ha) Good S.D.	Net Profit ($/ha) Poor S.D.
10	0.75	1000	2867.0	2620.0	55.0	310.0	283.8	25.7	5.7	556.8	892.4	846.2	840.0	825.0	-52.4	-21.2
15	0.75	667	1993.7	1746.7	55.0	217.3	191.1	23.8	3.8	556.8	797.9	751.7	831.0	815.0	33.1	63.3
20	0.75	500	1557.0	1310.0	55.0	171.0	144.8	22.9	2.9	556.8	750.7	704.5	818.0	799.0	67.3	94.5
25	0.75	400	1295.0	1048.0	55.0	143.2	117.0	22.3	2.3	556.8	722.3	676.1	797.0	764.0	74.7	87.9
30	0.75	333	1120.3	873.3	55.0	124.7	98.5	22.0	2.0	556.8	703.4	657.2	765.0	711.0	61.6	53.8
40	0.75	250	902.0	655.0	55.0	101.5	75.3	21.5	1.5	556.8	679.8	633.6	722.0	622.0	42.2	-11.6
50	0.75	200	771.0	524.0	55.0	87.6	61.4	21.2	1.2	556.8	665.6	619.4	684.0	544.0	18.4	-75.4
100	0.75	100	509.0	262.0	55.0	59.8	33.6	20.7	0.7	556.8	637.3	591.1	539.0	291.0	-98.3	-300.1
10	1.00	1000	2867.0	2620.0	55.0	310.0	283.8	25.7	5.7	556.8	892.4	846.2	846.0	836.0	-46.4	-10.2
15	1.00	667	1993.7	1746.7	55.0	217.3	191.1	23.8	3.8	556.8	797.9	751.7	840.0	829.0	42.1	77.3
20	1.00	500	1557.0	1310.0	55.0	171.0	144.8	22.9	2.9	556.8	750.7	704.5	832.0	819.0	81.3	114.5
25	1.00	400	1295.0	1048.0	55.0	143.2	117.0	22.3	2.3	556.8	722.3	676.1	822.0	800.0	99.7	123.9
30	1.00	333	1120.3	873.3	55.0	124.7	98.5	22.0	2.0	556.8	703.4	657.2	809.0	773.0	105.6	115.8
40	1.00	250	902.0	655.0	55.0	101.5	75.3	21.5	1.5	556.8	679.8	633.6	779.0	708.0	99.2	74.4
50	1.00	200	771.0	524.0	55.0	87.6	61.4	21.2	1.2	556.8	665.6	619.4	727.0	623.0	61.4	3.6
100	1.00	100	509.0	262.0	55.0	59.8	33.6	20.7	0.7	556.8	637.3	591.1	575.0	359.0	-62.3	-232.1
10	1.25	1000	2867.0	2620.0	55.0	310.0	283.8	25.7	5.7	556.8	892.4	846.2	835.0	831.0	-57.4	-15.2
15	1.25	667	1993.7	1746.7	55.0	217.3	191.1	23.8	3.8	556.8	797.9	751.7	833.0	828.0	35.1	76.3
20	1.25	500	1557.0	1310.0	55.0	171.0	144.8	22.9	2.9	556.8	750.7	704.5	828.0	822.0	77.3	117.5
25	1.25	400	1295.0	1048.0	55.0	143.2	117.0	22.3	2.3	556.8	722.3	676.1	822.0	810.0	99.7	133.9
30	1.25	333	1120.3	873.3	55.0	124.7	98.5	22.0	2.0	556.8	703.4	657.2	814.0	794.0	110.6	136.8
40	1.25	250	902.0	655.0	55.0	101.5	75.3	21.5	1.5	556.8	679.8	633.6	795.0	748.0	115.2	114.4
50	1.25	200	771.0	524.0	55.0	87.6	61.4	21.2	1.2	556.8	665.6	619.4	776.0	693.0	110.4	73.6
100	1.25	100	509.0	262.0	55.0	59.8	33.6	20.7	0.7	556.8	637.3	591.1	606.0	401.0	-31.3	-190.1

Table B10. Predicted average annual relative corn yield for a Tomotley soil with conventional drainage in eastern North Carolina.

Drain Spacing (m)	Drain Depth (m)	Relative Yield, % Good S.D	Relative Yield, % Poor S.D	Actual Yield, kg/ha Good S.D	Actual Yield, kg/ha Poor S.D	Gross Income, $/ha Good S.D	Gross Income, $/ha Poor S.D
10	0.75	83.0	81.5	8300	8150	830.0	815.0
15	0.75	78.5	74.5	7850	7450	785.0	745.0
20	0.75	75.1	66.5	7510	6650	751.0	665.0
25	0.75	71.5	58.6	7150	5860	715.0	586.0
30	0.75	67.5	49.4	6750	4940	675.0	494.0
40	0.75	60.0	39.3	6000	3930	600.0	393.0
50	0.75	56.4	30.7	5640	3070	564.0	307.0
100	0.75	47.3	23.3	4730	2330	473.0	233.0
10	1.00	84.6	84.0	8460	8400	846.0	840.0
15	1.00	84.3	82.9	8430	8290	843.0	829.0
20	1.00	81.8	78.8	8180	7880	818.0	788.0
25	1.00	77.7	71.5	7770	7150	777.0	715.0
30	1.00	74.6	64.1	7460	6410	746.0	641.0
40	1.00	67.6	48.8	6760	4880	676.0	488.0
50	1.00	61.8	38.9	6180	3890	618.0	389.0
100	1.00	49.0	24.8	4900	2480	490.0	248.0
10	1.25	83.0	83.0	8300	8300	830.0	830.0
15	1.25	83.4	83.1	8340	8310	834.0	831.0
20	1.25	83.3	82.4	8330	8240	833.0	824.0
25	1.25	81.9	79.2	8190	7920	819.0	792.0
30	1.25	78.0	72.1	7800	7210	780.0	721.0
40	1.25	72.4	58.3	7240	5830	724.0	583.0
50	1.25	66.0	45.2	6600	4520	660.0	452.0
100	1.25	50.4	25.9	5040	2590	504.0	259.0

Actual Yield is based on a potential yield of 10,000 kg/ha
Gross Income is based on a corn price of $0.10/kg

Table B11. Predicted average annual relative corn yield for a Tomotley soil with controlled drainage in the summer in eastern North Carolina.

Drain Spacing (m)	Drain Depth (m)	Relative Yield, % Good S.D	Relative Yield, % Poor S.D	Actual Yield, kg/ha Good S.D	Actual Yield, kg/ha Poor S.D	Gross Income, $/ha Good S.D	Gross Income, $/ha Poor S.D
10	0.75	81.8	79.4	8180	7940	818.0	794.0
15	0.75	76.4	69.7	7640	6970	764.0	697.0
20	0.75	72.0	60.3	7200	6030	720.0	603.0
25	0.75	68.0	52.3	6800	5230	680.0	523.0
30	0.75	64.4	44.3	6440	4430	644.0	443.0
40	0.75	57.8	35.6	5780	3560	578.0	356.0
50	0.75	54.1	27.9	5410	2790	541.0	279.0
100	0.75	46.2	21.7	4620	2170	462.0	217.0
10	1.00	84.3	82.9	8430	8290	843.0	829.0
15	1.00	81.8	78.0	8180	7800	818.0	780.0
20	1.00	78.0	70.6	7800	7060	780.0	706.0
25	1.00	73.0	61.7	7300	6170	730.0	617.0
30	1.00	69.3	54.0	6930	5400	693.0	540.0
40	1.00	62.4	41.2	6240	4120	624.0	412.0
50	1.00	57.6	34.2	5760	3420	576.0	342.0
100	1.00	46.8	22.3	4680	2230	468.0	223.0
10	1.25	84.4	83.8	8440	8380	844.0	838.0
15	1.25	83.1	81.0	8310	8100	831.0	810.0
20	1.25	81.1	76.3	8110	7630	811.0	763.0
25	1.25	77.7	69.2	7770	6920	777.0	692.0
30	1.25	72.2	60.7	7220	6070	722.0	607.0
40	1.25	66.1	48.1	6610	4810	661.0	481.0
50	1.25	60.1	37.7	6010	3770	601.0	377.0
100	1.25	47.4	22.7	4740	2270	474.0	227.0

Actual Yield is based on a potential yield of 10,000 kg/ha
Gross Income is based on a corn price of $0.10/kg

Table B12. Predicted average annual relative corn yield for a Tomotley soil with controlled drainage in the summer and winter in eastern North Carolina.

Drain Spacing (m)	Drain Depth (m)	Relative Yield, % Good S.D	Relative Yield, % Poor S.D	Actual Yield, kg/ha Good S.D	Actual Yield, kg/ha Poor S.D	Gross Income, $/ha Good S.D	Gross Income, $/ha Poor S.D
10	0.75	80.9	78.6	8090	7860	809.0	786.0
15	0.75	76.3	69.4	7630	6940	763.0	694.0
20	0.75	71.8	60.3	7180	6030	718.0	603.0
25	0.75	67.7	51.6	6770	5160	677.0	516.0
30	0.75	64.0	43.9	6400	4390	640.0	439.0
40	0.75	57.0	35.0	5700	3500	570.0	350.0
50	0.75	53.3	29.0	5330	2900	533.0	290.0
100	0.75	45.4	21.7	4540	2170	454.0	217.0
10	1.00	84.3	82.9	8430	8290	843.0	829.0
15	1.00	81.8	78.0	8180	7800	818.0	780.0
20	1.00	76.9	69.2	7690	6920	769.0	692.0
25	1.00	72.7	61.1	7270	6110	727.0	611.0
30	1.00	69.1	54.0	6910	5400	691.0	540.0
40	1.00	61.9	40.7	6190	4070	619.0	407.0
50	1.00	57.0	31.2	5700	3120	570.0	312.0
100	1.00	46.3	22.1	4630	2210	463.0	221.0
10	1.25	84.4	83.8	8440	8380	844.0	838.0
15	1.25	83.1	81.0	8310	8100	831.0	810.0
20	1.25	81.0	76.3	8100	7630	810.0	763.0
25	1.25	76.0	66.9	7600	6690	760.0	669.0
30	1.25	71.8	60.0	7180	6000	718.0	600.0
40	1.25	65.9	47.7	6590	4770	659.0	477.0
50	1.25	59.7	37.1	5970	3710	597.0	371.0
100	1.25	47.4	22.4	4740	2240	474.0	224.0

Actual Yield is based on a potential yield of 10,000 kg/ha
Gross Income is based on a corn price of $0.10/kg

Table B13. Economic analysis for the production of corn on a Tomotley soil with conventional drainage in eastern North Carolina. Cost and income results are on a $/ha basis.

Drain Spacing (m)	Drain Depth (m)	Drain per ha (m)	Initial Drainage System Cost Good S.D.	Initial Drainage System Cost Poor S.D.	Annual Drainage System Cost Good S.D.	Annual Drainage System Cost Poor S.D.	Annual Drainage Maintenance Cost Good S.	Annual Drainage Maintenance Cost Poor S.D.	Annual Production Cost	Total Annual Cost ($/ha) Good S.D.	Total Annual Cost ($/ha) Poor S.D.	Gross Income ($/ha) Good S.	Gross Income ($/ha) Poor S.D.	Net Profit ($/ha) Good S.	Net Profit ($/ha) Poor S.D.
10	0.75	1000	2867.0	2620.0	304.1	277.9	25.6	5.6	556.8	886.4	840.2	830.0	815.0	-56.4	-25.2
15	0.75	667	1993.7	1746.7	211.5	185.3	23.7	3.7	556.8	792.0	745.8	785.0	745.0	-7.0	-0.8
20	0.75	500	1557.0	1310.0	165.2	139.0	22.8	2.8	556.8	744.7	698.5	751.0	665.0	6.3	-33.5
25	0.75	400	1295.0	1048.0	137.4	111.2	22.2	2.2	556.8	716.4	670.2	715.0	586.0	-1.4	-84.2
30	0.75	333	1120.3	873.3	118.8	92.6	21.9	1.9	556.8	697.5	651.3	675.0	494.0	-22.5	-157.3
40	0.75	250	902.0	655.0	95.7	69.5	21.4	1.4	556.8	673.8	627.6	600.0	393.0	-73.8	-234.6
50	0.75	200	771.0	524.0	81.8	55.6	21.1	1.1	556.8	659.7	613.5	564.0	307.0	-95.7	-306.5
100	0.75	100	509.0	262.0	54.0	27.8	20.6	0.6	556.8	631.3	585.1	473.0	233.0	-158.3	-352.1
10	1.00	1000	2867.0	2620.0	304.1	277.9	25.6	5.6	556.8	886.4	840.2	846.0	840.0	-40.4	-0.2
15	1.00	667	1993.7	1746.7	211.5	185.3	23.7	3.7	556.8	792.0	745.8	843.0	829.0	51.0	83.2
20	1.00	500	1557.0	1310.0	165.2	139.0	22.8	2.8	556.8	744.7	698.5	818.0	788.0	73.3	89.5
25	1.00	400	1295.0	1048.0	137.4	111.2	22.2	2.2	556.8	716.4	670.2	777.0	715.0	60.6	44.8
30	1.00	333	1120.3	873.3	118.8	92.6	21.9	1.9	556.8	697.5	651.3	746.0	641.0	48.5	-10.3
40	1.00	250	902.0	655.0	95.7	69.5	21.4	1.4	556.8	673.8	627.6	676.0	488.0	2.2	-139.6
50	1.00	200	771.0	524.0	81.8	55.6	21.1	1.1	556.8	659.7	613.5	618.0	389.0	-41.7	-224.5
100	1.00	100	509.0	262.0	54.0	27.8	20.6	0.6	556.8	631.3	585.1	490.0	248.0	-141.3	-337.1
					0.0										
10	1.25	1000	2867.0	2620.0	304.1	277.9	25.6	5.6	556.8	886.4	840.2	830.0	830.0	-56.4	-10.2
15	1.25	667	1993.7	1746.7	211.5	185.3	23.7	3.7	556.8	792.0	745.8	834.0	831.0	42.0	85.2
20	1.25	500	1557.0	1310.0	165.2	139.0	22.8	2.8	556.8	744.7	698.5	833.0	824.0	88.3	125.5
25	1.25	400	1295.0	1048.0	137.4	111.2	22.2	2.2	556.8	716.4	670.2	819.0	792.0	102.6	121.8
30	1.25	333	1120.3	873.3	118.8	92.6	21.9	1.9	556.8	697.5	651.3	780.0	721.0	82.5	69.7
40	1.25	250	902.0	655.0	95.7	69.5	21.4	1.4	556.8	673.8	627.6	724.0	583.0	50.2	-44.6
50	1.25	200	771.0	524.0	81.8	55.6	21.1	1.1	556.8	659.7	613.5	660.0	452.0	0.3	-161.5
100	1.25	100	509.0	262.0	54.0	27.8	20.6	0.6	556.8	631.3	585.1	504.0	259.0	-127.3	-326.1

Table B14. Economic analysis for the production of corn on a Tomotley soil with controlled drainage in the summer in eastern North Carolina. Cost and income results are on a $/ha basis.

Drain Spacing (m)	Drain Depth (m)	Drain per ha (m)	Initial Drainage System Cost Good S.D.	Initial Drainage System Cost Poor S.D.	Control Structure Cost	Annual Drainage System Cost Good S.D.	Annual Drainage System Cost Poor S.D.	Annual Drainage Maintenance Cost Good S.D.	Annual Drainage Maintenance Cost Poor S.D.	Annual Production Cost	Total Annual Cost ($/ha) Good S.D.	Total Annual Cost ($/ha) Poor S.D.	Gross Income ($/ha) Good S.D.	Gross Income ($/ha) Poor S.D.	Net Profit ($/ha) Good S.D.	Net Profit ($/ha) Poor S.D.
10	0.75	1000	2867.0	2620.0	82.5	312.9	286.7	25.7	5.7	556.8	895.4	849.2	818.0	794.0	-77.4	-55.2
15	0.75	667	1993.7	1746.7	82.5	220.2	194.0	23.9	3.9	556.8	800.9	754.7	764.0	697.0	-36.9	-57.7
20	0.75	500	1557.0	1310.0	82.5	173.9	147.7	23.0	3.0	556.8	753.6	707.4	720.0	603.0	-33.6	-104.4
25	0.75	400	1295.0	1048.0	82.5	146.1	119.9	22.4	2.4	556.8	725.3	679.1	680.0	523.0	-45.3	-156.1
30	0.75	333	1120.3	873.3	82.5	127.6	101.4	22.0	2.0	556.8	706.4	660.2	644.0	443.0	-62.4	-217.2
40	0.75	250	902.0	655.0	82.5	104.4	78.2	21.6	1.6	556.8	682.8	636.6	578.0	356.0	-104.8	-280.6
50	0.75	200	771.0	524.0	82.5	90.5	64.3	21.3	1.3	556.8	668.6	622.4	541.0	279.0	-127.6	-343.4
100	0.75	100	509.0	262.0	82.5	62.7	36.5	20.7	0.7	556.8	640.2	594.0	462.0	217.0	-178.2	-377.0
10	1.00	1000	2867.0	2620.0	82.5	312.9	286.7	25.7	5.7	556.8	895.4	849.2	843.0	829.0	-52.4	-20.2
15	1.00	667	1993.7	1746.7	82.5	220.2	194.0	23.9	3.9	556.8	800.9	754.7	818.0	780.0	17.1	25.3
20	1.00	500	1557.0	1310.0	82.5	173.9	147.7	23.0	3.0	556.8	753.6	707.4	780.0	706.0	26.4	-1.4
25	1.00	400	1295.0	1048.0	82.5	146.1	119.9	22.4	2.4	556.8	725.3	679.1	730.0	617.0	4.7	-62.1
30	1.00	333	1120.3	873.3	82.5	127.6	101.4	22.0	2.0	556.8	706.4	660.2	693.0	540.0	-13.4	-120.2
40	1.00	250	902.0	655.0	82.5	104.4	78.2	21.6	1.6	556.8	682.8	636.6	624.0	412.0	-58.8	-224.6
50	1.00	200	771.0	524.0	82.5	90.5	64.3	21.3	1.3	556.8	668.6	622.4	576.0	342.0	-92.6	-280.4
100	1.00	100	509.0	262.0	82.5	62.7	36.5	20.7	0.7	556.8	640.2	594.0	468.0	223.0	-172.2	-371.0
10	1.25	1000	2867.0	2620.0	82.5	312.9	286.7	25.7	5.7	556.8	895.4	849.2	844.0	838.0	-51.4	-11.2
15	1.25	667	1993.7	1746.7	82.5	220.2	194.0	23.9	3.9	556.8	800.9	754.7	831.0	810.0	30.1	55.3
20	1.25	500	1557.0	1310.0	82.5	173.9	147.7	23.0	3.0	556.8	753.6	707.4	811.0	763.0	57.4	55.6
25	1.25	400	1295.0	1048.0	82.5	146.1	119.9	22.4	2.4	556.8	725.3	679.1	777.0	692.0	51.7	12.9
30	1.25	333	1120.3	873.3	82.5	127.6	101.4	22.0	2.0	556.8	706.4	660.2	722.0	607.0	15.6	-53.2
40	1.25	250	902.0	655.0	82.5	104.4	78.2	21.6	1.6	556.8	682.8	636.6	661.0	481.0	-21.8	-155.6
50	1.25	200	771.0	524.0	82.5	90.5	64.3	21.3	1.3	556.8	668.6	622.4	601.0	377.0	-67.6	-245.4
100	1.25	100	509.0	262.0	82.5	62.7	36.5	20.7	0.7	556.8	640.2	594.0	474.0	227.0	-166.2	-367.0

Table B15. Economic analysis for the production of corn on a Tomotley soil with controlled drainage in the summer and winter in eastern North Carolina. Cost and income results are on a $/ha basis.

Drain Spacing (m)	Drain Depth (m)	Drain per ha (m)	Initial Drainage System Cost Good S.D.	Initial Drainage System Cost Poor S.D.	Control Structure Cost	Annual Drainage System Cost Good S.D.	Annual Drainage System Cost Poor S.D.	Annual Drainage Maintenance Cost Good S.D.	Annual Drainage Maintenance Cost Poor S.D.	Annual Production Cost	Total Annual Cost ($/ha) Good S.D.	Total Annual Cost ($/ha) Poor S.D.	Gross Income ($/ha) Good S.D.	Gross Income ($/ha) Poor S.D.	Net Profit ($/ha) Good S.D.	Net Profit ($/ha) Poor S.D.
10	0.75	1000	2867.0	2620.0	82.5	312.9	286.7	25.7	5.7	556.8	895.4	849.2	809.0	786.0	-86.4	-63.2
15	0.75	667	1993.7	1746.7	82.5	220.2	194.0	23.9	3.9	556.8	800.9	754.7	763.0	694.0	-37.9	-60.7
20	0.75	500	1557.0	1310.0	82.5	173.9	147.7	23.0	3.0	556.8	753.6	707.4	718.0	603.0	-35.6	-104.4
25	0.75	400	1295.0	1048.0	82.5	146.1	119.9	22.4	2.4	556.8	725.3	679.1	677.0	516.0	-48.3	-163.1
30	0.75	333	1120.3	873.3	82.5	127.6	101.4	22.0	2.0	556.8	706.4	660.2	640.0	439.0	-66.4	-221.2
40	0.75	250	902.0	655.0	82.5	104.4	78.2	21.6	1.6	556.8	682.8	636.6	570.0	350.0	-112.8	-286.6
50	0.75	200	771.0	524.0	82.5	90.5	64.3	21.3	1.3	556.8	668.6	622.4	533.0	290.0	-135.6	-332.4
100	0.75	100	509.0	262.0	82.5	62.7	36.5	20.7	0.7	556.8	640.2	594.0	454.0	217.0	-186.2	-377.0
10	1.00	1000	2867.0	2620.0	82.5	312.9	286.7	25.7	5.7	556.8	895.4	849.2	843.0	829.0	-52.4	-20.2
15	1.00	667	1993.7	1746.7	82.5	220.2	194.0	23.9	3.9	556.8	800.9	754.7	818.0	780.0	17.1	25.3
20	1.00	500	1557.0	1310.0	82.5	173.9	147.7	23.0	3.0	556.8	753.6	707.4	769.0	692.0	15.4	-15.4
25	1.00	400	1295.0	1048.0	82.5	146.1	119.9	22.4	2.4	556.8	725.3	679.1	727.0	611.0	1.7	-68.1
30	1.00	333	1120.3	873.3	82.5	127.6	101.4	22.0	2.0	556.8	706.4	660.2	691.0	540.0	-15.4	-120.2
40	1.00	250	902.0	655.0	82.5	104.4	78.2	21.6	1.6	556.8	682.8	636.6	619.0	407.0	-63.8	-229.6
50	1.00	200	771.0	524.0	82.5	90.5	64.3	21.3	1.3	556.8	668.6	622.4	570.0	312.0	-98.6	-310.4
100	1.00	100	509.0	262.0	82.5	62.7	36.5	20.7	0.7	556.8	640.2	594.0	463.0	221.0	-177.2	-373.0
10	1.25	1000	2867.0	2620.0	82.5	312.9	286.7	25.7	5.7	556.8	895.4	849.2	844.0	838.0	-51.4	-11.2
15	1.25	667	1993.7	1746.7	82.5	220.2	194.0	23.9	3.9	556.8	800.9	754.7	831.0	810.0	30.1	55.3
20	1.25	500	1557.0	1310.0	82.5	173.9	147.7	23.0	3.0	556.8	753.6	707.4	810.0	763.0	56.4	55.6
25	1.25	400	1295.0	1048.0	82.5	146.1	119.9	22.4	2.4	556.8	725.3	679.1	760.0	669.0	34.7	-10.1
30	1.25	333	1120.3	873.3	82.5	127.6	101.4	22.0	2.0	556.8	706.4	660.2	718.0	600.0	11.6	-60.2
40	1.25	250	902.0	655.0	82.5	104.4	78.2	21.6	1.6	556.8	682.8	636.6	659.0	477.0	-23.8	-159.6
50	1.25	200	771.0	524.0	82.5	90.5	64.3	21.3	1.3	556.8	668.6	622.4	597.0	371.0	-71.6	-251.4
100	1.25	100	509.0	262.0	82.5	62.7	36.5	20.7	0.7	556.8	640.2	594.0	474.0	224.0	-166.2	-370.0

Average annual values of hydrologic components predicted by DRAINMOD for a Portsmouth sandy loam at Plymouth, NC. Values are averages predicted for a 20-yr period (1971-1990) in which the average annual rainfall = 132.1 cm.

Drain Spacing (m)	Drain Depth (m)	Depressional Storage = 0.5 cm R.Yld (%)	ET (cm)	Drn (cm)	Rnf (cm)	Depressional Storage = 2.5 cm R.Yld (%)	ET (cm)	Drn (cm)	Rnf (cm)
					Conventional Drainage				
10	0.75	83.5	75.7	52.3	4.4	82.3	75.8	54.7	1.9
15	0.75	83.4	76.4	51.1	4.9	82.0	76.5	53.8	2.1
20	0.75	82.8	77.2	49.6	5.6	81.4	77.3	52.8	2.3
25	0.75	81.6	78.0	47.9	6.4	79.9	78.2	51.7	2.5
30	0.75	79.8	78.8	46.2	7.4	76.8	79.0	50.6	2.8
40	0.75	75.1	80.4	42.8	9.2	68.7	80.7	48.3	3.4
50	0.75	71.7	81.6	39.9	10.8	61.0	82.2	46.2	3.9
100	0.75	59.2	86.2	27.6	18.5	33.4	86.5	37.7	8.1
10	1.00	81.4	69.9	60.0	2.6	81.0	70.0	61.5	1.0
15	1.00	81.6	70.3	59.2	2.9	81.2	70.5	60.8	1.2
20	1.00	81.8	71.0	58.2	3.3	81.2	71.1	60.0	1.3
25	1.00	82.1	71.8	57.0	3.7	81.1	71.8	59.1	1.5
30	1.00	82.0	72.6	55.5	4.3	80.8	72.8	58.0	1.7
40	1.00	80.9	74.6	52.1	5.7	78.3	74.8	55.4	2.3
50	1.00	77.4	76.6	48.6	7.3	72.7	77.0	52.7	2.8
100	1.00	61.8	82.6	34.4	15.3	42.2	84.2	42.4	5.8
10	1.25	79.9	67.2	63.9	1.5	80.0	67.2	64.8	0.6
15	1.25	80.0	67.3	63.6	1.7	80.0	67.4	64.6	0.6
20	1.25	80.1	67.5	63.2	1.9	80.0	67.6	64.3	0.7
25	1.25	80.2	67.9	62.5	2.2	80.1	68.0	63.8	0.8
30	1.25	80.4	68.4	61.6	2.5	80.2	68.5	63.1	0.9
40	1.25	80.6	69.9	59.2	3.5	79.7	70.0	61.2	1.3
50	1.25	80.3	71.8	56.0	4.7	78.0	72.1	58.6	1.9
100	1.25	69.8	82.1	39.0	11.4	49.8	81.7	46.0	4.7
					Controlled Drainage in Summer				
10	0.75	84.0	76.6	50.9	4.9	82.5	76.7	53.6	2.1
15	0.75	83.1	77.2	49.8	5.4	81.5	77.3	52.8	2.3
20	0.75	81.8	78.0	48.3	6.1	79.9	78.1	51.8	2.5
25	0.75	80.0	78.8	46.6	7.0	76.7	78.9	50.8	2.7
30	0.75	77.7	79.5	44.9	8.0	72.2	79.7	49.6	3.0
40	0.75	72.3	81.0	41.6	9.8	62.6	81.3	47.4	3.6
50	0.75	68.3	82.1	38.7	11.6	54.6	82.8	45.4	4.2
100	0.75	54.6	85.0	27.4	19.9	31.0	86.8	37.1	8.5
10	1.00	84.6	71.5	57.7	3.2	83.6	71.6	59.6	1.3
15	1.00	84.0	71.9	57.0	3.5	82.9	72.0	59.0	1.4
20	1.00	83.2	72.5	56.0	3.9	81.9	72.6	58.3	1.6
25	1.00	82.2	73.2	54.8	4.5	80.0	73.3	57.3	1.8
30	1.00	80.6	74.3	52.9	5.3	76.7	74.4	55.9	2.1
40	1.00	78.1	75.8	49.9	6.7	71.3	76.1	53.8	2.6
50	1.00	73.7	77.7	46.3	8.5	63.7	78.1	51.0	3.3
100	1.00	57.5	83.1	32.5	16.7	36.5	84.8	40.9	6.7
10	1.25	83.5	68.8	61.7	2.1	83.1	68.9	63.0	0.8
15	1.25	83.3	68.9	61.3	2.3	82.8	69.0	62.7	0.9
20	1.25	82.8	69.2	60.9	2.5	82.2	69.2	62.4	1.0
25	1.25	82.2	69.5	60.1	2.9	81.0	69.6	61.9	1.1
30	1.25	81.4	70.0	59.1	3.4	79.4	70.1	61.2	1.3
40	1.25	79.5	71.5	56.6	4.5	74.9	71.6	59.1	1.8
50	1.25	77.8	73.4	53.1	6.0	69.6	73.7	56.4	2.5
100	1.25	61.0	81.5	37.3	13.7	41.5	82.8	43.9	5.8
					Controlled Drainage in Summer and Winter				
10	0.75	84.0	79.0	47.1	6.2	82.5	79.1	51.0	2.2
15	0.75	83.1	79.4	45.9	7.1	81.5	79.5	50.4	2.4
20	0.75	81.8	80.0	44.2	8.2	79.9	80.1	49.6	2.6
25	0.75	79.7	80.6	42.3	9.4	76.4	80.8	48.5	3.0
30	0.75	76.5	81.2	40.6	10.5	71.1	81.5	47.4	3.4
40	0.75	72.2	82.4	37.4	12.6	62.2	82.8	45.5	4.0
50	0.75	68.4	83.3	34.0	15.1	54.4	84.0	43.2	5.1
100	0.75	53.9	85.5	22.1	24.7	29.1	87.2	34.5	10.6
10	1.00	84.6	75.3	52.7	4.4	83.6	75.3	55.7	1.4
15	1.00	84.0	75.5	51.7	5.1	82.9	75.6	55.3	1.5
20	1.00	83.2	76.0	50.3	6.1	81.9	76.1	54.6	1.7
25	1.00	82.2	76.5	48.6	7.2	80.0	76.6	53.6	2.1
30	1.00	80.9	77.2	47.0	8.1	77.3	77.4	52.6	2.4
40	1.00	77.9	78.7	43.0	10.6	70.8	78.8	50.3	3.2
50	1.00	72.7	80.1	38.8	13.3	62.3	80.7	47.4	4.2
100	1.00	57.5	84.2	24.6	23.5	35.9	86.0	36.4	9.9
10	1.25	83.5	72.9	56.5	3.1	83.1	72.9	58.7	0.8
15	1.25	83.3	73.0	55.8	3.6	82.8	73.0	58.5	0.9
20	1.25	82.8	73.2	54.8	4.3	82.2	73.3	58.1	1.1
25	1.25	82.2	73.6	53.5	5.3	81.0	73.7	57.3	1.4
30	1.25	81.4	74.1	52.0	6.3	79.4	74.2	56.5	1.6
40	1.25	79.5	75.3	48.2	8.9	74.8	75.6	54.3	2.4
50	1.25	77.6	76.9	43.9	11.5	69.3	77.4	51.4	3.5
100	1.25	60.6	83.1	27.0	22.2	40.1	84.5	38.1	9.7

Average annual values of hydrologic components predicted by DRAINMOD for a Tomotley sandy loam at Plymouth, NC. Values are averages predicted for a 20-yr period (1971-1990) in which the average annual rainfall = 132.1 cm.

Drain Spacing (m)	Drain Depth (m)	Depressional Storage = 0.5 cm R.Yld (%)	ET (cm)	Drn (cm)	Rnf (cm)	Depressional Storage = 2.5 cm R.Yld (%)	ET (cm)	Drn (cm)	Rnf (cm)
					Conventional Drainage				
10	0.75	83.0	78.0	47.9	6.5	81.5	78.1	51.8	2.5
15	0.75	78.5	79.6	44.1	8.6	74.5	79.9	49.4	3.1
20	0.75	75.1	81.1	40.8	10.5	66.5	81.6	47.1	3.7
25	0.75	71.5	82.2	37.1	13.0	58.6	83.1	44.8	4.5
30	0.75	67.5	83.1	33.6	15.6	49.4	84.1	42.8	5.5
40	0.75	60.0	84.3	28.1	20.0	39.3	85.9	38.5	7.9
50	0.75	56.4	85.0	23.8	23.5	30.7	86.8	35.3	10.2
100	0.75	47.3	86.6	13.2	32.5	23.3	89.5	25.5	17.3
10	1.00	84.6	74.0	55.2	3.2	84.0	74.1	57.1	1.3
15	1.00	84.3	75.2	52.8	4.5	82.9	75.3	55.4	1.8
20	1.00	81.8	76.6	49.6	6.2	78.8	76.9	53.2	2.4
25	1.00	77.7	78.3	46.1	8.0	71.5	78.7	50.8	3.0
30	1.00	74.6	79.7	42.3	10.4	64.1	80.5	48.2	3.7
40	1.00	67.6	81.9	35.4	15.1	48.8	83.1	43.4	5.9
50	1.00	61.8	83.3	29.8	19.2	38.9	85.0	39.6	7.8
100	1.00	49.0	85.9	16.0	30.4	24.8	88.7	27.9	15.7
10	1.25	83.0	71.1	59.8	1.7	83.0	71.2	60.8	0.6
15	1.25	83.4	72.1	57.9	2.5	83.1	72.1	57.9	2.5
20	1.25	83.3	73.5	55.5	3.6	82.4	73.6	57.6	1.4
25	1.25	81.9	75.0	52.3	5.2	79.2	75.3	55.3	1.9
30	1.25	78.0	76.8	48.8	6.9	72.1	77.3	52.7	2.6
40	1.25	72.4	79.8	41.1	11.5	58.3	80.9	47.2	4.4
50	1.25	66.0	81.8	34.6	16.0	45.2	83.2	42.8	6.4
100	1.25	50.4	85.4	18.2	28.8	25.9	88.0	29.9	14.4
					Controlled Drainage in Summer				
10	0.75	81.8	78.7	46.5	7.2	79.4	78.8	50.8	2.8
15	0.75	76.4	80.3	42.7	9.4	69.7	80.6	48.5	3.3
20	0.75	72.0	81.6	39.3	11.5	60.3	82.1	46.2	4.0
25	0.75	68.0	82.6	35.7	14.0	52.3	83.5	43.9	4.9
30	0.75	64.4	83.4	32.4	16.6	44.3	84.5	41.9	6.0
40	0.75	57.8	84.5	27.1	20.7	35.6	86.2	37.9	8.2
50	0.75	54.1	85.2	23.1	24.1	27.9	87.1	34.6	10.6
100	0.75	46.2	86.6	12.9	32.8	21.7	89.6	24.9	17.8
10	1.00	84.3	75.1	53.4	4.0	82.9	75.2	55.7	1.6
15	1.00	81.8	76.2	50.7	5.6	78.0	76.3	54.0	2.2
20	1.00	78.0	77.5	47.4	7.5	70.6	77.8	51.7	2.9
25	1.00	73.0	79.2	43.7	9.5	61.7	79.6	49.2	3.6
30	1.00	69.3	80.4	40.0	12.0	54.0	81.3	46.7	4.4
40	1.00	62.4	82.4	33.4	16.6	41.2	83.7	41.8	6.8
50	1.00	57.6	83.7	28.1	20.6	34.2	85.5	38.2	8.7
100	1.00	46.8	86.1	15.2	31.1	22.3	89.0	26.8	16.5
10	1.25	84.4	72.4	57.8	2.3	83.8	72.5	59.3	0.8
15	1.25	83.1	73.3	55.7	3.6	81.0	73.4	57.9	1.3
20	1.25	81.1	74.6	53.0	5.0	76.3	74.7	55.9	2.0
25	1.25	77.7	76.0	49.6	6.8	69.2	76.4	53.5	2.7
30	1.25	72.2	77.9	45.8	8.8	60.7	78.5	50.6	3.5
40	1.25	66.1	80.7	38.3	13.5	48.1	81.9	45.0	5.6
50	1.25	60.1	82.5	32.1	17.9	37.7	84.0	40.8	7.6
100	1.25	47.4	85.6	16.9	29.8	22.7	88.4	28.4	15.5
					Controlled Drainage in Summer and Winter				
10	0.75	80.9	81.1	41.6	9.6	78.6	81.2	48.1	3.0
15	0.75	76.3	82.2	37.2	12.8	69.4	82.5	45.9	3.8
20	0.75	71.8	83.2	33.1	16.0	60.3	83.8	43.6	4.9
25	0.75	67.7	84.0	29.5	18.8	51.6	84.8	41.1	6.4
30	0.75	64.0	84.4	26.5	21.4	43.9	85.5	38.9	7.9
40	0.75	57.0	85.2	21.8	25.4	35.0	86.9	34.5	10.9
50	0.75	53.3	85.6	18.4	28.3	29.0	87.7	31.0	13.6
100	0.75	45.4	86.7	10.0	35.5	21.7	89.8	22.0	20.4
10	1.00	84.3	79.3	45.2	7.8	82.9	78.3	52.3	1.8
15	1.00	81.8	80.1	40.7	11.5	78.0	79.2	50.3	2.8
20	1.00	76.9	81.1	36.4	14.9	69.2	80.5	47.8	4.0
25	1.00	72.7	82.2	32.5	17.6	61.1	82.0	45.0	5.3
30	1.00	69.1	82.4	31.0	18.9	54.0	82.7	43.2	6.3
40	1.00	61.9	83.8	25.0	23.5	40.7	85.1	36.9	10.2
50	1.00	57.0	84.7	20.7	26.9	31.2	86.4	33.3	12.6
100	1.00	46.3	86.4	10.9	35.0	22.1	89.4	22.3	20.6
10	1.25	84.4	75.9	52.1	4.4	83.8	75.9	55.5	0.9
15	1.25	83.1	76.7	47.8	7.9	81.0	76.8	53.6	2.0
20	1.25	81.0	77.7	43.4	11.2	76.3	78.0	51.2	3.1
25	1.25	76.0	79.0	39.2	14.2	66.9	79.5	48.3	4.6
30	1.25	71.8	80.4	35.0	16.9	60.0	81.2	44.9	6.2
40	1.25	65.9	82.6	28.0	21.8	47.7	83.9	39.0	9.4
50	1.25	59.7	83.8	22.9	25.6	37.1	85.4	34.7	12.2
100	1.25	47.4	86.2	11.6	34.5	22.4	89.0	22.8	20.4

Predicted annual nitrogen budget for corn production on a Portsmouth sandy loam with a depressional storage of 0.5 cm at Plymouth, NC. Values are averages for a 20-yr period (1971-90).

Drain Spacing (m)	Drain Depth (m)	Fertilizer Input (kg/ha)	Net Mineralization (kg/ha)	Rainfall Deposition (kg/ha)	Plant Uptake (kg/ha)	Denitrification (kg/ha)	Drainage Loss (kg/ha)	Runoff Loss (kg/ha)
Conventional Drainage								
10	0.75	150.0	67.7	7.8	108.0	82.8	18.2	0.4
15	0.75	150.0	67.6	7.8	108.4	81.9	16.5	0.4
20	0.75	150.0	67.6	7.7	108.6	81.6	14.6	0.5
25	0.75	150.0	67.5	7.6	109.0	81.3	12.7	0.5
30	0.75	150.0	67.3	7.6	108.7	82.3	10.9	0.6
40	0.75	150.0	67.2	7.4	103.5	88.5	8.8	0.8
50	0.75	150.0	67.1	7.2	99.5	94.3	7.3	1.0
100	0.75	150.0	67.3	6.5	80.9	115.0	3.9	1.9
10	1.00	150.0	69.8	8.1	101.4	78.1	36.7	0.2
15	1.00	150.0	69.4	8.0	102.3	79.1	33.7	0.2
20	1.00	150.0	69.1	8.0	103.6	79.8	29.6	0.3
25	1.00	150.0	68.9	8.0	104.9	80.7	25.4	0.3
30	1.00	150.0	68.6	7.9	105.8	82.3	21.5	0.3
40	1.00	150.0	68.2	7.7	106.5	85.5	15.2	0.5
50	1.00	150.0	68.0	7.6	105.1	90.2	11.2	0.6
100	1.00	150.0	67.0	6.8	85.6	114.1	5.0	1.5
10	1.25	150.0	73.0	8.2	98.2	62.5	66.8	0.1
15	1.25	150.0	72.6	8.2	98.2	64.4	61.3	0.1
20	1.25	150.0	72.2	8.2	98.6	66.8	55.6	0.1
25	1.25	150.0	71.8	8.1	99.3	70.1	49.5	0.2
30	1.25	150.0	71.3	8.1	99.8	73.9	43.1	0.2
40	1.25	150.0	70.4	8.0	102.2	80.8	30.8	0.3
50	1.25	150.0	69.5	7.9	104.1	86.3	21.0	0.4
100	1.25	150.0	68.2	7.2	97.4	104.5	6.1	1.1
Controlled Drainage in Summer								
10	0.75	150.0	68.5	7.8	112.2	81.4	16.0	0.4
15	0.75	150.0	68.3	7.7	111.0	81.8	14.7	0.4
20	0.75	150.0	68.2	7.7	109.7	82.6	13.1	0.5
25	0.75	150.0	68.1	7.6	108.6	83.4	11.5	0.6
30	0.75	150.0	67.9	7.5	107.0	85.2	10.0	0.7
40	0.75	150.0	67.8	7.3	100.2	92.3	8.1	0.9
50	0.75	150.0	67.5	7.2	95.3	98.8	6.9	1.2
100	0.75	150.0	67.1	6.4	75.7	122.1	3.8	2.1
10	1.00	150.0	70.6	8.0	111.3	77.1	27.9	0.3
15	1.00	150.0	70.4	8.0	111.4	78.3	25.6	0.3
20	1.00	150.0	70.1	7.9	110.4	80.1	22.8	0.3
25	1.00	150.0	69.9	7.9	109.8	82.1	19.8	0.4
30	1.00	150.0	69.5	7.8	108.4	85.3	16.2	0.5
40	1.00	150.0	69.1	7.6	105.7	89.7	12.5	0.7
50	1.00	150.0	68.8	7.5	102.3	95.2	9.5	0.8
100	1.00	150.0	67.3	6.7	79.7	120.5	4.5	1.9
10	1.25	150.0	73.4	8.1	109.8	67.3	48.8	0.2
15	1.25	150.0	73.2	8.1	109.4	69.1	44.9	0.2
20	1.25	150.0	72.8	8.1	108.7	71.5	40.4	0.2
25	1.25	150.0	72.5	8.0	108.2	74.9	35.8	0.2
30	1.25	150.0	72.1	8.0	107.5	78.5	31.1	0.3
40	1.25	150.0	71.4	7.9	106.2	85.6	22.5	0.4
50	1.25	150.0	70.4	7.7	105.2	91.2	15.7	0.6
100	1.25	150.0	67.9	7.0	85.3	116.3	5.3	1.6
Controlled Drainage in Summer and Winter								
10	0.75	150.0	67.4	7.6	112.1	85.2	11.4	0.5
15	0.75	150.0	67.3	7.6	110.9	85.4	10.6	0.6
20	0.75	150.0	67.3	7.5	109.5	85.9	9.7	0.7
25	0.75	150.0	67.2	7.4	108.7	86.1	8.6	0.8
30	0.75	150.0	67.2	7.3	105.3	88.9	7.8	0.9
40	0.75	150.0	67.1	7.1	99.8	94.3	6.5	1.2
50	0.75	150.0	66.9	6.9	95.0	100.4	5.7	1.5
100	1.00	150.0	66.9	6.0	74.7	123.1	3.2	2.5
10	1.00	150.0	68.8	7.8	111.2	86.8	15.0	0.3
15	1.00	150.0	68.6	7.8	111.3	87.6	13.7	0.4
20	1.00	150.0	68.4	7.7	110.3	88.6	12.4	0.5
25	1.00	150.0	68.2	7.6	109.6	89.4	11.0	0.6
30	1.00	150.0	68.1	7.5	108.4	91.1	9.8	0.7
40	1.00	150.0	67.7	7.3	105.5	94.1	7.7	1.0
50	1.00	150.0	67.6	7.0	100.7	99.8	6.3	1.3
100	1.00	150.0	66.9	6.1	79.8	120.8	3.5	2.5
10	1.25	150.0	70.9	8.0	109.6	88.6	21.3	0.2
15	1.25	150.0	70.7	7.9	109.4	89.4	19.2	0.3
20	1.25	150.0	70.4	7.9	108.6	90.6	17.1	0.3
25	1.25	150.0	70.1	7.8	107.7	91.9	15.1	0.4
30	1.25	150.0	69.8	7.7	107.4	93.1	13.2	0.5
40	1.25	150.0	69.3	7.5	106.1	95.7	10.2	0.7
50	1.25	150.0	68.6	7.2	106.0	97.1	7.7	1.0
100	1.25	150.0	67.2	6.2	84.5	117.6	3.7	2.2

Predicted annual nitrogen budget for corn production on a Portsmouth sandy loam with a depressional storage of 2.5 cm at Plymouth, NC. Values are averages for a 20-yr period (1971-90).

Drain Spacing (m)	Drain Depth (m)	Fertilizer Input (kg/ha)	Net Mineralization (kg/ha)	Rainfall Deposition (kg/ha)	Plant Uptake (kg/ha)	Denitrification (kg/ha)	Drainage Loss (kg/ha)	Runoff Loss (kg/ha)
			Conventional Drainage					
10	0.75	150.0	67.7	8.0	104.9	84.1	19.5	0.2
15	0.75	150.0	67.6	8.0	105.2	83.6	17.8	0.2
20	0.75	150.0	67.6	8.0	105.0	83.8	16.1	0.2
25	0.75	150.0	67.5	7.9	104.9	84.1	14.1	0.2
30	0.75	150.0	67.3	7.9	102.6	87.0	12.4	0.2
40	0.75	150.0	67.3	7.8	93.5	97.7	10.0	0.3
50	0.75	150.0	67.0	7.7	82.7	110.3	8.5	0.3
100	0.75	150.0	67.1	6.9	46.0	152.9	4.9	0.7
10	1.00	150.0	69.8	8.2	99.1	78.9	37.7	0.1
15	1.00	150.0	69.4	8.2	100.0	79.9	34.7	0.1
20	1.00	150.0	69.1	8.1	100.9	80.8	30.7	0.1
25	1.00	150.0	68.9	8.1	102.0	82.1	26.6	0.1
30	1.00	150.0	68.6	8.1	102.4	84.1	22.8	0.1
40	1.00	150.0	68.1	8.0	101.6	89.2	16.3	0.2
50	1.00	150.0	68.0	7.9	97.5	96.8	12.2	0.2
100	1.00	150.0	67.2	7.2	58.2	142.7	5.9	0.5
10	1.25	150.0	73.1	8.3	97.0	62.9	66.5	0.0
15	1.25	150.0	72.6	8.3	96.9	64.8	61.9	0.0
20	1.25	150.0	72.2	8.3	97.2	67.2	56.3	0.1
25	1.25	150.0	71.8	8.2	97.7	70.6	50.2	0.1
30	1.25	150.0	71.3	8.2	98.1	74.5	43.9	0.1
40	1.25	150.0	70.4	8.1	99.8	82.2	31.4	0.1
50	1.25	150.0	69.4	8.1	100.9	88.6	21.5	0.1
100	1.25	150.0	67.6	7.4	68.2	133.8	7.3	0.4
			Controlled Drainage in Summer					
10	0.75	150.0	68.5	8.0	108.4	83.4	17.2	0.2
15	0.75	150.0	68.3	8.0	107.0	84.2	16.0	0.2
20	0.75	150.0	68.2	7.9	105.3	85.6	14.6	0.2
25	0.75	150.0	68.1	7.9	102.5	88.1	12.9	0.2
30	0.75	150.0	67.9	7.8	97.9	93.0	11.5	0.2
40	0.75	150.0	67.8	7.7	85.1	106.3	9.5	0.3
50	0.75	150.0	67.5	7.6	73.9	119.3	8.1	0.3
100	0.75	150.0	67.2	6.8	42.8	156.6	4.6	0.7
10	1.00	150.0	70.6	8.1	108.4	78.5	28.9	0.1
15	1.00	150.0	70.3	8.1	108.2	80.0	26.7	0.1
20	1.00	150.0	70.1	8.1	106.8	82.2	24.0	0.1
25	1.00	150.0	69.9	8.1	104.9	85.3	21.1	0.1
30	1.00	150.0	69.5	8.0	101.9	90.0	17.5	0.2
40	1.00	150.0	69.1	7.9	96.2	98.1	13.8	0.2
50	1.00	150.0	68.9	7.8	87.7	109.1	10.8	0.3
100	1.00	150.0	67.6	7.1	50.5	151.6	5.4	0.6
10	1.25	150.0	73.4	8.2	108.2	68.1	49.5	0.1
15	1.25	150.0	73.2	8.2	107.4	70.1	45.6	0.1
20	1.25	150.0	72.8	8.2	106.4	72.9	41.1	0.1
25	1.25	150.0	72.5	8.2	105.2	76.9	36.4	0.1
30	1.25	150.0	72.1	8.1	103.5	81.3	31.9	0.1
40	1.25	150.0	71.4	8.1	99.6	91.1	23.4	0.1
50	1.25	150.0	70.5	8.0	94.8	100.7	16.7	0.2
100	1.25	150.0	68.0	7.3	58.3	144.6	6.3	0.5
			Controlled Drainage in Summer and Winter					
10	0.75	150.0	67.4	7.9	108.3	87.2	12.9	0.2
15	0.75	150.0	67.3	7.9	106.8	87.8	12.2	0.2
20	0.75	150.0	67.3	7.9	105.2	88.9	11.4	0.2
25	0.75	150.0	67.2	7.8	102.5	90.9	10.3	0.2
30	0.75	150.0	67.1	7.8	96.7	96.3	9.4	0.3
40	0.75	150.0	67.0	7.6	84.6	108.9	8.1	0.3
50	0.75	150.0	66.9	7.4	73.8	121.6	7.1	0.4
100	0.75	150.0	67.0	6.5	39.9	160.0	4.4	0.9
10	1.00	150.0	68.8	8.1	108.4	88.2	16.4	0.1
15	1.00	150.0	68.5	8.0	108.1	89.2	15.3	0.1
20	1.00	150.0	68.4	8.0	106.7	90.5	14.2	0.1
25	1.00	150.0	68.2	8.0	104.8	92.4	12.7	0.2
30	1.00	150.0	68.0	7.9	102.2	95.5	11.4	0.2
40	1.00	150.0	67.7	7.8	95.9	102.8	9.3	0.3
50	1.00	150.0	67.7	7.6	85.4	114.6	7.9	0.3
100	1.00	150.0	67.1	6.7	49.2	152.8	4.5	0.8
10	1.25	150.0	71.0	8.1	108.1	89.2	22.5	0.1
15	1.25	150.0	70.7	8.1	107.4	90.2	20.5	0.1
20	1.25	150.0	70.4	8.1	106.3	91.6	18.6	0.1
25	1.25	150.0	70.1	8.1	104.7	93.5	16.5	0.1
30	1.25	150.0	69.8	8.0	103.3	95.6	14.7	0.1
40	1.25	150.0	69.3	7.9	99.4	101.1	11.8	0.2
50	1.25	150.0	68.6	7.7	94.8	107.4	9.3	0.3
100	1.25	150.0	67.4	6.7	55.8	148.1	4.8	0.9

Predicted annual nitrogen budget for corn production on a Tomotley sandy loam with a depressional storage of 0.5 cm at Plymouth, NC. Values are averages for a 20-yr period (1971-90).

Drain Spacing (m)	Drain Depth (m)	Fertilizer Input (kg/ha)	Net Mineralization (kg/ha)	Rainfall Deposition (kg/ha)	Plant Uptake (kg/ha)	Denitrification (kg/ha)	Drainage Loss (kg/ha)	Runoff Loss (kg/ha)
			Conventional Drainage					
10	0.75	150.0	64.8	7.6	115.8	80.3	11.5	0.6
15	0.75	150.0	64.3	7.4	110.6	85.5	9.6	0.8
20	0.75	150.0	63.8	7.3	105.2	90.7	8.0	1.2
25	0.75	150.0	63.5	7.0	99.5	97.1	6.7	1.5
30	0.75	150.0	63.4	6.8	93.1	104.6	5.8	2.0
40	0.75	150.0	63.2	6.4	81.1	116.5	4.5	2.4
50	0.75	150.0	62.9	6.1	75.9	122.2	3.7	3.0
100	0.75	150.0	62.7	5.3	63.2	135.3	1.9	3.8
10	1.00	150.0	68.1	8.0	113.0	79.1	23.5	0.3
15	1.00	150.0	67.3	7.8	114.7	81.7	17.0	0.4
20	1.00	150.0	66.2	7.7	113.8	84.8	12.4	0.5
25	1.00	150.0	65.5	7.5	108.8	90.9	9.7	0.8
30	1.00	150.0	64.7	7.3	104.0	96.3	7.8	1.1
40	1.00	150.0	63.8	6.9	93.3	106.9	5.6	1.8
50	1.00	150.0	63.5	6.5	84.7	115.4	4.5	2.5
100	1.00	150.0	62.7	5.5	65.3	133.4	2.3	3.8
10	1.25	150.0	65.5	8.1	107.3	64.0	47.6	0.1
15	1.25	150.0	66.5	8.1	109.6	72.3	34.5	0.2
20	1.25	150.0	66.7	7.9	111.7	79.5	23.4	0.3
25	1.25	150.0	66.3	7.8	112.4	84.5	15.7	0.5
30	1.25	150.0	65.7	7.6	108.7	91.0	11.4	0.7
40	1.25	150.0	64.7	7.2	100.8	100.7	7.2	1.3
50	1.25	150.0	64.1	6.8	90.6	110.7	5.4	1.9
100	1.25	150.0	62.9	5.6	67.8	131.9	2.6	3.6
			Controlled Drainage in Summer					
10	0.75	150.0	65.5	7.6	114.8	82.5	10.8	0.7
15	0.75	150.0	64.9	7.4	107.2	89.2	9.0	1.0
20	0.75	150.0	64.4	7.2	100.7	95.9	7.6	1.4
25	0.75	150.0	63.9	6.9	94.5	102.5	6.3	1.8
30	0.75	150.0	63.7	6.7	88.6	109.4	5.5	2.2
40	0.75	150.0	63.3	6.4	77.9	119.6	4.3	2.7
50	0.75	150.0	63.1	6.1	72.7	125.3	3.5	3.2
100	0.75	150.0	62.7	5.3	61.7	136.8	1.8	4.0
10	1.00	150.0	68.8	7.9	116.8	80.2	18.8	0.3
15	1.00	150.0	67.8	7.7	114.3	84.9	14.1	0.6
20	1.00	150.0	66.7	7.6	109.6	90.2	10.8	0.8
25	1.00	150.0	65.9	7.4	102.4	97.8	8.6	1.1
30	1.00	150.0	65.2	7.1	96.8	103.7	7.1	1.5
40	1.00	150.0	64.1	6.7	86.4	113.6	5.2	2.2
50	1.00	150.0	63.6	6.4	79.0	120.8	4.2	2.9
100	1.00	150.0	62.7	5.4	62.3	136.1	2.1	4.1
10	1.25	150.0	67.1	8.1	114.9	68.7	35.8	0.2
15	1.25	150.0	67.8	7.9	114.9	76.5	25.9	0.3
20	1.25	150.0	67.8	7.8	112.4	84.9	18.0	0.5
25	1.25	150.0	67.2	7.6	109.1	91.2	12.6	0.8
30	1.25	150.0	66.4	7.4	102.1	99.1	9.5	1.0
40	1.25	150.0	65.1	7.0	92.3	109.1	6.4	1.8
50	1.25	150.0	64.3	6.6	82.7	118.1	4.8	2.4
100	1.25	150.0	62.9	5.6	63.7	135.6	2.2	4.0
			Controlled Drainage in Summer and Winter					
10	0.75	150.0	64.0	7.3	113.0	85.4	8.3	0.9
15	0.75	150.0	63.6	7.1	106.4	91.1	7.1	1.4
20	0.75	150.0	63.4	6.8	100.0	97.5	6.1	1.8
25	0.75	150.0	63.2	6.5	93.8	103.9	5.1	2.3
30	0.75	150.0	63.1	6.3	87.8	110.4	4.6	2.7
40	0.75	150.0	63.0	6.0	76.9	121.0	3.6	3.1
50	0.75	150.0	62.8	5.7	71.3	126.8	3.0	3.5
100	0.75	150.0	62.7	5.0	60.2	138.3	1.5	4.2
10	1.00	150.0	65.0	7.5	116.4	85.4	9.3	0.7
15	1.00	150.0	64.4	7.2	113.7	88.0	7.6	1.1
20	1.00	150.0	64.0	6.9	107.9	93.3	6.3	1.5
25	1.00	150.0	63.6	6.7	101.7	98.8	5.4	2.0
30	1.00	150.0	63.9	6.5	95.9	104.9	5.0	2.1
40	1.00	150.0	63.4	6.1	85.1	115.0	3.9	2.8
50	1.00	150.0	63.0	5.8	78.1	121.8	3.2	3.5
100	1.00	150.0	62.8	5.1	62.4	136.2	1.6	4.3
10	1.25	150.0	64.5	7.8	114.8	82.5	15.4	0.4
15	1.25	150.0	65.0	7.5	114.5	85.7	11.4	0.7
20	1.25	150.0	65.1	7.2	112.1	90.1	8.7	1.0
25	1.25	150.0	64.9	7.0	106.4	96.3	6.9	1.4
30	1.25	150.0	64.5	6.7	101.0	101.5	5.7	1.8
40	1.25	150.0	63.9	6.3	91.8	110.1	4.2	2.5
50	1.25	150.0	63.5	5.9	81.9	119.2	3.4	3.0
100	1.25	150.0	62.8	5.1	64.7	134.3	1.7	4.1

Predicted annual nitrogen budget for corn production on a Tomotley sandy loam with a depressional storage of 2.5 cm at Plymouth, NC. Values are averages for a 20-yr period (1971-90).

Drain Spacing (m)	Drain Depth (m)	Fertilizer Input (kg/ha)	Net Mineralization (kg/ha)	Rainfall Deposition (kg/ha)	Plant Uptake (kg/ha)	Denitrification (kg/ha)	Drainage Loss (kg/ha)	Runoff Loss (kg/ha)
			Conventional Drainage					
10	0.75	150.0	64.8	7.9	112.2	82.6	13.2	0.2
15	0.75	150.0	64.2	7.8	103.4	91.2	11.4	0.3
20	0.75	150.0	63.8	7.7	92.1	101.8	9.8	0.3
25	0.75	150.0	63.5	7.6	79.9	114.8	8.7	0.4
30	0.75	150.0	63.3	7.4	66.6	129.9	7.9	0.5
40	0.75	150.0	63.3	7.0	52.1	146.3	6.0	0.8
50	0.75	150.0	63.0	6.6	40.6	158.2	5.3	1.0
100	0.75	150.0	62.8	5.6	30.2	170.2	3.1	1.7
10	1.00	150.0	68.1	8.1	110.9	79.6	24.7	0.1
15	1.00	150.0	67.2	8.0	111.8	82.9	18.4	0.1
20	1.00	150.0	66.2	8.0	108.8	88.1	13.6	0.2
25	1.00	150.0	65.3	7.8	99.7	98.3	11.1	0.3
30	1.00	150.0	64.6	7.7	89.0	109.9	9.4	0.3
40	1.00	150.0	63.8	7.3	66.5	133.1	7.4	0.5
50	1.00	150.0	63.5	7.0	53.1	146.7	6.1	0.7
100	1.00	150.0	62.8	5.8	32.3	169.1	3.5	1.5
10	1.25	150.0	65.5	8.2	106.3	64.4	48.2	0.0
15	1.25	150.0	66.4	8.2	108.0	72.7	35.4	0.1
20	1.25	150.0	66.7	8.1	109.6	80.5	24.1	0.1
25	1.25	150.0	66.2	8.0	108.2	87.4	16.6	0.2
30	1.25	150.0	65.6	7.9	100.3	97.9	12.4	0.2
40	1.25	150.0	64.6	7.6	80.7	119.9	8.7	0.4
50	1.25	150.0	63.9	7.2	62.2	139.3	7.0	0.6
100	1.25	150.0	63.1	6.0	34.3	167.5	3.9	1.3
			Controlled Drainage in Summer					
10	0.75	150.0	65.4	7.9	109.9	86.1	12.6	0.2
15	0.75	150.0	64.9	7.8	96.6	97.9	11.0	0.3
20	0.75	150.0	64.3	7.7	83.0	111.1	9.6	0.4
25	0.75	150.0	63.9	7.5	71.4	123.8	8.4	0.5
30	0.75	150.0	63.6	7.3	60.1	137.1	7.5	0.7
40	0.75	150.0	63.4	6.9	47.5	151.5	5.8	0.9
50	0.75	150.0	63.2	6.5	36.9	161.8	5.0	1.1
100	0.75	150.0	62.9	5.5	27.8	173.1	2.9	1.8
10	1.00	150.0	68.8	8.1	113.9	81.5	20.2	0.1
15	1.00	150.0	67.8	8.0	108.6	88.8	15.7	0.2
20	1.00	150.0	66.7	7.9	99.4	99.0	12.3	0.2
25	1.00	150.0	65.9	7.7	86.3	112.4	10.3	0.3
30	1.00	150.0	65.1	7.6	75.4	124.2	8.9	0.4
40	1.00	150.0	64.1	7.2	57.2	142.9	6.8	0.7
50	1.00	150.0	63.6	6.8	46.5	154.3	5.6	0.9
100	1.00	150.0	63.0	5.7	28.9	172.8	3.0	1.8
10	1.25	150.0	67.1	8.2	113.2	69.6	36.5	0.1
15	1.25	150.0	67.8	8.1	111.0	78.9	26.9	0.1
20	1.25	150.0	67.8	8.0	105.9	90.0	19.2	0.2
25	1.25	150.0	67.2	7.9	97.4	101.0	14.1	0.2
30	1.25	150.0	66.4	7.8	85.9	113.9	11.0	0.3
40	1.25	150.0	65.1	7.4	67.6	134.4	7.9	0.6
50	1.25	150.0	64.2	7.0	52.2	150.2	6.3	0.8
100	1.25	150.0	63.3	5.8	29.8	171.8	3.3	1.6
			Controlled Drainage in Summer and Winter					
10	0.75	150.0	63.9	7.8	108.5	88.7	10.3	0.2
15	0.75	150.0	63.6	7.7	95.8	100.1	9.4	0.3
20	0.75	150.0	63.3	7.5	82.7	112.8	8.4	0.4
25	0.75	150.0	63.1	7.3	69.8	126.6	7.6	0.6
30	0.75	150.0	63.0	7.0	59.4	138.5	6.8	0.8
40	0.75	150.0	63.0	6.6	46.9	152.6	5.3	1.0
50	0.75	150.0	63.0	6.2	39.4	159.3	4.4	1.3
100	0.75	150.0	62.8	5.2	27.7	173.3	2.6	2.1
10	1.00	150.0	65.9	8.0	113.5	86.2	12.5	0.1
15	1.00	150.0	65.2	7.9	108.0	92.0	10.6	0.2
20	1.00	150.0	64.6	7.7	96.9	103.1	9.1	0.3
25	1.00	150.0	64.2	7.5	84.6	115.2	8.1	0.5
30	1.00	150.0	63.9	7.3	75.0	125.5	7.3	0.6
40	1.00	150.0	63.3	6.7	56.1	144.7	5.8	1.0
50	1.00	150.0	63.1	6.3	41.7	159.2	4.9	1.3
100	1.00	150.0	62.9	5.3	28.8	172.2	2.6	2.0
10	1.25	150.0	64.5	8.1	113.0	83.2	16.8	0.1
15	1.25	150.0	66.0	8.0	110.7	88.0	13.3	0.2
20	1.25	150.0	66.1	7.8	105.5	95.3	10.8	0.3
25	1.25	150.0	64.9	7.6	93.9	107.2	9.1	0.4
30	1.25	150.0	64.5	7.4	84.6	117.0	7.8	0.6
40	1.25	150.0	63.8	6.9	66.9	135.9	6.2	0.9
50	1.25	150.0	63.4	6.5	50.8	152.0	5.1	1.2
100	1.25	150.0	63.2	5.3	29.0	172.0	2.7	1.9

APPENDIX 6

PUBLICATIONS RESULTING FROM OR RELATED TO THIS RESEARCH PROJECT

1. Dissertations

Munster, C. L. 1992. Effects of Water Table Management on Transport of the Pesticide Aldicarb. PhD Dissertation. Department of Biological and Agricultural Engineering, N. C. State University, Raleigh, NC 409 p.

Susanto, R. H. 1993. Hydraulic Head Losses near Agricultural Drains. PhD Dissertation. Department of Biological and Agricultural Engineering, N. C. State University, Raleigh, NC 113 p.

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2. Conference Presentations

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