Abstract.

Diggs, Jonathan Andrew. Simulation of nitrogen and hydrology loading of forested fields in eastern North Carolina using DRAINMOD-N II. (under the direction of Dr. R. W. Skaggs and Dr. G. M. Chescheir)

A new version of DRAINMOD-N (DRAINMOD-N II) was used to evaluate the combined effects of soil variability, vegetation, drainage intensity, climate, and management practices on the hydrology and nitrogen (N) transport in forests. A better understanding of these processes will be useful in the development of management practices for reducing N loads from forests and in future large-scale modeling studies.

The objective of this study was to accurately model nitrogen loading at the field scale for three Coastal Plain forests in North Carolina using DRAINMOD-N II. Supporting objectives were to accurately model the hydrology of three forested fields using DRAINMOD, to determine litterfall and N uptake at the study sites, and to evaluate DRAINMOD and DRAINMOD-N II model accuracy by comparing predictions with measured values.

Water table elevations, drainage losses, and water quality were continuously measured at the study sites from 1995-2001. Soils on two of the fields were organic; the third field had a highly organic mineral soil. DRAINMOD was used to simulate the hydrology of the forested sites from 1995-2001. Very porous, highly organic soils made it difficult to determine hydrology input parameters using standard field methods. Several input parameters were

calculated from measurements of water table elevation and drainage outflow or from model calibration.

DRAINMOD-N II was used to predict cumulative N process rates and N losses in drainage. Litterfall production and N uptake inputs were determined using the forest productivity model PnET-CN. Michaelis-Menten input parameters for nitrification and denitrification in DRAINMOD-N II were determined by calibration. N mineralization was modeled as a function of organic matter (OM) content in the soil (initial OM and OM added by litterfall) and organic carbon decomposition rates.

DRAINMOD predicted water table elevations and drainage losses reasonably well when compared to observed data. Despite difficulties encountered in accurately determining the soil properties of the forest surface layers, and the hydrologic effect of maturing trees on evapotranspiration, the average absolute daily difference (*AADD*) of the water table depth predictions from 1995-2001 ranged from 13.0-28.4 cm, and the model efficiency, *E*, of the water table depth predictions ranged from 0.59-0.83. R^2 values for the daily drainage rate predictions from 1996-2001 ranged from 0.69-0.85. Model efficiency (*E*), values for the daily drainage rate predictions from 1996-2001 ranged from 0.68-0.70. The normalized errors in cumulative drainage predictions from 1996-2001 ranged from -17.1 to 2.7 %.

DRAINMOD-N II performed reasonably well in predicting N concentrations and cumulative N loads. Using a three-year calibration, the model generally overpredicted N losses during the validation period. Normalized errors in predicting cumulative NO_3-N loads from 1996-

2001 ranged from -2.5 to 28.9 % for the three fields. Normalized errors in predicting cumulative NH_4-N loads for the 1996-2001 period ranged from -48.2 to 54.6 %. Normalized errors in predicting cumulative dissolved inorganic nitrogen (DIN) loads ranged from -6.4 to 23.9 %. The model was also calibrated using a six-year calibration for a better understanding of N transport processes and for use in future modeling studies.

The results of this study documented the reliability of DRAINMOD for predicting water table depth and outflow volume from forested fields on highly organic soils. The study also showed the potential of DRAINMOD-N II for simulating N fate and transport in forested systems. DRAINMOD-N II predictions of N loads depended on the DRAINMOD hydrology predictions. Most of the input parameters for DRAINMOD-N II were determined from the literature or by calibration. A more accurate evaluation of the applicability of DRAINMOD-N II for modeling forested systems will require more field and/or laboratory measurements to determine model inputs.

SIMULATION OF NITROGEN AND HYDROLOGY LOADING OF FORESTED FIELDS IN EASTERN NORTH CAROLINA USING DRAINMOD-N II.

By

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DEDICATION

To Mom and Dad - Thanks for everything. I love you both.

To **JESUS CHRIST,** nothing is possible without You.
I am the vine, you are the branches. If a man abides in me and I in him,
he will bear much fruit; apart from me you can do nothing.
John 15:5

Thank You for loving me.
Just as the Father has loved me, I have also loved you. Abide in my love.
John 15:9

Thank You for changing me.
If anyone is in Christ he is a new creation; the old has gone, the new has come!
2 Corinthians 5:17

BIOGRAPHY

Jonathan Andrew Diggs was born on August 10, 1979 in Newport News, Virginia to James and Sandy Diggs. He has two brothers, Greg and Michael. He grew up in Mathews County, Virginia on the Chesapeake Bay.

He received a Bachelor of Science in Biological Systems Engineering at Virginia Tech in May of 2001. After finishing his undergraduate degree, he went to North Carolina State University to pursue a master's degree in Biological and Agricultural Engineering.

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CHAPTER 1: INTRODUCTION

BACKGROUND

Nitrogen (N) loads from nonpoint source pollution have led to detrimental impacts on receiving waters in coastal regions (U.S. EPA, 1993). Nitrate-nitrogen (NO_3-N) losses from agricultural fields have been shown to increase N concentrations in groundwater and surface water, which can lead to contamination of drinking water supplies and eutrophication of receiving waters (Gilliam et al., 1999). While decreased water quality has been observed in response to artificial drainage on agricultural fields, uncertainty remains about the effect of drained forested fields on downstream water quality (Amatya et al., 1998).

Past work in eastern North Carolina has shown that nutrient exports from managed pine plantations can be similar to baseline exports from natural stands (Amatya et al., 1998). However, Chescheir et al. (2003) found that nutrient exports from managed pine plantations in eastern North Carolina vary significantly. The authors studied the effect of soil variability, vegetation, drainage intensity, and physiographic location on hydrology and nutrient export. They reported that variations in soil organic content can affect the nutrient export from forest sites. However, the impacts of vegetation, drainage intensity, and physiographic location were not evident in the database they studied. Vegetation can affect the amount of evapotranspiration (ET) at the site and therefore the drainage volume. Artificial drainage could increase total N losses because of an increase in drainage volume. In addition, poorly drained soils often have increased anaerobic zones where denitrification can occur, which could lower the concentration of NO_3-N in outflow.

When forest management practices such as harvesting and fertilization are used, studies have shown that an increase in N export is possible, if only for a few months or years after the management event (Shepard, 1994). Several studies performed in the southeastern U.S. on drained forests have shown that harvesting can lead to increased N losses (Lebo et al., 1998; Fisher, 1981; Ensign et al., 2001). Harvesting alters the hydrology of the forest, and less N is removed through plant uptake. Nitrogen fertilization increases the amount of N in the system and can lead to increased N losses from forested fields.

Nitrogen transport in managed forests is a complex process. Soil variability, vegetation, drainage intensity, physiographic location, climate, and management practices all have an effect on N transport in the soil-water-plant system. Nitrogen models can provide a method of simulating the combined effects of these factors to develop a better understanding of N transport in forests. Nitrogen models can also provide a useful method for developing and evaluating management practices for reducing N loads from forests.

DRAINMOD-N II – MODEL DESCRIPTION

DRAINMOD-N II was developed to simulate nitrogen dynamics and turnover in the soil-water-plant system under different management techniques and soil conditions (Youssef, 2003). Driving hydrologic input parameters are determined from the water table management model *DRAINMOD 5.1* (Skaggs, 1978; Skaggs et al. 1991). The model simulates N transport using the multi-phase form of the one-dimensional, advective-dispersive-reactive (ADR) equation. The model includes a detailed N cycle and a simplified carbon (C) cycle to simulate N dynamics and turnover in the soil-water-plant system under different management scenarios and soil conditions. *DRAINMOD-N* II model output includes daily predictions of NO_3-N and ammonium-nitrogen (NH_4-N) in the soil solution and drainage outflow and cumulative rates of simulated N transformation processes.

DRAINMOD-N II has several improvements over the previous model, *DRAINMOD-N* (Breve, 1994). These changes were necessary for simulating N fate and transport on highly organic forested fields. *DRAINMOD-N* uses a simplified N cycle, which did not consider NH_4-N as a mineral pool. Chescheir et al. (2003) found that losses of NH_4-N from forested fields in eastern North Carolina can be significant. *DRAINMOD-N* also did not consider amending soils with organic N sources or temporal changes in soil organic nitrogen (ON) content. Litterfall from trees in forests adds a significant amount of organic N to the soil every year; therefore, the old version of the model could not simulate forest N cycling accurately. Since the old version of the model did not consider temporal changes in ON content, it would be impossible to accurately simulate N cycling for several consecutive years. The new version of the model considers NH_4-N as a mineral pool, ON amendment, and temporal changes in ON content. The model also has an improved denitrification routine. The model improvements increased the potential of *DRAINMOD-N* II to accurately simulate N fate and transport in a forested system.

Nitrogen Cycle

DRAINMOD-N II considers a detailed N cycle that includes three N pools: NO_3-N, ammoniacal nitrogen (NH_X-N), and organic nitrogen (ON) (Youssef, 2003). The NH_X-N pool, which includes ammonia-nitrogen (NH_3-N) and NH_4-N, can be ignored for simplification if it is reasonable to do so based on environmental and soil conditions. As shown in Figure 1.1, the model considers the following N transformation processes: atmospheric deposition, application of mineral N fertilizers, application of ON sources, N plant uptake, N mineralization and immobilization, nitrification, denitrification, NH_3 volatilization, and NO_3-N and NH_X-N losses due to leaching and surface runoff (Youssef, 2003).

Carbon Cycle

The availability of C is an important factor to consider when modeling N dynamics, especially in highly organic forested systems. Denitrification requires available C to proceed, and the processes of mineralization and immobilization are a consequence of C cycling in the soil-water system. *DRAINMOD-N* II simulates C dynamics and turnover based on a simplified C cycle (Youssef, 2003). As shown in Figure 1.2, it includes three soil organic matter (SOM) pools: active, slow, and passive as well as two added organic matter (AOM) pools: metabolic and structural. The SOM pools refer to organic carbon (OC) that is present in the soil as opposed to AOM, which refers to OC that is added through application of manures or crop residues. Each pool of organic matter is characterized by its OC content, potential rate of decomposition, and its carbon-to-nitrogen (C:N) ratio. In addition, each pool has a corresponding ON pool, and the five pools comprise the one ON pool shown in Figure 1.1. The active pool has the fastest turnover rate among the SOM pools, followed by the slow pool and then the passive pool. The active pool includes microbial biomass and metabolites, the slow pool represents more stable decomposition products, and the passive pool represents the most stable OM.

Modes of Operation

DRAINMOD-N II has three different modes of operation. The first mode, 'basic mode', considers NO_3-N as the only mineral N pool, and is used as a simplification when environmental conditions permit. The second mode, 'normal mode', considers NO_3-N and NH_4-N, and the third mode, 'volatilization mode', considers NO_3-N, NH_3-N, and NH_4-N. If the NH_X-N pool is considered, the model automatically switches between normal and volatilization modes according to soil pH.

Governing Equation

DRAINMOD-N II uses a multi-phase form of the one-dimensional advection-dispersion-reaction (ADR) equation to simulate N transport. The equation is 'multi-phase' because it considers the gaseous, aqueous, and solid phases of N species transport. It is 'one-dimensional' because the N transport is described in the vertical direction from the soil surface to the top of the impermeable layer. Transport through advection is mass transfer in the aqueous phase that occurs due to a hydraulic gradient. Transport through dispersion occurs due to molecular diffusion and mechanical dispersion (Wong, 2003). Nitrogen species can be accumulated or depleted based on several microbial processes, and the equation describes this with a source/sink term.

The multi-phase form of the one-dimensional ADR equation, written in terms of species in the aqueous phase, is the following,

$$\frac{\partial}{\partial t}\left(\theta_a + \frac{\theta_g}{H} + \rho_b K_d\right)C_a = \frac{\partial}{\partial z}\left(\theta_a D_a + \theta_g \frac{d_g}{H}\right)\frac{\partial C_a}{\partial z} - \frac{\partial(v_a C_a)}{\partial z} + S \qquad (1.1)$$

where θ_a and θ_g are the volumetric fractions [L^3L^{-3}] of the aqueous and gaseous phases, respectively, ρ_b is the dry bulk density of the solid phase [ML^{-3}], K_d is the distribution coefficient [L^3M^{-1}], H is Henry's coefficient, C_a is the species concentration [ML^{-3}] in the aqueous phase, D_a is the coefficient of hydrodynamic dispersion [L^2T^{-1}] that characterizes dispersive transport in the aqueous phase, d_g is the molecular diffusion coefficient [L^2T^{-1}] that characterizes diffusive transport in the gaseous phase, v_a is the volumetric flux of the aqueous phase [LT^{-1}], S is a source/sink term [$ML^{-3}T^{-1}$] that characterizes additional processes (plant uptake, transformations, etc.), t is time [T], and z is a spatial coordinate [L] (Youssef, 2003).

The source/sink term describes the cumulative affect of a number of N transformation processes on a particular N species. The source/sink term for NH_X-N can be defined as follows,

$$S = S_{hyd} + S_{min,NH4} + S_{dep,NH4} + S_{fer,NH4} - S_{imm,NH4} - S_{nit} - S_{upt,NH4} - S_{rnf,NH4} \qquad (1.2)$$

where S_{hyd} is urea hydrolysis rate, $S_{min,NH4}$ is ammonium mineralization rate, $S_{dep,NH4}$ is rate of ammonium deposition through precipitation, $S_{fer,NH4}$ is ammonium fertilization rate, $S_{imm,NH4}$ is ammonium immobilization rate, S_{nit} is rate of ammonium lost by nitrification, $S_{upt,NH4}$ is rate of ammonium plant uptake, and $S_{rnf,NH4}$ is the rate of ammonium lost in surface runoff (all units in [$ML^{-3}T^{-1}$]).

The source/sink term for NO_3-N is defined by,

$$S = S_{dep,NO3} + S_{fer,NO3} + S_{nit} + S_{min,NO3} - S_{imm,NO3} - S_{den} - S_{upt,NO3} - S_{rnf,NO3} \qquad (1.3)$$

where $S_{dep,NO3}$ is rate of nitrate deposition through precipitation, $S_{fer,NO3}$ is nitrate fertilization rate, $S_{min,NO3}$ is nitrate mineralization rate, $S_{imm,NO3}$ is nitrate immobilization rate, S_{den} is the denitrification rate, $S_{upt,NO3}$ is rate of nitrate plant uptake, and $S_{rnf,NO3}$ is rate of nitrate lost in surface runoff (all units in [$ML^{-3}T^{-1}$]). Nitrate mineralization occurs only if the model is run in basic mode, which does not consider NH_X-N. Nitrate immobilization will occur only if the NH_x-N pool is depleted.

Carbon and Nitrogen Transformations

<u>Effect of Environmental Factors on C and N Transformations</u>

Most processes affecting C and N transformations in the soil-water system are driven by microbial activity. Any changes in the soil-water environment that affect microbial activity will have an impact on C and N transformation rates. Youssef (2003) described the effect of soil temperature, soil moisture, and soil pH on C and N transformations by defining a dimensionless response function for each factor. An overall response function that describes the cumulative effect of these environmental factors is defined using a linear combination the individual response functions. The C and N transformation process rates are defined in the model as follows,

$$k = f_e \, k_{opt} \qquad (1.4)$$

where k is the actual process rate, k_{opt} is the optimum process rate, assuming ideal environmental conditions, and f_e is the dimensionless overall response factor that takes values from 0 to 1.

In *DRAINMOD-N* II, the effect of pH on microbial processes is set to be optional. When the effect of pH is ignored, f_e may be expressed as,

$$f_e = f_t f_{sw} \qquad (1.5)$$

where f_t is the temperature response function and f_{sw} is the soil water response function. If the effect of pH is included, the two most influential factors are used to quantify f_e,

$$f_e = min\{f_t\, f_{sw},\ f_t\ f_{pH},\ f_{sw}\ f_{pH}\} \qquad (1.6)$$

where f_{pH} is the pH response function.

The temperature response function, f_t, is based on a form of the Van't Hoff equation with variable Q_{10},

$$f_t = \exp[-0.5\beta T_{opt} + \beta T(1 - 0.5T / T_{opt})] \qquad (1.7)$$

where β is an empirical coefficient, T is temperature [^{o}C], T_{opt} is the optimum temperature [^{o}C] at which f_t equals unity. As temperature increases, microbial activity increases to a threshold value. If the temperature continues to increase, microbial activity begins to decline.

In *DRAINMOD-N* II, two soil water response functions were developed. One function was developed for denitrification, which proceeds optimally at complete saturation and decreases to zero as the water content decreases to a certain threshold saturation. The other function was developed for the other C and N transformation processes, which have a range of saturation values below complete saturation in which the process proceeds optimally. If the soil water content exceeds or is less than the optimum saturation range, the process rate will be limited (Youssef, 2003).

The soil water response function for denitrification, $f_{sw,dn}$, is defined as,

$$f_{sw,dn} = \begin{cases} 0 & s < s_{dn} \\ \left(\dfrac{s - s_{dn}}{1 - s_{dn}}\right)^{e1} & s \geq s_{dn} \end{cases} \qquad (1.8)$$

where s is the relative saturation, dimensionless, s_{dn} is a threshold relative saturation, dimensionless, below which denitrification does not occur, and *e1* is an empirical exponent (Youssef, 2003).

Soil water effect on the all other C and N transformation processes is quantified by,

$$f_{sw} = \begin{cases} f_s + (1 - f_s)\left(\dfrac{1-s}{1-s_u}\right)^{e2} & s_u < s \le 1 \\ 1 & s_l \le s \le s_u \\ f_{wp} + (1 - f_{wp})\left(\dfrac{s - s_{wp}}{s_l - s_{wp}}\right)^{e2} & s_{wp} \le s \le s_l \end{cases} \quad (1.9)$$

where s_u and s_l define the upper and lower limits of the relative saturation range within which the biological proceeds at optimum rate, s_{wp} is the relative saturation at permanent wilting point, f_s and f_{wp} are the values of the soil water function at saturation, and permanent wilting point, respectively, and *e2* is an empirical exponent (Youssef, 2003).

The pH response function is defined as,

$$f_{pH} = \begin{cases} f_{\min} + (1 - f_{\min})\left(\dfrac{pH - pH_{\min}}{pH_l - pH_{\min}}\right)^{e3} & pH_{\min} \le pH < pH_l \\ 1 & pH_l \le pH \le pH_u \\ f_{\max} + (1 - f_{\max})\left(\dfrac{pH_{\max} - pH}{pH_{\max} - pH_u}\right)^{e3} & pH_u < pH \le pH_{\max} \end{cases} \quad (1.10)$$

where pH_{min} and pH_{max} are the limits of the pH range that could occur in the system, pH_l and pH_u define the upper and lower bounds of a pH range within which the transformation proceeds at the optimum rate, f_{min} and f_{max} are the values of the response function at pH_{min} and pH_{max}, respectively, and *e3* is an empirical exponent (Youssef, 2003).

Application of Animal Waste and Crop Residues

DRAINMOD-N II was originally developed for agricultural systems and simulates the application of organic material as animal waste and crop residues. In application of animal waste, N is applied in both organic and mineral forms. The fertilizer component handles the mineral N application, and the SOM component handles the organic portion of animal waste, as well as crop residues. For forested systems, organic matter is added by litterfall from the trees. The litterfall can be simulated using *DRAINMOD-N* II by defining the properties of the litterfall organic material. Added OM is characterized by its C:N ratio, its lignin-to-nitrogen (L:N) ratio, and its OC content. Organic matter that is added is divided into the metabolic and structural pools, based on its lignin-to-nitrogen (L:N) ratio,

$$F_{met} = 0.85 - 0.018LNR_{add} \quad (1.11)$$

$$F_{str} = 1 - F_{met}$$

where F_{met} and F_{str} are the metabolic and structural fractions of added OM, respectively, and LNR_{add} is the lignin-to-nitrogen ratio of added OM. This method separates the slowly decomposable fraction of OM, which is represented by the lignin content, from the readily decomposable fraction.

When OM is added to the structural and metabolic pools, the OC content of both pools changes. The C:N ratio of the metabolic pool changes depending on the C:N ratio of the added OM. The structural pool OC decomposition rate is a function of the lignin content and a potential decomposition rate. Therefore, when OM is added the structural pool decomposition rate changes (Youssef, 2003).

Organic C Decomposition and N Mineralization/Immobilization

N mineralization and immobilization is a result of carbon cycling between pools (Youssef, 2003). The total amount of OC released from a given pool j, $OC_{rel,j}$ [$MM^{-1}T^{-1}$], is given by,

$$OC_{rel,j} = f_e \, K_{dec,j} \, OC_j \quad (1.12)$$

where f_e is a dimensionless environmental response function, $K_{dec,j}$ is a first order decomposition rate constant [T^{-1}], and OC_j is the OC content of pool j [MM^{-1}]. As OC is released from the various pools, some OC is potentially available for N mineralization to occur.

The gross N mineralization that occurs due to the OC release from a given pool j, $N_{min,j}$ [$MM^{-1}T^{-1}$], is given by,

$$N_{\min,j} = \frac{OC_{rel,j}}{CNR_j} \quad (1.13)$$

where CNR_j is the C:N ratio of pool j.

Organic C that is not released can be moved from one pool to another, and Figure 1.2 shows the possible pathways for OC resynthesis for each pool. Organic C synthesis from pool j to pool k, $OC_{syn,jk}$ [$MM^{-1}T^{-1}$] is given by,

$$OC_{syn,jk} = \alpha_{jk} e_{jk} OC_{rel,j} \tag{1.14}$$

where α_{jk} is a dimensionless mass fraction of OC released from pool *j* and resynthesized into pool *k* and e_{jk} is a dimensionless synthesis efficiency factor for OC flow from pool *j* into pool *k*.

The gross N immobilization that occurs due to OC moving from one pool to other available pools, $N_{imm,j}$ [$MM^{-1}T^{-1}$], is determined by,

$$N_{imm,j} = \sum_k \frac{OC_{syn,jk}}{CNR_k} \tag{1.15}$$

The net N mineralization or immobilization associated with C flows for all pools is given by,

$$S_{\min/imm} = \frac{\rho_b}{\theta_a} \sum_j (N_{\min,j} - N_{imm,j}) \tag{1.16}$$

where $S_{min,imm}$ is the rate of net N mineralization/immobilization [$ML^{-3}T^{-1}$].

<u>Nitrification</u>

In *DRAINMOD-N* II, nitrification is modeled using Michaelis-Menten kinetics with respect to NH_4-N and is described by,

$$S_{nit} = f_e f_{inh} V_{\max,nit} \left(\frac{C_{NH4}}{K_{m,nit} + C_{NH4}} \right) \left(\frac{\rho_b}{\theta_a} \right) \tag{1.17}$$

where f_e is the dimensionless environmental response function, f_{inh} is a dimensionless response function for nitrification inhibitors, $V_{max,nit}$ is the maximum nitrification rate [$MM^{-1}T^{-1}$], $K_{m,nit}$ is the half-saturation constant [MM^{-3}], the substrate concentration at which the reaction rate is half $V_{max,nit}$, and C_{NH4} is the ammonium concentration [MM^{-1}] (Youssef, 2003).

The nitrification process is limited if the ammonium concentration is below a threshold value and the process behaves as a first-order function. Once the ammonium concentration reaches a threshold value, nitrification rate is no longer limited by ammonium supply and the process proceeds as a zero-order function. *DRAINMOD-N* II simulates the effect of any added nitrification inhibitors on nitrification rate by using the response function, f_{inh}, which has values from 0 to 1 based on the concentration of nitrification inhibitors in the soil system.

Denitrification

In *DRAINMOD-N* II, denitrification rate is represented using Michaelis-Menten kinetics with respect to NO_3-N,

$$S_{den} = f_e f_z V_{\max,den}\left(\frac{C_{NO3}}{K_{m,NO3} + C_{NO3}}\right)\left(\frac{\rho_b}{\theta_a}\right) \tag{1.18}$$

where S_{den} is the denitrification rate [$ML^{-3}T^{-1}$], $V_{max,den}$ is the maximum denitrification rate [$MM^{-1}T^{-1}$], C_{NO3} is the NO_3-N concentration [ML^{-3}], and $K_{m,NO3}$ is the NO_3-N half-saturation constant [ML^{-3}]. Organic C availability has been shown to be important in regulating denitrification rates. The influence of OC is simulated using a empirical function relating carbon availability with depth,

$$f_z = e^{-\alpha z} \tag{1.19}$$

where α is an empirical exponent, and z is the depth from the soil surface [L] (Youssef, 2003).

Plant Uptake

Plant uptake for NO_3-N and NH_4-N is simulated in *DRAINMOD-N* II by using the following functions,

$$S_{upt,NO3} = \min\begin{cases} S_{upt}\dfrac{N_{NO3}}{N_{NO3} + N_{NH4}} \\ N_{NO3} \end{cases} \tag{1.20}$$

$$S_{upt,NH4} = \min\begin{cases} S_{upt}\dfrac{N_{NH4}}{N_{NO3} + N_{NH4}} \\ N_{NH4} \end{cases} \tag{1.21}$$

where $S_{upt,NO3}$ and $S_{upt,NH4}$ are the actual uptake rates [$ML^{-3}T^{-1}$] from the NO_3-N and NH_4-N pools, respectively, and N_{NO3} and N_{NH4} are the sum of the aqueous and solid phase concentrations [ML^{-3}] of NO_3-N and NH_4-N, respectively.

Estimation of potential plant uptake, S_{upt} [$ML^{-3}T^{-1}$], is given by,

$$S_{upt} = \frac{N_{crp} f_{upt}}{D_{root}} \tag{1.22}$$

where N_{crp} is the total amount of N taken up by plants during the growing season [ML^{-2}], f_{upt} is the fractional N-uptake demand [T^{-1}], which is given as an empirical N-uptake versus growing season relationship, and D_{root} [L] is the effective rooting depth.

The model assumes that NO_3-N and NH_4-N are both equally available to plants, and the plants take the N species up in relative proportions. When one N species is used up, the plant will take up N from the remaining species pool. When N demand exceeds available N, the plant takes up whatever N is left and N stress occurs. The model does not simulate the effect of N stress on crop yield.

Atmospheric Deposition

Functions for atmospheric deposition to the surface layer are defined as follows,

$$S_{dep\,NO3} = \frac{fC_{rain,NO3}}{\Delta z} \tag{1.23}$$

$$S_{dep,NH4} = \frac{fC_{rain,NH4}}{\Delta z} \tag{1.24}$$

where S_{dep} is the rainfall deposition rate [$ML^{-3}T^{-1}$], $C_{rain,NO3}$ and $C_{rain,NH4}$ are the NO_3-N and NH_4-N concentrations in rain, respectively, and f is the infiltration rate.

Surface Runoff

Surface runoff loss of aqueous N species is quantified using the following equation,

$$S_{rnf,X} = \frac{q_{rnf} C_{rnf,X}}{\Delta z} \tag{1.25}$$

where $S_{rnf,X}$ is the rate of NO_3-N or NH_4-N loss in runoff [$ML^{-3}T^{-1}$], q_{nrf} is runoff rate [LT^{-1}] as predicted by *DRAINMOD* and $C_{rnf,X}$ is the concentration [ML^{-3}] of NO_3-N or NH_4-N in runoff.

MODEL TESTING

Field testing of the *DRAINMOD* 5.1/*DRAINMOD-N* II models was conducted using six years (1992-1997) of data from an experimental site in the Lower Coastal Plain of North Carolina, near Plymouth (Youssef et al, 2003a; Youssef et al, 2003b). The model was tested for a corn-wheat-soybean rotation on four 1.7-ha fields under conventional (free) and controlled drainage. The authors stressed that the test of the model should be regarded as incomplete, since most input parameters were not measured in the field or laboratory. Automatic measurements were taken of water table depth midway between drains, subsurface drainage flow rates, and meteorological data. Flow-proportional NO_3-N samples were taken from subsurface drainage biweekly or more frequently during high-flow events.

The hydrologic simulation model *DRAINMOD* 5.1 was shown to produce ‘good’ results when comparing predicted and measured values of water table depth. The predicted water table depth was between 11.8-13.9 cm of measured values on average for the four fields. The average coefficient of determination (R^2) for water table depth was between 0.71 and 0.77, showing good agreement.

Predictions of subsurface drainage rates showed ‘generally good’ agreement between observed drainage rates. The absolute normalized error was 5.7 and 12.1 % between observed and predicted drainage rates. The average R^2 values were 0.65 to 0.73 for the four fields, which shows ‘fair to good’ agreement. The authors cited the underprediction of drainage rates during high flow events as the primary cause of disagreement (Youssef et al., 2003a).

DRAINMOD-N II was used to predict annual NO_3-N leaching losses and the results were compared with measured values. The average absolute normalized error for annual NO_3-N losses in subsurface drainage were 19.9 – 46.0 %, which showed ‘fair to good’ agreement. However, the absolute normalized error in predicting NO_3-N leaching losses was less than 25 % in half of the 24 simulated field$\times$years. The authors stated that errors in predicting water table depth and drainage rates were the primary causes of disagreement and noted a strong influence of the hydrologic predictions of *DRAINMOD* 5.1 on the performance of *DRAINMOD-N* II. In addition, it was not feasible to properly initialize the model due to lack of measurements, and so the predictions for 1992 were unreliable (Youssef et al., 2003b).

DRAINMOD-N II did an 'excellent' job in predicting cumulative NO_3-N leaching losses over the entire six-year simulation period. Cumulative NO_3-N leaching losses were overpredicted by 2.1 % for one plot and underpredicted by 5.9-10.2 % for the other three plots. Although there were sometimes large discrepancies between observed and predicted annual NO_3-N leaching losses, prediction errors in cumulative NO_3-N losses were very small (Youssef et al., 2003b).

The authors stated that the results of the field modeling showed the potential for the widespread use of *DRAINMOD-N* II to simulate N dynamics and turnover in agricultural ecosystems. They stressed that further research should be conducted to test the model with independent measurements of model input parameters before widespread use (Youssef et al., 2003b).

MODELING FORESTED CONDITIONS

DRAINMOD-N II was originally developed and tested for application in agricultural systems. Since it incorporates a detailed N cycle as well as a simplified C cycle, *DRAINMOD-N* II should be able to simulate N transport and turnover in forested systems with accurate parameterization and a few minor modifications.

DRAINMOD-N II estimates potential plant uptake of NO_3-N and NH_4-N as a function of relative yield, which is predicted by *DRAINMOD* 5.1. Relative yield in *DRAINMOD* 5.1 is predicted for each growing season as a function of different growth stresses on the crop. A new relative yield is predicted for each crop and for each growing season. However, trees grow continually from year to year, and the current plant uptake method inadequately describes the cumulative effect of each year's climate on forest development. Therefore, it is necessary to develop an estimate of potential N uptake for a given year that depends on the physiological development of the forest.

DRAINMOD-N II simulates the application of organic material such as manure and plant residue for a specific day and quantity. Litterfall from coniferous forests occurs in varying amounts, depending on the foliar production of the forest. Foliar production is a function of the carbon and nitrogen cycling in the soil-water-plant system; it changes every year depending on the physiological development of the forest. Litterfall from loblolly pine forests occurs continuously all year, but in varying amounts depending on season as well as climate factors, such as heavy rainfall and winds. It is necessary to develop a method to estimate foliar production and to simulate variable application of litterfall.

In a comprehensive study of nutrient export from forests in eastern North Carolina, Chescheir et al. (2003) found that annual total nitrogen exports were typically less than 7.5 kg ha^{-1} yr^{-1}. However, the authors reported that annual N losses from some fields with highly organic soils in that study were significantly higher, with loads as high as 23.9 kg ha^{-1} yr^{-1}. These highly organic soils have hydrologic characteristics, such as very high saturated conductivities in the top layers, which are not well understood. In addition, there is uncertainty in the rates of certain N transformation processes, which could explain the higher N losses. A study of these forested fields would be useful for *DRAINMOD-N* II model evaluation and for developing a better understanding of the field properties that affect the hydrology and N losses from these fields.

OBJECTIVES

The goal of this study is to accurately model nitrogen loading at the field scale for three forests in the Coastal Plain of eastern North Carolina using *DRAINMOD-N* II. Specific objectives of the project are:

1. To accurately model the hydrology of three forested fields using *DRAINMOD*.
2. To determine litterfall and N uptake at the study sites and develop methods in *DRAINMOD-N* II to quantify these processes.
3. To evaluate the accuracy of the *DRAINMOD* and *DRAINMOD-N* II models by comparing predictions with measured values.

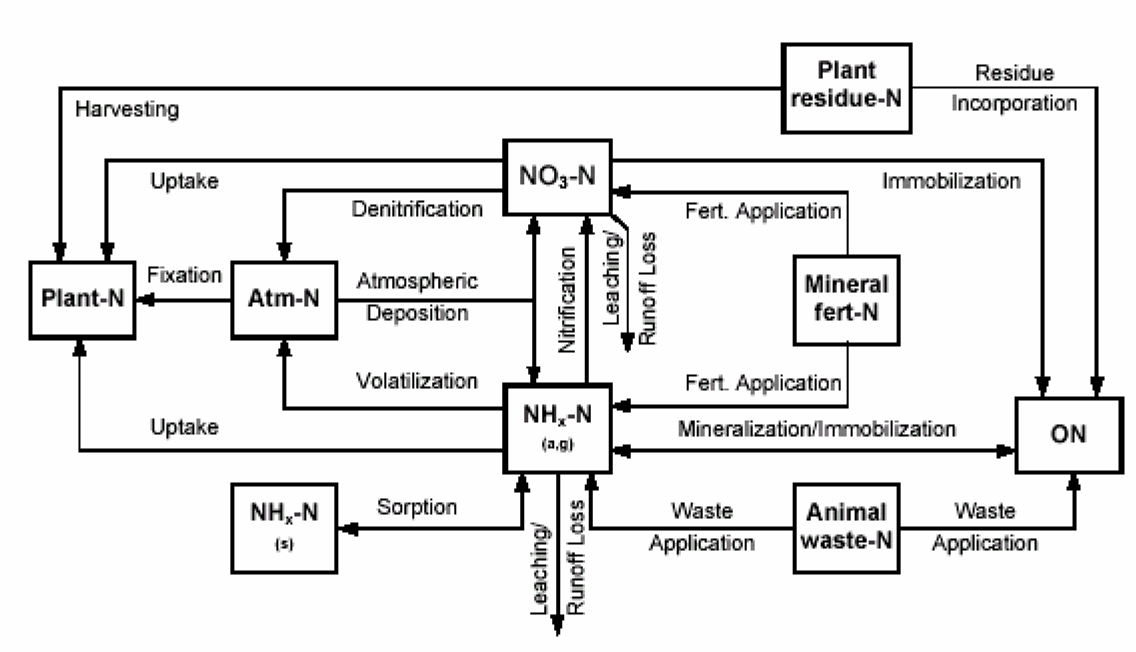

Figure 1.1 Nitrogen cycle as modeled in *DRAINMOD-N* II (Youssef, 2003)

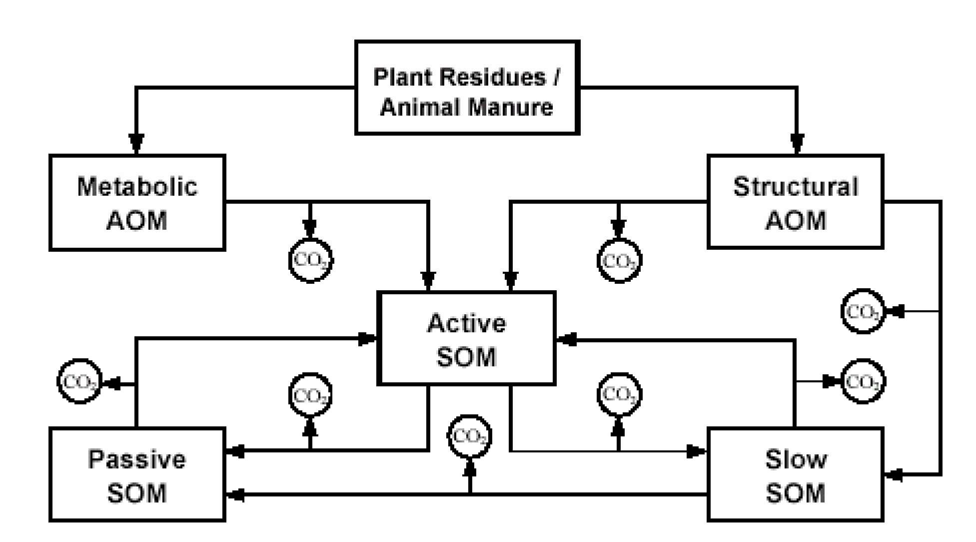

Figure 1.2 Carbon cycle as modeled in *DRAINMOD-N* II (Youssef, 2003)

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CHAPTER 2: METHODS

SITE DESCRIPTION

To test the accuracy of *DRAINMOD-N* II on forested fields, seven years (1995-2001) of hydrologic and water quality data were recorded from three managed loblolly pine forests in the Lower Coastal Plain of North Carolina. The three forested fields are located in Weyerhaeuser's Parker Tract near the town of Plymouth and are designated as F3, F5, and F6, as shown in Figures 2.1 and 2.2.

Field – F3

Field F3 is 47 ha and was planted with loblolly pine in 1983. The field is nearly flat and has open ditches for water table management that are spaced approximately 80-m apart and 1.0-m deep with an outlet weir maintained at an elevation 0.70 m below the average soil surface. The soil is classified as the Cape Fear series (fine, mixed, semiactive Typic Umbraquult). As observed in the field, the soil is dark sandy loam in the top 25 cm with 5-15 % organic matter, sandy clay loam at 25 to 60 cm depth, sandy loam at 60 to 75 cm depth, and gray sandy clay from 75 to 155 cm depth.

Field – F5

Field F5 is 128 ha and was planted with loblolly pine in 1984 and partially thinned in late September 2000. The nearly flat field has open ditches that are approximately 100-m apart and 1.0-m deep with an outlet weir maintained at an elevation 0.70 m below the average soil surface. The soil is classified as the organic Belhaven (Loamy, mixed, dysic, thermic Terric Haplosaprists) and Pungo (Dysic, thermic Typic Haplosaprists) series. As observed in the field, the soil is a black to reddish brown, mucky organic (25-90 % OM) in the top 45 cm, dark yellowish brown loam at 45 to 70 cm depth, and brown sandy loam at 70 to 150 cm depth.

Field – F6

Field F6 is 90 ha and was planted with loblolly pine in 1992. The field has open ditches that are approximately 100-m apart and 0.9-m deep with an outlet weir maintained at an elevation 0.6 m below the average soil surface. F6 has an organic soil of the Belhaven series. As observed in the field, the soil is a very dark brown to black organic (20-95 % OM) in the top 50 cm and dark greyish brown sandy loam at 50 to 85 cm depth. Observations were not made below 85 cm depth, but it is reasonable to assume properties similar to F5 below that depth.

HYDROLOGY MEASUREMENTS

Weather

Rainfall was collected from 1995-2001 using automatic recorders at two locations (R1 and R6) as shown in Figure 2.2. Automatic tipping bucket gauges were used and the number of tips was recorded using an electronic datalogger (Onset Hobo ® or Omnidata ® event loggers). The data were downloaded every two weeks, and manual gauges were used to back up and provide calibration for the automatic measurements.

R6 was also the site of a full weather station, which measured air temperature, wind speed, relative humidity, net radiation, solar radiation, and rainfall. Data were recorded every 30 minutes using a Campbell Scientific CR10X datalogger ®.

Water Table

Water table depth measurements were made in the center of each field at the midpoint between two drainage ditches (Figure 2.2) from 1995-2001. Water table monitoring wells were constructed out of 4-in. PVC pipe and screened at various depths. Water table elevations were recorded using a float-and-pulley system and an automatic datalogger (Blue Earth Research ST485 ® or Omnidata ®). The float and pulley system was replaced with an Infinity 222 ® datalogger in 2001. Data from the dataloggers were downloaded about every two weeks and any necessary calibrations were made at that time.

Flow

Drainage outflow is measured in the main drainage canal at the outlet of each field (Figure 2.2) from 1996-2001. At the outlet, there are two automatic stage gauges, one upstream and one downstream of a V-shaped weir (120^o). The automatic stage gauges were constructed with 4-in. PVC wells and a pulley/float system. The rotation of the pulley is measured using a potentiometer and is recorded by a datalogger (Blue Earth Research ST485

®). The upstream stage was also measured using a chart recorder for verification and backup of the digital system. The data were downloaded every two weeks and any necessary calibrations were made at that time.

With a V-notched weir and upstream and downstream stage measurements, it is possible to calculate the drainage outflow rate from a given field, even during submergence. When the downstream water level was below the weir invert, the following equation was used to determine the flow rate over a sharpcrested, 120^{o} V-notched weir (Grant and Dawson, 2001),

$$Q = 4.33\, H^{2.5} \tag{2.1}$$

where Q is the flow rate (ft^3 s^{-1}) and H is the upstream water stage above the V notch (m). When the weir was submerged, the following equation was used to determine the flow rate (Brater et al., 1996),

$$Q = \left(4.36 H_1^{2.5}\right) * \left[1 - \left(\frac{H_1}{H_2}\right)^{0.5}\right]^{0.385} \tag{2.2}$$

where H_1 is the upstream height of water above the bottom of the V notch (ft), and H_2 is the downstream height of water above the bottom of the V notch (ft). Very infrequently, data from both the digital automatic recorders and the charts would be unavailable. In such cases, estimates of stage were made using data from other nearby fields, which were instrumented for other studies. Resulting measurements, in this case, were treated as approximate.

WATER QUALITY MEASUREMENTS

Water quality samples from the drainage outflow were taken upstream of the V-notch weir at the outlet of each field from 1996-2001. Flow-weighted composite samples and discrete samples were taken by an automatic sampler depending on the sampling mode (Figure 2.2). In discrete mode, samples were taken in individual bottles at timed intervals to measure changes in nutrient concentrations that often occur during a storm event. The microprocessor signaled the automatic sampler to take discrete samples based on rapid rising or falling of measured stage. In composite mode, the microprocessor signaled the sampler to take samples after a certain volume of water had flowed over the weir and combined the samples in a single bottle. Composite or discrete samples were collected every two weeks. Grab samples (500 mL) were manually taken at each two-week collection. All samples were kept on ice until they could be put in a laboratory freezer, where they remained frozen until analysis. Concentrations of NO_3-N and NH_4-N were measured colormetrically with a Lachat Quickchem 8000 Instrument, using standard methods (APHA, 1992).

Samplers were in flow-proportional, composite mode most of the time. When the samplers were in discrete mode, sufficient samples were taken so that linear interpolation could be used to estimate daily nutrient concentrations between measurements. The daily nutrient export load was determined by multiplying the nutrient concentration by the measured outflow volume for each day.

HYDROLOGY SIMULATIONS

Modeling Scenario

Hydrology simulations were performed with the water table management model *DRAINMOD* 5.1 (Skaggs, 1978; Skaggs et al., 1991). Calibration of the model input parameters was performed using measured water table elevation and drainage data from 1996-2001. The extensive calibration period was required due to the difficulty in determining accurate input parameters for the highly organic and highly porous soils and because of relatively long periods of missing water table elevation data. The accuracy of *DRAINMOD-N* II predictions is very dependent on the accuracy of the *DRAINMOD* hydrology predictions (Youssef, 2003). Therefore, it was important to have the most accurate hydrology simulations possible to accurately assess *DRAINMOD-N* II model predictions. Hydrologic simulations of 1995 were also performed for each field to establish the initial condition for the *DRAINMOD-N* II simulations.

DRAINMOD Model Description

DRAINMOD was developed to characterize drainage and water table control practices in flat (<2.0 % slope), poorly drained soils. The model is based on a water balance for a section of soil midway between two parallel drains, which may be either open ditches or buried drain tubes. The model can be applied for open ditches by simulating very large subsurface drains. The section of soil has a unit surface area and extends from the impermeable layer to the soil surface. The water balance for a particular time increment is given by,

$$\Delta V_a = D + ET + DS - F \qquad (2.3)$$

where ΔV_a is the change in air volume or water free pore space (cm), D is the drainage (cm) from the section, ET is evapotranspiration (cm), DS is deep seepage (cm), and F is infiltration (cm).

A separate water balance is used to determine the volume of infiltration, runoff, and surface storage that occurs in response to precipitation,

$$P = F + \Delta S + RO \qquad (2.4)$$

where P is precipitation (cm), ΔS is the change in volume of water in surface storage (cm), and RO is runoff (cm).

The water balance is calculated in 1-h increments on days with rainfall. If no rainfall occurs, the time step is two hours. If rainfall does not occur and drainage is low, the time step is one day. If the rainfall rate exceeds the infiltration capacity, time increments of ≤ 0.1 h are used for infiltration calculations.

Infiltration

The Green-Ampt equation describes infiltration and is given by,

$$f = K_s + K_s M_d S_f F \qquad (2.5)$$

where f is the infiltration rate (cm/h), F is the cumulative infiltration (cm), K_s is the vertical hydraulic conductivity of the transmission zone (cm/h), M_d is the difference between final and initial volumetric water contents ($cm^3\ cm^{-3}$), and S_f is the effective suction at the wetting front (cm). *DRAINMOD* uses a simplification of the Green-Ampt equation for a given soil with a given initial water content,

$$f = A / F + B \qquad (2.6)$$

where A ($cm^2\ h^{-1}$) and B ($cm\ h^{-1}$) are parameters that depend on soil properties, initial water content and distribution, and surface conditions. The infiltration parameter A is defined as,

$$A = K_s M_d S_f \qquad (2.7)$$

The infiltration parameter B is equal to K_s.

Surface Drainage

There are two parameters that describe surface drainage in *DRAINMOD.* The maximum surface storage (cm) defines the amount of water that can be stored on the soil surface before surface runoff begins. Kirkham's depth for flow to drains (cm) represents the storage in small depressions due to surface cover characteristics and surface grading. Kirkham's depth is used when predicting subsurface drainage during ponded conditions.

Subsurface Drainage

The model uses the Hooghoudt equation (Bouwer and van Schilfgaarde, 1963) to predict subsurface drainage based on water table elevation by assuming an elliptical water table profile between drains and assuming horizontal streamlines in the saturated region. The Hooghoudt equation is a steady state function, but it can be applied using small time steps because the water table drawdown is typically very slow (Bouwer and van Schilfgaarde, 1963). The Hooghoudt equation is given by,

$$q = \frac{4Km^2 + 8Kmd_e}{L^2} \tag{2.8}$$

where q is the drainage flux, (cm h^{-1}), m is the midpoint water table height above the drain (cm), K is the effective lateral hydraulic conductivity (cm h^{-1}), L is the drain spacing (cm), and d_e is the equivalent depth of the impermeable layer below the drain (cm). Equations to solve for the equivalent depth were determined by Moody (1967) and are computed internally in *DRAINMOD.*

When water is ponded above Kirkham's depth, water on the surface can move freely and most of the flow will be concentrated near the ditches. In this situation, the assumption of horizontal streamlines does not hold and another method is required. The model uses Kirkham's equation (Kirkham, 1957) to predict outflow when the water on the surface is ponded above Kirkham's depth.

Evapotranspiration

Evapotranspiration (ET) accounts for water loss from the soil by evaporation from the soil surface and by transpiration from plants. Determination of ET in DRAINMOD is a two-step process. First, daily potential evapotranspiration (PET) is calculated using an appropriate method from atmospheric data. PET is a function of net solar radiation, temperature, humidity, and wind velocity. Different methods are chosen based primarily on atmospheric data availability. PET represents the maximum amount of water that will be removed from the soil system by evaporation and transpiration when sufficient soil water is available.

Once PET is determined, a check is made to determine if soil water conditions are limiting. The soil water content at the lower limit is defined as the water content below which plants can no longer obtain water. If the soil water content is greater than the lower limit, ET is equal to PET. If the soil water content is less than the lower limit, ET is limited to the rate that upward flux supplies water to the root zone. The upward flux is the transfer of water in the unsaturated zone through capillary action from the vicinity of the water table to the root zone. If sufficient water is available through upward flux, ET is equal to PET. If sufficient water is not available through upward flux, ET demand is satisfied by removing water from the root zone, creating a dry zone. When the dry zone encompasses the root zone, ET is limited to the upward flux rate.

DRAINMOD Input Parameters

<u>Weather</u>

Measured hourly precipitation data from the R1 gauge were used for the F3 simulation, and data from the R6 gauge were used for the F5 and F6 simulations. Monthly average rainfall for the duration of the study is shown in Table 2.1. Since a full weather station was available at R6, the Penman-Monteith method was used to estimate PET from 1996-2001 for each simulation (Monteith, 1965).

Since the weather station at R6 was not established until 1996, PET for 1995 was initially estimated from climate data from the Tidewater Research Station (TRS) near Plymouth, NC using both the Penman-Monteith method and Thornthwaite (Thornthwaite, 1948) methods. The Penman-Monteith method overpredicted PET, and the Thornthwaite method underpredicted PET in comparison to the other estimates of PET from R6 for 1996-2001. An average of the two methods' predictions was used in simulating the hydrology of 1995. Monthly estimated PET for the study for each year and field is shown in Table 2.2.

Drainage System Parameters

Drainage system parameters include inputs that describe surface and subsurface components of the drainage system. The maximum surface storage is the volume of water that must be filled before surface drainage can occur. In a forested system, surface drainage is typically very poor; the maximum surface storage (STMAX) was set to be 10 cm for F3 and 15 cm for F5 and F6. Kirkham's depth (STORRO) was set to be 5 cm for F3 and 10 cm for F5 and F6.

Subsurface drainage parameters include inputs that describe drain depth and spacing, drain effective radius, drain hydraulic capacity (drainage coefficient), depth to impermeable layer, and height of controlled drainage structures. The drain effective radius was set to be 30 cm for all fields, which is used to describe open ditches. It was assumed that the ditches would provide enough drainage capacity for the peak drainage rates. The drainage coefficients were set to values higher than the highest measured drainage rate for each field. The depth to impermeable layer was not measured in the field, but it was estimated to be 250 cm for all fields, which is just below the lowest measured water table depth for the six years of measurements.

Saturated Hydraulic Conductivity

Since artificial drainage primarily involves lateral flow to drains, a very important input parameter in *DRAINMOD* is lateral saturated hydraulic conductivity. Hydraulic conductivity describes the resistance to water flow through the soil. Hydraulic conductivity in F3 was measured using the auger hole method (van Beers, 1970), and the results are shown in Table 2.3. However, the auger hole method only provides an estimate of saturated conductivity at a single point in the field, and it only represents a limited depth of the soil profile. In fields F5 and F6, the lateral saturated hydraulic conductivities are too high to measure using this method. Therefore, it was necessary to calibrate this parameter for input to *DRAINMOD.*

A method to aid in calibration of hydraulic conductivity was developed that is based on measured drainage outflow and water table depth. The Hooghoudt equation (2.8) is a relationship that considers the drainage system design and the hydraulic conductivity of the soil to determine drainage outflow based on water table depth. The first term in the

Hooghoudt equation, $\frac{4Km^2}{L^2}$, describes the flow that occurs above the drain, or in the case of ditches, the flow that occurs above the water surface in the ditch. The second term, $\frac{8Kd_e m}{L^2}$, describes the flow that occurs below the water level in the ditch. It is possible to separate the hydraulic conductivity for the entire profile, *K*, into an effective conductivity, K_e, for the soil above the ditch bottom and another conductivity, K_b, for the soil below the ditch bottom. The effective conductivity of the soil above the drain, K_e, can then be separated into as many layers as necessary as shown by,

$$K_e = \frac{K_i L_i + K_{i+1} L_{i+1} + \ldots + K_n L_n}{L_i + L_{i+1} + \ldots + L_n} \tag{2.9}$$

where K_i is the saturated lateral hydraulic conductivity of layer *i,* and *n* is the number of layers, and L_i is the depth of layer *i*. If the Hooghoudt equation is combined with equation 2.9, a relationship between water table depth and drainage outflow can be formed. The new relationship is a function of the drainage system properties and the individual conductivities of a multi-layered soil system as shown by,

$$q = \frac{4m^2 \left(\frac{K_i L_i + K_{i+1} L_{i+1} + \ldots + K_n L_n}{L_i + L_{i+1} + \ldots + L_n} \right) + 8K_b m d_e}{L^2} \tag{2.10}$$

A plot of measured height above the weir, *m*, versus measured drainage outflow, *q,* was constructed for each field for two years of data (1996-1997). To determine the flow rate for a given elevation, the height of the water table was taken in consideration. For example, if the water table reached the middle of the top layer, the depth of the top layer, L_i, would be equal to one-half L_i. If the water table reached the bottom of the top later, L_i would be equal to zero, and so on. In this way, the proper weight would be given to each layer in determining the flow rate for different water table depths.

Equation 2.10 was plotted for each field for different conductivities and layer depths until a best fit was determined as shown in Figures 2.3-2.5. The hydraulic conductivities that corresponded to the best fit (by inspection) were used as input parameters in the model for each field. Table 2.4 shows the hydraulic conductivities and soil layers that were used for each field.

Soil Water Characteristic

The soil water characteristic describes how tightly the water is held in the soil profile in the unsaturated state. The soil water characteristic is an input to *DRAINMOD*, and it is also used to determine other soil property inputs such as the volume drained-water table depth relationship and upward flux. The soil water characteristic was determined by taking a total of 15-21 undisturbed soil cores from two pits from each field. The cores were taken at four different layers from 0-170 cm, and the soil water characteristic analysis was performed using a pressure plate apparatus (Richards, 1965). Figures 2.6-2.8 show the measured soil water characteristic for each field at different layers. The vertical hydraulic conductivities were also determined from these undisturbed samples, as shown in Table 2.5.

Upward Flux

Upward flux is the rate of water transport upward through the soil profile in the unsaturated zone through capillary action. The rate of upward flux depends on the unsaturated hydraulic conductivity of the soil profile, which is rarely measured. An initial estimate of upward flux was determined using the *DRAINMOD* soil preparation program, which uses a numerical solution to the Darcy-Buckingham equation, given by,

$$q = -K(h)\frac{dh}{dz} + K(h) \tag{2.11}$$

where q is flux (cm hr^{-1}), z is the vertical position coordinate, h is the pressure head (cm), and $K(h)$ is the unsaturated hydraulic conductivity (cm hr^{-1}). The unsaturated hydraulic conductivity is determined using the Millington and Quirk method (1960). Skaggs (1980) provides a more complete description of the numerical method used in the soil preparation program to solve for upward flux. Some calibration of upward flux was required for input into the model. Table 2.6 shows calibrated upward flux values for each field.

Volume Drained – Water Table Depth Relationship

The volume drained-water table depth relationship is used to determine the change in water table depth when a given amount of water is removed or added. The volume drained-water table depth relationship was calculated from the soil water characteristic using the *DRAINMOD* soil preparation program. However, the calculated relationships required calibration to accurately model the forest hydrology. The calibration was necessary because soil cores only represent a tiny fraction of the actual soil system. The real forested system has various root and animal burrow holes and is very heterogeneous. With calibration it is possible to determine an estimate of the volume drained-water table depth relationship based on a greater soil volume.

To aid in the parameter calibration, a simple method was developed to estimate the slope of the water table depth-volume drained relationship. The slope of the relationship is equal to the drainable porosity. An estimate of drainable porosity can be determined from a given precipitation event by measuring the change in water table depth that occurs in response to measured rainfall as shown by,

$$f_{por} = \frac{P}{\Delta WTD} \tag{2.12}$$

where f_{por} is the drainable porosity (cm cm^{-1}), P is precipitation (cm), and ΔWTD is the change in water table depth (cm).

This method provides an estimate of drainable porosity for soil in the range of depths for which the water table rose during the precipitation event. Therefore, it was necessary to make estimates of drainable porosity using many different precipitation events so that the entire soil profile could be represented.

Care was taken such that storms would not be selected in which the rainfall was used to fill up a dry zone. By selecting rainfall events that occurred in wet periods, it was assumed that the rainfall only filled the drainable pore space and not the dry zone. Most precipitation events were selected during the fall and winter months when ET was the lowest. Some spring and summer events were selected if there had been other recent rainfall events.

An estimate of drainable porosity was determined for many storms for each field, and the estimates were plotted versus water table depth as shown in Figures 2.9-11 for F3, F5, and F6. From the plots, estimates of drainable porosity for different soil layers were made. A linear water table depth-volume drained relationship was defined for each layer with drainable porosity as the slope. Figure 2.12 shows the calibrated volume drained-water table depth relationships for each field.

Lateral Seepage

F5 is near a deep drainage canal, which caused significant seepage losses. A road between the canal and F5 was constructed by piling the soil from ditches and canals onto the highly organic soil, which included the remains of trees. The trees and organic soil provided a high conductivity conduit beneath the road, resulting in high seepage losses. The problem was addressed in late 1998 by digging a deep trench along the road and backfilling with mineral soil (Chescheir et al., 2003).

To simulate the seepage problem in 1996-1999 and the subsequent mineral soil backfilling, lateral seepage input parameters in *DRAINMOD* were calibrated. Lateral seepage in *DRAINMOD* is defined by the thickness of a transmissive layer below the impermeable layer, the hydraulic head of receiving waters, the distance from the field to receiving waters, and the lateral hydraulic conductivity of the zone between the field and the receiving waters. The transmissive layer below the impermeable layer in the system was assumed to be zero. The hydraulic head of the water in the canal is an average value that is measured from the top of the impermeable layer, and it was set to 100 cm. The distance from the field to the canal was set to be 20 m.

The primary calibration parameter was the lateral conductivity of the zone between the field and the receiving waters. The lateral hydraulic conductivity was set to 1.1 cm h^{-1} from 1996-1998. Since a trench was dug along the road and backfilled with mineral soil in late 1998, the conductivities were set to 0.75, 0.5, and 0.25 cm h^{-1} for 1999, 2000, and 2001, respectively, based on calibration. The decrease in conductivities over the three years could be attributed to increased compaction of the mineral backfill soil and the increased clogging of the mineral soil pores.

The lateral hydraulic conductivity input in *DRAINMOD* cannot be changed from year to year for a single run. Therefore, four separate simulations were performed for F5 as follows: one run from 1996-1998, and three runs for the individual years of 1999-2001. The previous year's predicted water table depth for the last day of the year was used as the initial water table depth for each simulation from 1999-2001.

Crop parameters

There was no specific crop specified for the simulations and relative yield was not predicted. Instead, only crop parameters that affect the hydrology were considered for input, including the effective rooting depth and the moisture content at the lower limit. The effective rooting depth is used to define the zone from which water can be removed to satisfy ET demand. The effective rooting depth for mature loblolly pine in F3 and F5 was specified to be 45 cm. This depth compares well to rooting depths of 37 to 50 cm, which were used in another hydrologic study of a loblolly pine plantation using *DRAINMOD* (Amatya et al., 2001). Since the trees were planted in 1992 for F6, the mature rooting depth could not be used, and calibration was required. Table 2.7 shows the rooting depths that were used for F6 for each year. The rooting depth of F5 was set to 20 cm for 2001 to account for the thinning that occurred at the end of 2000.

The rooting depth input parameter in *DRAINMOD* cannot be changed from year to year for a single run. Six separate simulations were performed for F6 for each year of the study, and the initial water depth was adjusted each year to match the previous year's predictions.

The lower limit parameter is the lowest soil water content in which plant transpiration occurs. This parameter is sometimes estimated as the wilting point, but the wilting point was not measured directly in this study. Therefore, the lower limit was estimated as approximately 0.25 $cm^3\ cm^{-3}$ less than the saturated water content (personal communication, G. Chescheir, 17 June 2002). The estimated lower limits of F3, F5, and F6 were 0.38, 0.40, and 0.46 $cm^3\ cm^{-3}$, respectively.

Infiltration

The infiltration rate and the surface storage capacity of most pine forests are very high (McCarthy et al., 1991). The infiltration parameters were estimated from the soil water characteristic data using the DRAINMOD soil preparation program. The soil preparation program uses the Mein and Larson (1973) method to define the suction at the wetting front, S_f. The soil preparation program then uses equation 2.7 to estimate the Green-Ampt infiltration parameter A. The infiltration parameter B is equal to the vertical hydraulic conductivity of the transmissive zone, K_s. Since the surface storage for each field was very high, the model was relatively insensitive to the infiltration parameters. The infiltration input parameters for each field are shown in Table 2.8.

NITROGEN SIMULATIONS

Modeling Scenario

Nitrogen simulations were performed using the nitrogen fate and transport model *DRAINMOD-N* II (Youssef, 2003). The model was used to simulate both NO_3-N and NH_4-N forms of N. The model was initially calibrated using three years of data from 1996-1998. To have an accurate calibration for 1996, it was necessary to begin the simulations in 1995. Hydrologic processes can have long-term effects on water quality. Hydrologic simulations were performed for 1995 using calibrated input values, and predicted water table elevations were compared with measured values. Drainage flow rates were not measured in 1995, and it was impossible to assess the accuracy of the flow predictions. *DRAINMOD-N* II was calibrated from 1996-1998 by comparing predicted cumulative N loads with measured values and by comparing annual process rates of denitrification, mineralization, and plant uptake with literature values. Model validation was performed by simulating N loads from 1995-2001 and comparing simulated and measured values from 1999-2001.

After the initial calibration and validation phase of the study, another calibration was performed using all six years of water quality data. The model performed fairly well using the initial calibration values, but a more extensive calibration was beneficial for determining the input parameters more accurately. The extensive calibration parameters are useful for a better description of the complex forested system and for future studies requiring these input parameters. The six-year calibration and modifications from the initial calibration will be discussed at the end of this chapter.

Many of the *DRAINMOD-N* II input parameters used to simulate the forested stands were taken from Youssef (2003). That study was performed at the TRS research station, which is less than 5 km from the Parker Tract sites. Some input parameters taken from the Youssef (2003) study were not site-specific. For other input parameters, it was assumed that the parameters would not change significantly because of the proximity and/or similarity of the study sites. The duplicated input parameters will not be discussed, and the reader is referred to Youssef (2003) for a thorough description of all input parameters. The remainder of the section describes the critical input parameters used in *DRAINMOD-N* II to describe N fate and transport on the forested sites.

General Parameters

General parameters describe how *DRAINMOD-N* II will operate to perform the simulations. NH_X-N was considered in all three simulations, and a uniform grid was used with a 5.0-cm grid size. *DRAINMOD*-predicted soil temperatures were used in the simulation (Luo et al, 2000). Since litterfall deposits organic nitrogen onto the soil, the application of organic nitrogen was included.

Soil Parameters

The soil parameters were input by defining soil layers from the surface to the impermeable layer. The same soil layers that were specified in the *DRAINMOD* hydrology simulations were also specified in *DRAINMOD-N* II. The lateral saturated hydrologic conductivities that were used in DRAINMOD, as shown in Table 2.4, were used as inputs in *DRAINMOD-N* II. The silt-plus-clay fraction was estimated to be 0.65 based on the official soil series descriptions (NRCS, 2003).

Model inputs of estimated wilting point, bulk density, soil pH, and ammonium distribution coefficient for each field and layer are shown in Tables 2.9-2.11. Bulk density was determined from the undisturbed soil cores that were used for the soil water characteristic analysis. There was some discrepancy in the measured bulk density values for F5. In the first pit, the average bulk density from the 0-30 cm layer was 1.12 g cm^{-3}, and the bulk density from the 30-45 cm layer was 1.94 g cm^{-3}. From the other pit, the measured bulk density was 0.83 g cm^{-3} for the top layer, which was 0-45 cm thick. Eight additional cores were taken from F5, and the average bulk density of the top layer was determined to be 1.0 g cm^{-3}. The model performed best during calibration using a bulk density value of 0.9 g cm^{-3} for the top layer. Experience has shown that collecting soil cores in the field can lead to compaction of the sample, which would result in a higher bulk density.

Soil pH was measured in wells screened at four different depths from February 2000 to April 2001. Table 2.12 shows the average measured pH values for each depth and field with calculated standard deviations.

The wilting point is the water content of the top layer of soil at which the plant can no longer extract water and is usually approximated as the water content at 15 MPa suction. However, the water content was not measured for either field at 15 MPa suction, so the following method to estimate wilting point was used.

Badr (1978) measured the wilting point in seven organic soils from the Coastal Plain of North Carolina and found wilting points that averaged 0.2 $cm^3\ cm^{-3}$. Some of the largest wilting point values varied from 0.25 to 0.35 $cm^3\ cm^{-3}$. Zeiliguer et al. (2002) reported a regression equation that allows for the prediction of wilting point given the soil clay, organic carbon, and silt contents.

$$w_{1500} = K_{clay}\text{*(clay content)} + K_{oc}\text{(org. C content)} + K_{silt}\text{*(silt content)} \qquad (2.13)$$

where K_{clay}, K_{oc}, and K_{silt} are regression coefficients that are equal to 0.39, 1.0, and 0.035, respectively, and clay, silt, and organic carbon contents are entered as fractions. The regression equation, data from the Badr (1978) study, and the measured soil water characteristics were all used to estimate the wilting points for different layers in each field.

DRAINMOD-N II uses a linear Freundlich isotherm to describe the partitioning between the solid and liquid phases of NH_4-N (Youssef, 2003). The linear isotherm is described by,

$$C_s = K_d C_a \qquad (2.14)$$

where C_s is the concentration of ammonium in the solid phase [M L^{-3}], C_a is the concentration of ammonium in the aqueous phase [M L^{-3}], and K_d is the ammonium distribution coefficient [$L^3\ M^{-1}$].

Youssef (2003) used distribution coefficients (K_d) for different layers that varied from 2.0 to 2.6 $cm^3\ g^{-1}$. Little is known about exchange reactions of NH_4-N in forest soils (Matschonat et al., 1996). However, Smethurst et al. (1999) determined distribution coefficients for ammonium in organic and mineral horizons of several forest soils. The authors reported distribution coefficients as high as 10 $cm^3\ g^{-1}$ for the organic horizons with NH_4-N solution concentrations greater than 1.0 mg L^{-1}. The authors reported that the distribution coefficients for the mineral horizons were significantly lower than those for the organic horizons. The distribution coefficients of the mineral horizons were lower than 5 $cm^3\ g^{-1}$. Estimates of the distribution coefficients for the study fields were made by model calibration, with the initial values from Youssef (2003).

The calibrated distribution coefficients were higher for F6 than for F3 and F5. The organic matter content of F6 is higher than F3, and it is therefore reasonable that the K_d values should be higher. Hesterberg (1998) found that the sorption of metal cations increased with pH, and Kithome et al (1999) found that the sorption of ammonium increased with pH on a soil with very high cation exchange capacity. Hesterberg (1998) stated that one of the reasons for the increased sorption of metal cations was due to the deprotonation of the absorbing soil surfaces. Organic matter contains carboxylic and phenolic acids, and as the pH increases, the OH groups of the acids are deprotonated. Deprotonation could provide more negatively charged sites for positively charged ammonium to be adsorbed. Since the average pH of F6 is considerably higher than F5, it is reasonable to assume that the distribution coefficient of F6 would be higher than F5 as well. A detailed description of the calibration process is shown in Appendix A.

Crop parameters

The same rooting depth parameters that were used for the *DRAINMOD* hydrology simulations were used as the rooting depths for *DRAINMOD-N* II. The rooting depth for F3 and F5 was specified as 45 cm, and the rooting depths for F6 are shown in Table 2.7.

Nitrogen Uptake Parameters

In *DRAINMOD-N* II, nitrogen uptake is estimated as a function of the predicted yield from *DRAINMOD*. *DRAINMOD* cannot adequately predict the relative yield of trees because the model does not simulate the cumulative effect of climate on tree physiology from year to year. Therefore, it was necessary to estimate nitrogen uptake using another method. A modification was made to *DRAINMOD-N* II to allow potential N uptake to be a monthly input parameter instead of being computed from the relative yield predictions from *DRAINMOD*.

The forest productivity model *PnET-CN* (Aber et al., 1997) was used in this study to estimate N uptake. The model was selected because it is a relatively simple lumped-parameter model that considers historic climate data and a variety of vegetation characteristics that can be adjusted for loblolly pine. The model was designed to have very few site-specific input parameters for ease of model use. An earlier version of the model, *PnET* II (Aber et al., 1995), was tested for a loblolly pine plantation in southeastern NC by Sun et al., (2000), and many of the input parameters were already available. In addition to estimating monthly N uptake, the model also predicts annual foliar production, which is necessary for determining the addition of organic matter to the soil system through litterfall. The litterfall component of the model is discussed in a following section.

PnET-CN Model Description

The *PnET-CN* model (Aber et al., 1997) was developed to simulate C, N, and water interactions in forest ecosystems. It is a generalized, lumped-parameter model that operates at a monthly time step at the field-to-watershed scale. The model uses monthly inputs of climate and N deposition to predict photosynthesis, evapotranspiration, N cycling, and N uptake.

A simple monthly water balance is used in *PnET-CN*, which is the same water balance that was used in *PnET* (Aber et al., 1992). The water balance is calculated on a monthly basis using measured precipitation. A constant fraction of water that is lost due to interception and evaporation in the forest canopy is subtracted from the added precipitation each month. A fraction of water that is lost due to macropore drainage is subtracted from the remaining precipitation. This water does not enter the available soil water pool and is lost as drainage. The fractions of interception loss and macropore drainage loss can both be specified by the user, but the default values are 0.15 and 0.1, respectively. The available capacity of the soil water pool is defined by a parameter called the water holding capacity (cm), which is the available amount of water in the top 100 cm of soil at field capacity. Transpiration is subtracted from the available water pool and is calculated as a function of photosynthesis and the water use efficiency (WUE). Water use efficiency is the amount of C fixed per mass of water transpired. Any water in excess of the soil water capacity is lost as drainage.

The C cycle includes processes of photosynthesis, respiration, plant C allocation, litterfall, and decomposition. The N cycle includes processes of mineralization, nitrification, plant N uptake, leaching losses, and plant N allocation. Both cycles are shown in Figure 2.13. Plant N uptake is calculated as a function of the N content in the plant and the maximum storage capacity of N in the plant. As the internal plant N pool increases, the demand for N uptake decreases. Aber et al. (1997) provides a more detailed description of the C and N cycling processes.

The model's photosynthetic routine (*PnET-Day*) has been validated using C flux data from an eddy covariance tower in MA (Aber et al., 1996). The water balance component of the model (*PnET*) was compared with stream flow data in New Hampshire (Aber et al., 1992). The N cycling routine was tested against measured values of production, N cycling, and nitrate loss in New Hampshire (Aber et al., 1997; Aber and Driscoll, 1997). The hydrology and productivity components of the model were successfully validated in eastern North Carolina by Sun et al. (2000). Pan et al. (2003) reported that *PnET-CN* predicted N leaching losses and N retention rates compared well to measured values in the Chesapeake Bay watershed.

PnET-CN Model Inputs

Model inputs include climate and N deposition parameters, site history and disturbance parameters, and vegetation parameters. The climate and N deposition parameters include monthly values of average maximum and minimum temperature, photosynthetic active radiation (PAR), total precipitation, and total NO_3-N and NH_4-N deposition. The model considers long-term effects of climate, disturbance, and land use history, and long term records of data are beneficial to model accuracy. Monthly precipitation was taken from measured data at the Plymouth, NC weather station from 1933-1995 (Evans, 1991; SERCC, 2003), and measured data from R6 were used for 1996-2001. Maximum and minimum monthly air temperature data were obtained from measured data at Plymouth from 1949-2001 (SERCC, 2003). The temperature data from 1949-2001 were averaged for each month and used in the climate file for 1933-1947. PAR was determined from measured gross radiation at the weather station at R6 from 1996-2001. An average of the six years of PAR data was used for each year from 1933-1995.

Average monthly deposition was determined from measured concentrations of rainwater from 1996-2001. The majority of the rainfall concentration measurements were made at the R6 weather station. However, when data were missing from the R6 station, some concentrations were used from Carteret, NC, which is also in the coastal plain physiographic region. Nitrogen deposition values were determined by multiplying the concentration of NO_3-N or NH_4-N in rainfall by the precipitation for a given month. Since N deposition has increased over the past century due to industrialization, it was assumed that N deposition before 1900 was 20 % of the current level and increased linearly as a constant ramp function to current values (S. Ollinger, personal communication, 23 July 2003; Pan et al., 2003).

Site disturbance parameters include land use history and tree mortality and removal through harvesting or fires. The three fields were unmanaged forests until the 1970's when ditches were installed. Harvesting was modeled for each forest by assigning 'biomass mortality' and 'fraction removed' parameters. The biomass mortality corresponds to the fraction of trees that were cut, and the fraction removed corresponds to the fraction of trees that were removed from the site. Both parameters were set to 0.85.

The majority of the vegetation input parameters are designed to be constant across all forest types. Vegetation input parameters that change based on forest type were for the most part estimated from the 'pine' scenario in Aber et al. (1995) and in Aber et al. (1997). Pan et al. (2003) demonstrated success using these parameters for loblolly pine in the Chesapeake Bay watershed. Since the 'pine' input parameters were developed for forests in the northeastern United States, some modifications were made for the conditions in the lower coastal plain of North Carolina using inputs from Sun et al. (2000). In addition, some parameters were calibrated by comparing N uptake values from the literature with predicted uptake and by comparing predicted drainage with measured drainage. Table 2.13 shows the critical vegetation input parameters that were used for the simulations and the sources of those parameters.

PnET-CN Modeling Results

Simulations were performed for each field; the only difference between runs was the timing of harvest disturbances. The model was incapable of adequately simulating N uptake immediately after a harvest. For an unknown reason, N uptake predictions peaked in January and February, when this should be the time of lowest N uptake in reality. After about 10 years the simulations of N uptake are much more reasonable. Since the F3 harvest occurred in 1982, there is adequate time until 1996 for the predictions of uptake to be reasonable. Therefore, estimates of N uptake for F5 and F6 were made from the F3 predictions.

PnET-CN did a fair job in simulating monthly drainage from 1996 to 2001 for F3. Figure 2.14 shows monthly *PnET-CN* predicted drainage versus measured drainage from F3, and Figure 2.15 shows cumulative monthly predicted drainage versus measured drainage from F3. On average the model overpredicted annual drainage by 7.7 cm yr^{-1}. The model overpredicted drainage by 28 % over the entire 6-year simulation period. Sun et al. (2000) found that *PnET II,* which has similar hydrology and productivity components, also overpredicted drainage for a southeastern loblolly pine plantation.

Ducey and Allen et al. (2001) performed a regression model analysis on 14 forested stands in the southeastern United States. Eleven of the stands were lower coastal plain sites. The authors estimated that N uptake rates were between 47 and 103 kg ha^{-1} yr^{-1}. The variability was a response to the soil and drainage properties of each site. In a report by the North Carolina Forest Nutrition Cooperative (NCFNC, 1997), N uptake values were simulated using a regression model for stand ages from 5 to 25 years. The model predicted uptake rates between 62 and 135 kg ha^{-1} yr^{-1}, with the smallest values occurring at 5 years and the largest values occurring at about 15 years.

PnET-CN predicted uptake rates between 83 and 97 kg ha^{-1} yr^{-1} for F3. It was assumed that the uptake from F5 would be the same as from F3, since they were similar in stand age. Nitrogen uptake for F6 was considered as a fraction of the predicted uptake for F3. The fraction was based on results from NCFNC (1997), which considered uptake from 5-25 years of stand age. Estimates of N uptake by field and year are shown in Table 2.14.

These predictions correspond to actual estimated uptake rates instead of the potential uptake rates that are required in the modified *DRAINMOD-N* II. The potential uptake rates were estimated by calibrating *DRAINMOD-N* II. In the calibration process, predictions of actual uptake from *PnET-CN* were compared with predictions of actual uptake from *DRAINMOD-N* II. The estimates of potential N uptake that were used in the model are also shown in Table 2.14.

Organic Nitrogen Application Parameters

Organic nitrogen is applied to forested fields by litterfall. Litterfall from coniferous trees occurs continuously, all year. To simulate this continuous process, monthly estimates of litterfall production were required. *PnET-CN* predicts annual foliar production. Needles from loblolly pine trees fall about every two years (Sun et al., 2000). To predict litterfall from foliar production, litter production for a given year was estimated by averaging the previous two years' foliar production. For example, the predicted foliar productions for 1993 and 1994 were averaged to estimate the litterfall for 1995. Monthly litterfall was estimated from annual litterfall using a normalized loblolly pine litterfall distribution from Dalla-Tea et al. (1991). The normalized litterfall distribution is shown in Figure 2.16.

PnET-CN simulations were performed for all three fields, and the estimated monthly litterfall productions for each field are shown in Figure 2.17. Annual predicted litterfall productions for each field are shown in Table 2.15. The average annual litterfall productions for F3, F5, and F6 were estimated to be 3500, 3400, and 1400 kg ha^{-1} yr^{-1}, respectively. Measured annual loblolly pine litterfall rates from the literature are shown in Table 2.16. The measured annual litterfall rates from the literature varied from 1900 to 4600 kg ha^{-1} yr^{-1}, and the average litterfall rate was 3400 kg ha^{-1} yr^{-1}.

In *DRAINMOD-N* II, applied organic matter is characterized by its organic C content, lignin content, carbon-to-nitrogen ratio (C:N), and application method. Litterfall was simulated as surface-applied organic matter. The organic C, organic N, and lignin contents were each determined from the literature as shown in Table 2.17. The average values from the literature were used as inputs in the model. A C:N ratio of 110 was calculated from the literature values of organic C and N content. Despite the limited amount of studies with lignin measurements, Meentemeyer (1978) states that the lignin concentration for a particular tree species is consistent within a region.

Transformation Parameters

The transformation parameters include parameters that describe processes of fertilizer application, urea hydrolysis, nitrification, denitrification, pH control, and volatilization. There was no fertilizer applied on the simulated fields during the simulated years, and therefore the parameters describing the processes of fertilizer application and urea hydrolysis had no impact on model predictions. The pH flag was set to 1, which corresponds to the model resetting the pH to the initial value after each year.

Nitrification

Nitrification in *DRAINMOD-N* II is described using Michaelis-Menten kinetics. Youssef (2003) performed an extensive literature review of measured values of the Michaelis-Menten maximum reaction rate for nitrification, $V_{max,nit}$, in agricultural soils. Maximum nitrification rates in that review ranged from 4.0 to 38.0 μg N g^{-1} soil d^{-1}, with the higher rates in studies with neutral to slightly alkaline soils. The Michaelis-Menten half saturation constant for nitrification, $K_{m,nit}$, was measured by Malhi and McGill (1982) and found to be 153.6-186.3 μg N g^{-1} soil. However, Nishio and Fujimoto (1990) found values of $K_{m,nit}$ equal to 0.86 μg N g^{-1} soil, which is much less than the Malhi and McGill (1982) study. Nishio and Fujimoto (1990) attributed the difference to the incubation times in the two studies. Youssef (2003) used values of $V_{max,nit}$ and $K_{m,nit}$ equal to 14 μg N g^{-1} soil d^{-1} and 10 μg N g^{-1} soil, respectively.

An extensive literature search was performed for this study to determine $V_{max,nit}$ for forested soils, but only one study was found in which the parameter was measured. Stark and Firestone (1996) found $V_{max,nit}$ to be 33.4 and 9.6 μg N g^{-1} soil d^{-1} for the top 0-1 cm and 1-9 cm of soil, respectively. However, the pH of the soil in their study was 6.5, which is considerably higher than the measured pH values for F3, F5, and F6. Since the Michaelis-Menten parameters for nitrification in forested conditions could not confidently be obtained from the literature, it was necessary to determine these parameters by calibration.

Calibration was performed by adjusting the Michaelis-Menten nitrification parameters to match the observed ratio of nitrate to ammonium with the predicted ratio for the calibration period. For example, if the model overpredicted nitrate loss but underpredicted ammonium loss, it was assumed that the model was overpredicting nitrification. Increasing $V_{max,nit}$ and reducing $K_{max,nit}$ both had the effect of increasing nitrification. The calibrated $V_{max,nit}$ values for F3, F5, and F6 were 6.0, 15.0, and 15.0 μg N g^{-1} soil d^{-1}, respectively. The calibrated $K_{m,nit}$ values for F3, F5, and F6 were 42.0, 42.0, and 25.0 μg N g^{-1} soil, respectively. A more detailed discussion of the calibration process is given in Appendix A.

Denitrification

Denitrification in *DRAINMOD-N* II is described using Michaelis-Menten kinetics with respect to NO_3-N. Youssef (2003) performed an extensive literature review and reported measured values of the maximum denitrification rate, $V_{max,den}$, and the half saturation constant, $K_{m,NO3}$. $V_{max,den}$ ranged from 3.3 to 150.0 μg N g^{-1} soil d^{-1}, and $K_{m,den}$ ranged from 1.8 to 170.0 mg N L^{-1}. The majority of these studies were performed on lands used for pasture or row crop agriculture. Youssef (2003) used values of $V_{max,den}$ and $K_{m,NO3}$ equal to 3.5 μg N g^{-1} soil d^{-1} and 45.0 mg N L^{-1}, respectively.

No studies were found that measured the Michaelis-Menten denitrification parameters for forested, highly organic soils. Therefore it was necessary to estimate these parameters by calibration. Calibration was conducted by comparing predicted and observed N losses in drainage and by comparing predicted cumulative annual denitrification rates with measured denitrification rates from the literature. The denitrification rate was increased if the model was accurately predicting ammonium losses but overpredicting nitrate losses. The calibrated $V_{max,den}$ value for each field was 3.0 μg N g^{-1} soil d^{-1}. The calibrated $K_{m,NO3}$ value for F3 and F5 was 45.0 mg N L^{-1} and 25.0 mg N L^{-1} for F6. A more detailed discussion of the calibration process is given in Appendix A.

The effect of soil organic matter on denitrification rate is defined using a depth function (Equation 1.19). The exponent alpha is used to describe the effect of soil organic matter on denitrification rate. Denitrification requires available C to proceed and alpha reflects the C availability as a function of depth. Youssef (2003) used 0.05 as the value for alpha, and values of alpha equal to 0.05, 0.008, and 0.008 were used for F3, F5, and F6, respectively. Lower values of alpha correspond to higher values of the carbon availability response function, f_z, as shown in Equation 1.19. As shown in Equation 1.18, higher values of f_z result in higher denitrification rates. Since F5 and F6 are organic soils with very high C contents, carbon availability is not a limiting factor for denitrification, and the alpha values were very low.

Organic Matter Parameters

Organic matter parameters include the initial soil organic matter content in the top layer and the environmental response function for organic C decomposition. In addition, the percentage of initial total organic carbon is assigned to either the active, slow, or passive organic matter pools. Each pool is defined by the C:N ratio and the rate of decomposition.

The initial soil organic matter content was determined by measuring the organic C and N in the top 20 cm of soil for each field. Twenty samples were taken from F3 and twelve samples were taken from F5 and F6 each in May of 2003. The samples were taken at depths of 0-5, 5-10, 10-15, and 15-20 cm. The samples were oven dried and sieved to 200 μm for analysis. The organic C and N contents as well as the calculated C:N ratios are shown in Table 2.18.

Youssef (2003) assigned 40 % of the initial soil organic matter content to the slow pool and 60 % to the passive pool. Since mineralization rates were not measured in these fields, the assignment of the percent initial organic content to the pools was determined by calibration. Calibration was performed by comparing the measured and observed N losses in drainage and by comparing predicted mineralization rates with rates from the literature. Reducing the organic matter allocation to the slow pool and increasing the allocation to the passive pool reduced the mineralization rate. After calibration, field F3 had 47.5 % of the initial organic matter in the slow pool and 52.5 % in the passive pool. Field F5 had 22 and 78 % in the slow and passive pools, respectively. Field F6 had 14 and 86 % in the slow and passive pools, respectively. A more detailed discussion of the calibration process is given in Appendix A.

The C:N ratios of the SOM pools were determined from the measured values in Table 2.18. Kelly et al. (1997) specified C:N ratios for the active, slow, and passive pools for the CENTURY model, which has a similar C cycle as *DRAINMOD-N* II. In that study, the C:N ratios of the slow pools were consistently higher than those from the passive pools. Therefore, it was estimated that the C:N ratio of the slow pool would be about 20 % higher than the passive pool. A more detailed discussion of the OM pool allocation is given in Appendix B.

The model initially sets the metabolic and structural pools to be empty. In the beginning of 1995, each field already had a significant amount of organic matter on the ground surface due to litterfall. Some of this organic matter would be decomposed and available for mineralization. Therefore it is unreasonable to assume that the metabolic and structural pools would initially be empty.

The initial organic matter content of the metabolic and structural pools was simulated by a large application of organic matter at the beginning of the simulations. The amount of the application was determined by iteration. For this process, a version of the model was used that reports the organic C content of each pool after each day. The goal of the iteration process was to maintain an equilibrium C content of the metabolic and structural pools from the start of the simulation.

The model was run first with no initial application. The organic carbon content of the metabolic and structural pools increases gradually with time and eventually reaches equilibrium. Equilibrium is reached because the organic matter is continuously applied through litterfall and is decomposed. The amount of organic matter that corresponds to the equilibrium C content was then determined. The amount of organic matter was determined from the organic C content of litterfall (Table 2.17). The model was then run with the initial organic matter application. The process was repeated until the organic C content of the structural and metabolic pools remained in equilibrium throughout the simulation.

Model Initialization Parameters

Since the N simulations began in 1995 and the first calibration year was in 1996, it was assumed that the model initialization parameters would have a negligible effect on model predictions by 1996. The model initialization parameters from Youssef (2003) were used for each simulation.

Model Calibration 1996-2001

The model was recalibrated using water quality data from 1996-2001 to determine more accurate input parameters. Only the changes in input parameters from the original calibration will be discussed in this section.

<u>Six-year Calibration for F3</u>

After calibration from 1996-2001, nitrification was increased by changing Michaelis-Menten maximum reaction rate for nitrification, $V_{max,nit}$, from 6.0 to 8.0 μg N g^{-1} soil d^{-1}. $K_{max,nit}$ was changed from 42.0 to 27.0 μg N g^{-1} soil. Mineralization was reduced by changing the proportions of the slow and passive pools of the initial organic C content. The percentage of the initial organic C content in the slow pool changed from 47.5 to 42.0 % after the six-year calibration. The percentage in the passive pool changed from 52.5 to 58 % after calibration.

Six-year Calibration for F5

The ammonium distribution coefficient parameters were changed from the values shown in Table 2.10 for the initial calibration to 2.3 $cm^3\ g^{-1}$ for the top 130 cm of soil and 2.0 $cm^3\ g^{-1}$ for 130-250 cm depth. Nitrification was decreased by changing the Michaelis-Menten maximum reaction rate for nitrification, $V_{max,nit}$, from 15.0 to 9.0 µg N g^{-1} soil d^{-1}. Denitrification was increased by changing the Michaelis-Menten parameters for denitrification, $V_{max,den}$ and $K_{m,NO3}$. $V_{max,den}$ and $K_{m,NO3}$ were equal to 3.0 µg N g^{-1} soil d^{-1} and 45.0 mg N L^{-1}, respectively, after the initial calibration. After the six-year calibration, $V_{max,den}$ and $K_{m,NO3}$ changed from 4.0 µg N g^{-1} soil d^{-1} and 22.0 mg N L^{-1}, respectively.

Mineralization was reduced by changing the proportions of the slow and passive pools of the initial organic C content. The percentage of the initial organic C content in the slow pool changed from 22 to 20 % after the six-year calibration. The percentage in the passive pool changed from 78 to 80 % after calibration.

Six-year Calibration for F6

The ammonium distribution coefficient parameters were decreased from the values shown in Table 2.11 for the initial calibration to the values shown in Table 2.19 for the six-year calibration. The nitrification rate was increased slightly by increasing the Michaelis-Menten half-saturation constant for nitrification, $K_{m,nit}$, from 25.0 to 30.0 µg N g^{-1} soil.

The full input files for *DRAINMOD-N* II for each field and for the 1996-2001 calibrations are attached in Appendices C-E.

STATISTICAL PARAMETERS

Several statistical parameters were used to evaluate the accuracy of the model predictions of water table elevation and drainage. The first parameter is the average absolute daily difference, *AADD,* which is defined as,

$$AADD = \frac{\sum_{i=1}^{n} \left| P_i - O_i \right|}{n} \tag{2.15}$$

where O_i and P_i are the i^{th} observed and predicted value of a parameter, respectively, and n is the number of data points. The *AADD* is the average of the absolute value of all the model prediction errors for a given set of predictions.

The second statistical parameter is the average daily difference, ADD, which is defined as,

$$ADD = \frac{\sum_{i=1}^{n} \left(P_i - O_i \right)}{n} \tag{2.16}$$

The *ADD* is the average of the model prediction errors for a given set of predictions. The statistic does not use the absolute value of the prediction errors and is useful for reporting the degree of bias for a given set of predictions. Positive values of *ADD* correspond to model overprediction, and negative values correspond to underprediction.

The third statistical parameter is the coefficient of determination, R^2, which is defined as,

$$R^2 = \frac{\left\{ \sum_{i=1}^{n} \left(O_i - \overline{O} \right)\left(P_i - \overline{P} \right) \right\}^2}{\sum_{i=1}^{n} \left(O_i - \overline{O} \right)^2 \sum_{i=1}^{n} \left(P_i - \overline{P} \right)^2} \tag{2.17}$$

where $\overline{O}$ and $\overline{P}$ are the average observed and predicted values, respectively. R^2 varies from 0 to 1 and describes the degree of association between observed and predicted values. A value of R^2 equal to 1 indicates the model describes all the variability of the measured data, whereas a value of 0.2 would indicate the model only describes 20 % of the variability (Amatya and Skaggs, 2001).

The fourth statistical parameter is the Nash-Sutcliffe coefficient or the coefficient of efficiency, *E*, which is described by (Nash and Sutcliffe, 1970),

$$E = 1 - \frac{\sum_{i=1}^{n} \left(O_i - P_i \right)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \tag{2.18}$$

The coefficient of efficiency varies from minus infinity to 1.0, with higher values indicating better agreement. Negative values of *E* mean that the model-predicted values are worse than simply using the observed mean (Loague and Green, 1991). The coefficient of efficiency is a useful parameter when describing model error because it is sensitive to differences in the observed and simulated means and variances (Amatya and Skaggs, 2001). The coefficient of variation describes the degree of association about the best-fit line through the data, whereas the coefficient of efficiency describes the degree of association about a 1:1 line through the data, which represents zero model error. If the best-fit line through the data has a biased slope, R^2 will be higher than E.

Another statistic, the percent-normalized error, NE, was used to compare observed and predicted cumulative drainage,

$$NE = \frac{\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} O_i}{\sum_{i=1}^{n} O_i} \tag{2.19}$$

The percent-normalized error describes the percent error of the cumulative drainage predictions. Since it is normalized, it is useful for comparing model accuracy between simulated years and fields.

Table 2.20 describes the assumed numerical significance of such descriptors as 'excellent', 'very good', etc. for water table depth for each of the statistical parameters. The true meaning of AADD and ADD is difficult to evaluate for drainage. These parameters should be evaluated by comparing them to the average observed drainage for each simulation period. Therefore, using generalized qualitative descriptors for these parameters for drainage flow is unreasonable.

Table 2.1: Measured monthly rainfall (in cm) at the R1 and R6 gauges from 1995 to 2001.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
R1	**1995**	7.0	15.0	6.7	5.0	5.6	24.9	6.2	12.1	3.8	10.0	8.3	5.9	110.3
	1996	9.5	7.3	13.2	6.3	4.6	6.6	19.8	13.3	23.0	15.5	8.3	8.7	135.9
	1997	7.3	4.9	8.9	6.1	7.1	5.1	11.3	9.9	9.6	6.0	9.9	7.9	93.9
	1998	15.1	9.7	12.0	6.9	16.0	11.6	6.3	15.8	4.8	5.2	7.5	15.2	126.2
	1999	9.8	4.5	7.0	4.1	6.9	7.5	7.8	16.3	37.8	19.1	4.7	2.8	128.2
	2000	11.3	3.7	9.3	13.5	8.5	13.4	14.4	16.3	24.2	0.1	7.0	5.1	126.6
	2001	3.4	6.4	7.9	2.7	7.3	14.2	12.4	10.1	2.1	1.3	3.5	1.9	73.2
R6	**1995**	8.6	14.7	8.2	6.2	5.7	24.9	6.2	12.1	3.8	10.0	8.3	5.9	114.3
	1996	10.9	8.7	12.4	5.4	5.7	9.7	18.5	13.3	22.3	16.8	5.9	7.0	136.5
	1997	7.5	6.6	8.0	6.1	8.6	6.1	8.5	9.6	9.9	7.2	9.9	7.9	95.7
	1998	15.1	15.0	10.8	7.3	16.0	12.1	4.9	13.6	3.0	5.6	7.3	14.8	125.5
	1999	8.9	5.8	7.0	5.9	11.0	11.1	5.9	18.6	38.5	16.6	5.7	2.6	137.6
	2000	11.3	3.7	9.3	13.3	9.1	12.3	10.2	16.3	24.2	0.1	7.4	4.8	121.8
	2001	3.4	6.1	6.9	2.6	8.1	15.7	16.7	7.7	2.4	1.4	2.8	0.9	74.7

Table 2.2: Estimated potential evapotranspiration from the research sites from 1995 to 2001.

R1	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1995	3.4	3.7	7.5	11.4	11.8	11.5	13.9	12.4	8.5	6.9	3.6	2.8	97.4
1996	2.9	4.9	6.2	11.4	10.0	10.7	11.7	9.7	7.3	7.6	3.7	2.6	88.7
1997	2.1	3.3	6.2	8.4	11.4	11.7	12.4	13.8	9.1	7.1	3.9	3.0	92.4
1998	2.4	2.6	5.0	8.2	10.6	12.3	13.8	12.9	11.4	8.8	5.6	3.6	97.0
1999	3.5	4.4	6.8	10.4	12.4	11.4	15.2	12.8	7.0	7.2	5.4	3.6	100.1
2000	3.1	4.2	6.5	7.7	13.7	13.9	11.6	10.7	8.0	9.1	4.2	3.7	96.2
2001	4.3	4.5	7.1	11.4	13.6	13.3	12.8	13.8	10.6	8.6	4.9	3.4	108.2

Table 2.3: Measured lateral hydraulic conductivity of F3 using the auger hole method.

Hole	Hole Depth cm	Lateral K cm/h
1	65	14
2	79	45
3	80	68
4	89	58
5	101	13

Table 2.4: Saturated lateral conductivity input parameters for each field.

F3		**F5**		**F6**	
Depth, cm	K, cm hr^{-1}	Depth, cm	K, cm hr^{-1}	Depth, cm	K, cm hr^{-1}
0-30	700	0-45	650	0-30	700
30-40	650	45-55	400	30-45	350
40-50	100	55-68	10	45-60	10
50-70	40	68-250	5	60-240	5
70-250	5				

Table 2.5: Measured values of vertical saturated conductivity from undisturbed soil samples from two soil pits in each field (standard deviations in parentheses).

Field Layer	**Depth** cm	**Pit One** cm hr^{-1}	**Pit Two** cm hr^{-1}	**Field Average** cm hr^{-1}
F3 1	0-40	12(2.0)	15(1.1)	13(1.7)
F3 2	40-90	15(6.3)	0.37(0.1)	10(5.5)
F3 3	90-170	0.1(0.01)	0.03(0.01)	0.07(0.01)
F5 1	0-40	40(3.7)	330(46)	140(27)
F5 2	40-90	0.58(0.25)	19(0.07)	9.7(0.18)
F5 3	90-170	2.5(0.37)	1.5(0.26)	2.0(0.31)
F6 1	0-40	28(4.9)	240(67)	130(44)
F6 2	40-90	54(6.3)	19(1.0)	36(4.6)
F6 3	90-170	0.56(0.31)	0.8(0.09)	0.66(0.25)

Table 2.6: Upward flux input values for each field.

	F3	F5	F6
	cm h^{-1}	cm h^{-1}	cm h^{-1}
0	0.5	0.5	0.5
20	0.5	0.5	0.5
30	0.5	0.5	0.5
35	0.5	0.39	0.37
40	0.5	0.24	0.23
45	0.43	0.16	0.15
60	0.057	0.054	0.050
75	0.015	0.015	0.031
90	0.006	0.010	0.017
120	0.0018	0.003	0.0025
150	0.0010	0.0005	0.0005
175	0.0005	0	0
200	0.0005	0	0
225	0	0	0

Table 2.7: Calibrated DRAINMOD rooting depths for F6 for 1995-2001.

Year	1995	1996	1997	1998	1999	2000	2001
Stand Age, yr	3	4	5	6	7	8	9
Rooting Depth, cm	6	6	9	15	23	31	38

Table 2.8: Infiltration DRAINMOD input parameters for each field.

Water Table Depth	F3		F5		F6	
cm	A	B	A	B	A	B
0	0	13.5	0	137	0	135
10	1.72	13.5	41.92	137	33.91	135
20	3.43	13.5	53.93	137	51.33	135
40	6.6	13.5	67.89	137	72.45	135
60	9.29	13.5	72.25	137	81.28	135
80	10.86	13.5	74.94	137	83.49	135
100	11.92	13.5	77.28	137	85.14	135
150	13.51	13.5	75.73	137	88.58	135
200	13.51	13.5	75.73	137	88.58	135
1000	13.51	13.5	75.73	137	88.58	135

Table 2.9: Soil input parameters for *DRAINMOD-N* II for F3.

Layer	Layer Depth cm	Wilting Point $cm^3\ cm^{-3}$	Bulk Density $g\ cm^{-3}$	pH	K_d $cm^3\ g^{-1}$
1	30	0.14	1.24	4.1	2.8
2	40	0.14	2.00	4.1	2.8
3	50	0.24	2.00	3.9	2.8
4	70	0.24	2.00	3.9	2.8
5	255	0.24	1.66	3.7	2.0

Table 2.10: Soil input parameters for *DRAINMOD-N* II for F5.

Layer	Layer Depth cm	Wilting Point $cm^3\ cm^{-3}$	Bulk Density $g\ cm^{-3}$	pH	K_d $cm^3\ g^{-1}$
1	46	0.29	0.90	3.9	2.8
2	56	0.27	1.96	3.9	2.8
3	68	0.29	1.96	3.9	2.8
4	130	0.34	2.00	3.8	2.4
5	250	0.13	2.00	3.8	2.0

Table 2.11: Soil input parameters for *DRAINMOD-N* II for F6.

Layer	Layer Depth cm	Wilting Point $cm^3\ cm^{-3}$	Bulk Density $g\ cm^{-3}$	pH	K_d $cm^3\ g^{-1}$
1	30	0.32	0.90	4.2	3.7
2	45	0.32	0.90	4.2	3.0
3	60	0.32	1.96	4.2	2.8
4	130	0.18	2.00	4.4	2.4
5	250	0.13	2.00	4.6	2.0

Table 2.12: Mean pH measurements from each field with standard deviations in parentheses.

Sampling Depth (cm)	25-50	50-75	75-100	100-125	Total
F3	4.1(0.2)	3.9(0.1)	3.8(0.1)	3.8(0.2)	**3.83**(0.15)
F5	3.9(0.5)	3.9(0.2)	3.9(0.3)	3.8(0.3)	**3.87**(0.25)
F6	4.0(0.2)	4.1(0.1)	4.3(0.1)	4.6(0.2)	**4.35**(0.24)

Table 2.13: Critical *PnET-CN* input parameters for loblolly pine stand with sources.

Parameter Description	**Parameter Abbreviation**	**Value for Loblolly Pine**	**Source**
Intercept of the Regression Relationship between Max. Photosynthesis and N Concentration (nmol CO2 g^{-1} leaf s^{-1})	AmaxA	5.3	Aber et al., 1995
Slope of the Regression Relationship between Max. Photosynthesis and N Concentration (nmol CO2 g^{-1} leaf s^{-1} $\%^{-1}$ of N)	AmaxB	21.5	Aber et al., 1995
Optimum Air Temperature	PsnTOpt	28	Sun et al., 2000
Specific Leaf Weight (g (projected m^2 leaf)$^{-1}$)	SLWMax	230	calibrated
Half Saturation Light Level	HalfSat	291	Sun et al., 2000
Light Extinction Coefficient	K	0.46	Sun et al., 2000
Growing Degree Days for Leaf to Start Growing (^{o}C-d)	GDDFolStart	900	Aber et al., 1995
Growing Degree Days for Leaf to Stop Growing (^{o}C-d)	GDDFolStop	1600	Aber et al., 1995
Foliage Retention Time (yr)	FolReten	2	Sun et al., 2000
Water Use Efficiency Constant (mg C g^{-1} H_2O)	WUE	10.2	calibrated
Soil Water Holding Capacity (cm)	WHC	20	Sun et al., 2000
Minimum N concentration in root litter (%)	RLPctN	1.2	Aber et al., 1997
Minimum N concentration in foliar litter (%)	FLPctN	0.4	Aber et al., 1997
Minimum N concentration in wood litter (%)	WLPctN	0.2	Aber et al., 1997
Maximum fractional increase in N concentrations	FolNConRange	0.7	Aber et al., 1997

Table 2.14: *PnET-CN* predicted actual uptake and calibrated potential uptake for input in *DRAINMOD-N* II.

	Actual Uptake, kg ha^{-1}		**Potential Uptake, kg ha^{-1}**	
	F3 & F5	**F6**	**F3 & F5**	**F6**
1995	91.7	60.7	110.0	72.9
1996	88.5	60.9	106.2	73.0
1997	86.0	62.3	103.2	74.8
1998	97.6	73.2	117.1	87.8
1999	93.7	76.1	112.4	91.4
2000	84.2	73.7	101.1	88.5
2001	83.3	80.2	100.0	96.2

Table 2.15: Estimated annual litterfall for F3, F5, and F6 in kg ha^{-1} yr^{-1}.

	Litterfall Predictions, kg ha^{-1}		
	F3	**F5**	**F6**
1995	2910	2770	820
1996	3110	3000	1030
1997	3500	3350	1210
1998	3730	3580	1360
1999	3750	3630	1500
2000	3780	3370	1680
2001	4080	3960	1920
Maximum	4080	4000	1910
Minimum	2920	2770	820
Average	3500	3400	1400

Table 2.16: Values of measured annual litterfall as reported in the literature.

Author, Year of Publication	Location	Stand Age	Yearly Litterfall, kg ha^{-1}	Notes
Nemeth, 1973	Beaufort Co. NC	8	2640	
		9	3590	
		11	3700	
Vose and Allen, 1991	Kinston, NC	9	3177	control
		9	2858	add 112 kg N/ha
		9	3044	add 336 kg N/ha
		9	4348	control
		9	4394	add 112 kg N/ha
		9	3356	add 224 kg N/ha
		9	4554	add 336 kg N/ha
	Walterboro, SC	12	2323	control
		12	2936	add 112 kg N/ha
		12	3937	add 224 kg N/ha
		12	3545	add 336 kg N/ha
		12	3190	control
		12	3390	add 122 kg N/ha
		12	4150	add 336 kg N/ha
	Kinston, NC	14	1853	control
		14	2546	add 122 kg N/ha
		14	2750	add 336 kg N/ha
		14	2643	control
		14	3280	add 122 kg N/ha
		14	3539	add 336 kg N/ha
Dalla-Tea et al., 1991	Gainesville, FL	6	2500	weed control
		6	3100	fertilization
		6	4600	fert + weed control
		7	3200	weed control
		7	3900	annual fertilization
		7	4500	fert + weed control
Average			3400	
Standard Deviation			720	

Table 2.17: Loblolly pine litterfall properties from the literature.

Source	Location	Lignin Content, %	Organic C Content, %	Organic N Content, %	Stand Age, yr
Finzi et al., 2001	Piedmont, NC	20.9 23.6	50.2 49.7	0.49 0.49	15 16
Finzi et al., 2002	Piedmont, NC	20.2 16.86	51 51.6	0.38 0.37	
Meentemeyer, 1978	Coastal Plain, NC	18.6			8-9
McNeil et al., 1988	Piedmont and Coastal Plain of NC, SC, and VA			0.52	various
Lockaby et al., 1986	Coastal Plain, LA			0.58	18
Dalla-Tea et al., 1994	Coastal Plain, FL			0.45	6-7
Average		**20.0**	**50.6**	**0.47**	

Table 2.18: Measured organic C and N content from each field with calculated C:N ratios.

		%C	%N	C:N
F3	0-5	11.3	0.67	16.9
	5-10	8.8	0.54	16.1
	10-15	6.1	0.37	16.6
	15-20	4.6	0.27	17.3
	Average	7.7	0.46	16.6
F5	0-5	26.5	0.84	31.5
	5-10	31.9	0.84	37.9
	10-15	39.5	0.90	44.0
	15-20	31.3	0.81	38.7
	Average	32.3	0.85	38.1
F6	0-5	32.3	1.49	21.7
	5-10	35.4	1.60	22.1
	10-15	38.5	1.46	26.4
	15-20	38.9	1.24	31.4
	Average	36.3	1.45	25.1

Table 2.19: Ammonium distribution coefficient values for F6 after six-year calibration.

Layer	Layer Depth cm	K_d - F5 $cm^3\ g^{-1}$	K_d - F6 $cm^3\ g^{-1}$
1	30	2.3	2.8
2	45	2.3	2.8
3	60	2.3	2.5
4	130	2.2	2.4
5	250	2.0	2.0

Table 2.20: Assumed numerical significance of qualitative descriptors of statistical parameters.

	Water table depth		**Water table depth and drainage**	
	AADD cm	**ADD** cm	**R^2**	**E**
Excellent	<5	<2	0.9-1.0	0.85-1.0
Very Good	5-10	2-7	0.8-0.9	0.75-0.85
Good	10-20	7-15	0.7-0.8	0.65-0.85
Fair	20-30	15-25	0.6-0.7	0.55-0.65
Poor	>30	>25	<0.6	<0.55

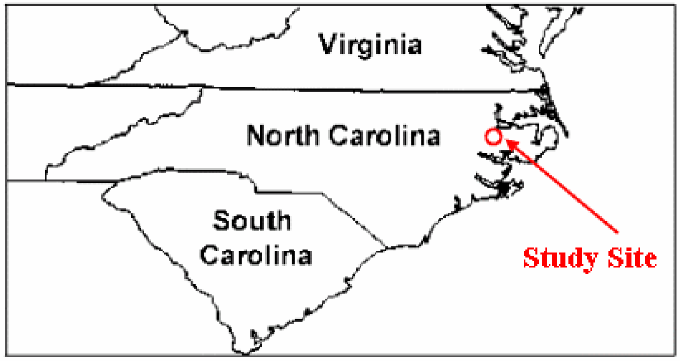

Figure 2.1: Location of research site.

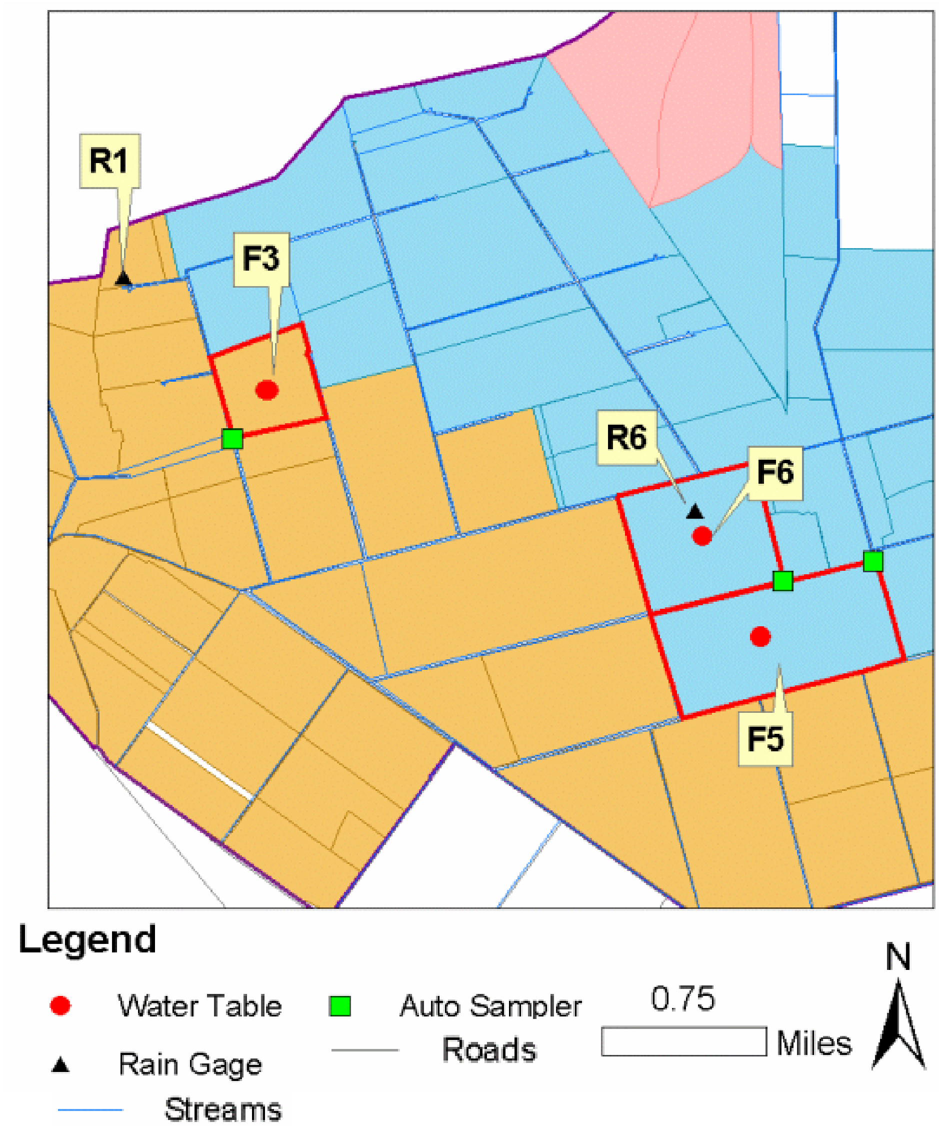

Figure 2.2: Map of study area designating fields F3, F5, and F6 and indicators for hydrology and water quality sampling locations.

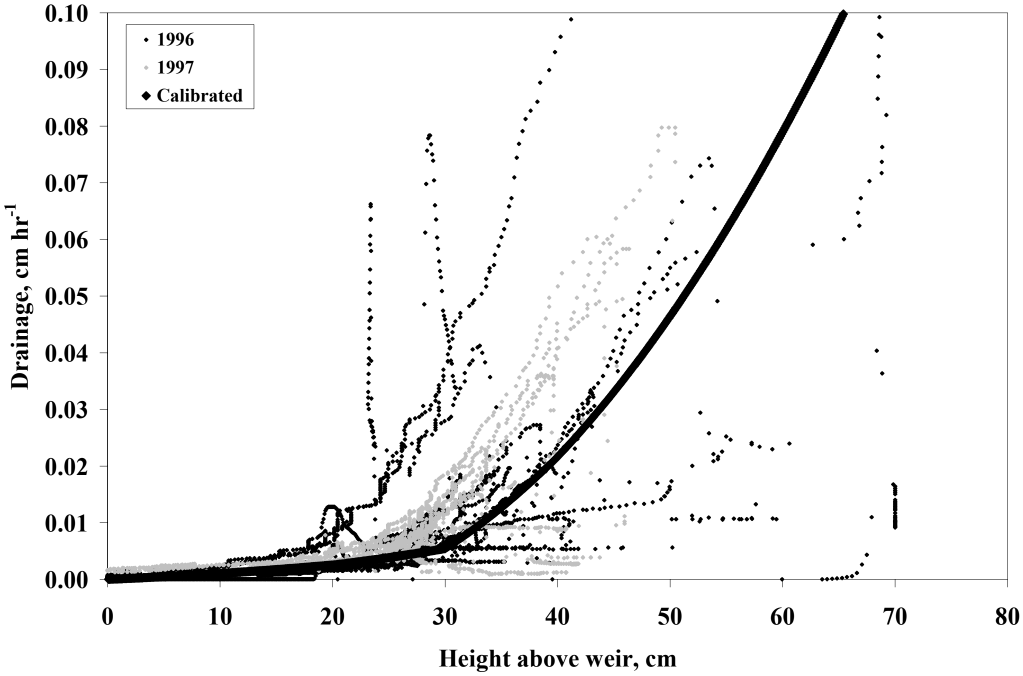

Figure 2.3: Drainage versus height above weir to determine hydraulic conductivity of F3 using flow data from 1996 and 1997.

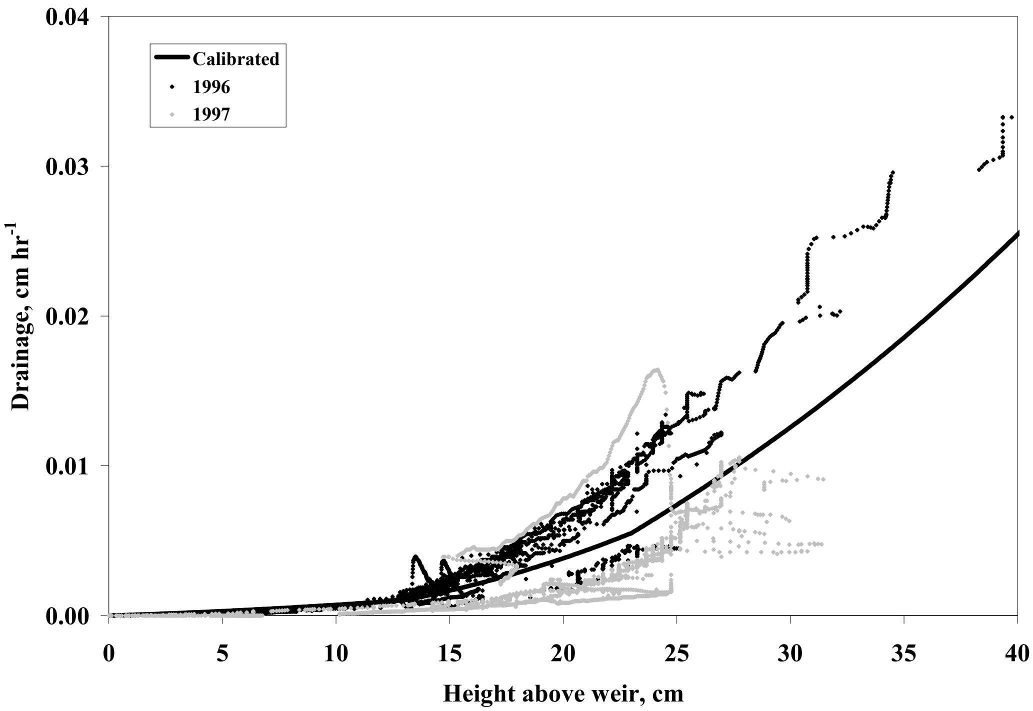

Figure 2.4: Drainage versus height above weir to determine hydraulic conductivity of F5 using flow data from 1996 and 1997.

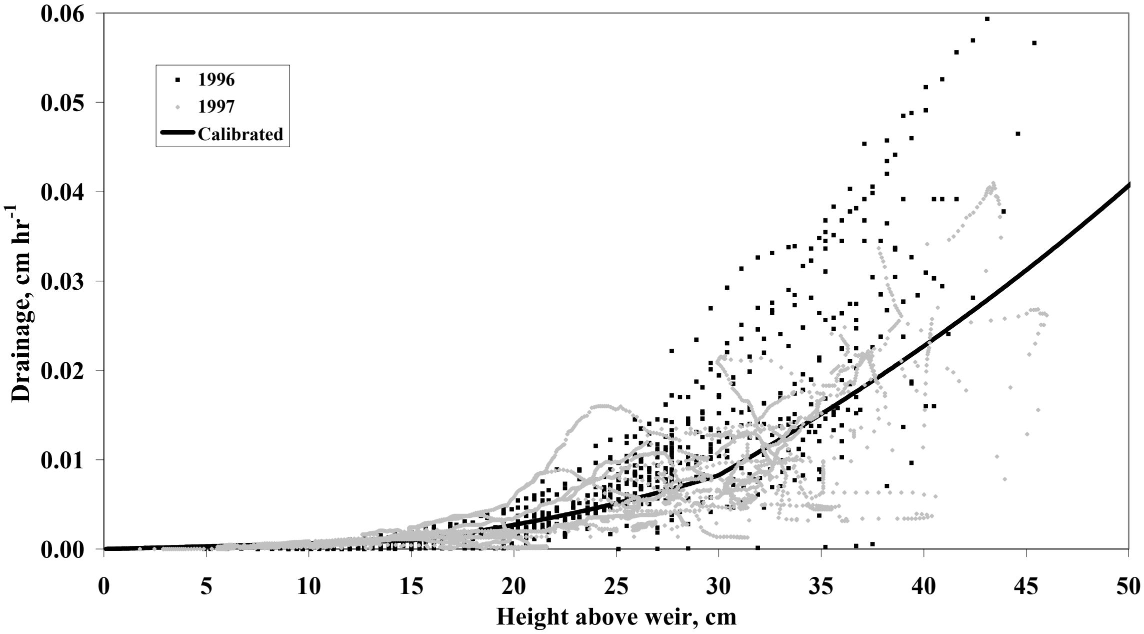

Figure 2.5: Drainage versus height above weir to determine hydraulic conductivity of F6 using flow data from 1996 and 1997.

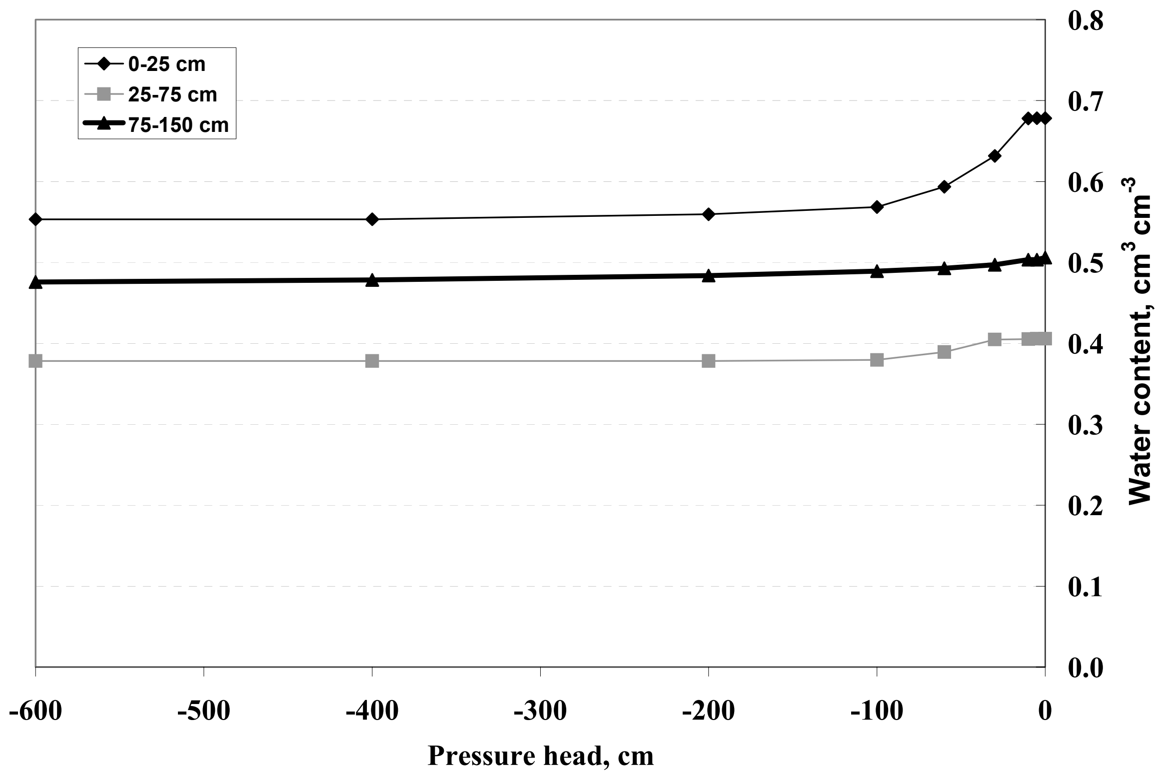

Figure 2.6: Measured soil water characteristic for three layers in F3.

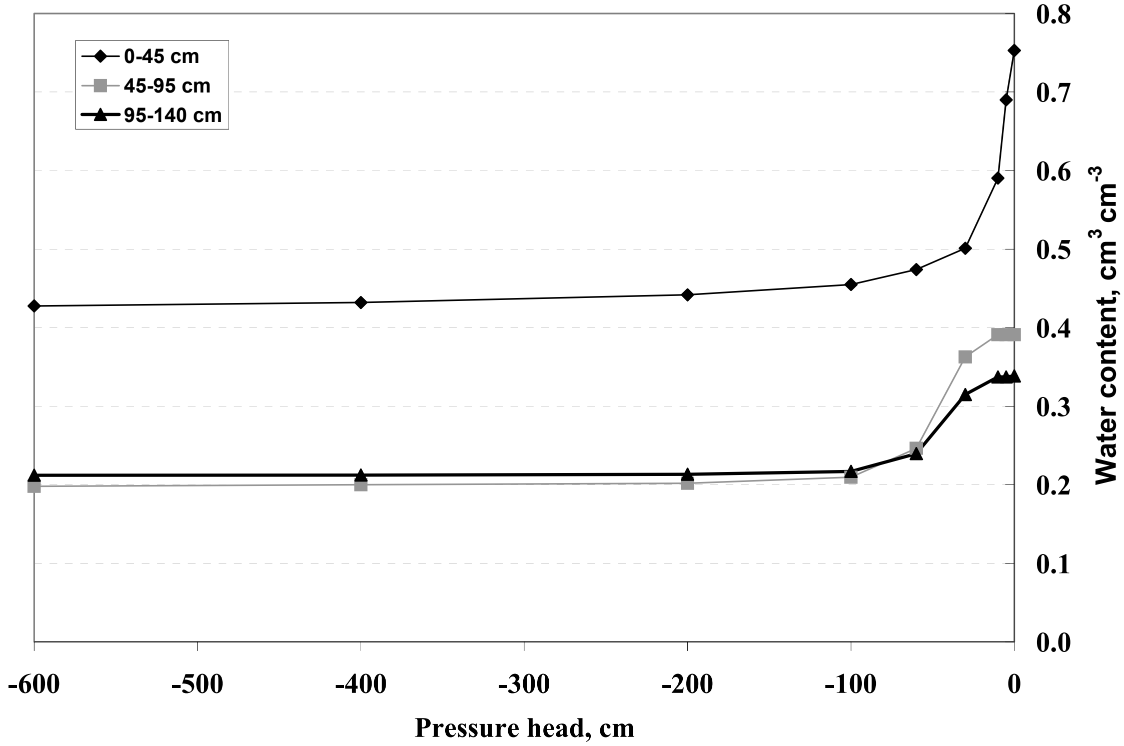

Figure 2.7: Measured soil water characteristic for three layers in F5.

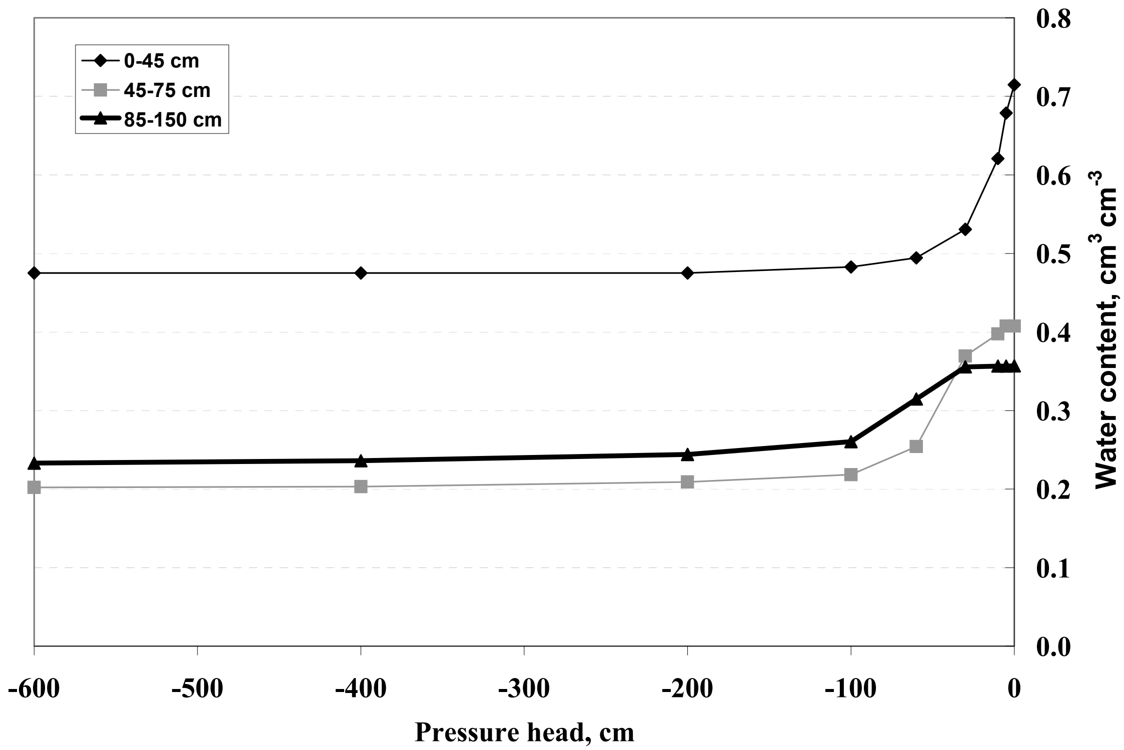

Figure 2.8: Measured soil water characteristic of three layers in F6.

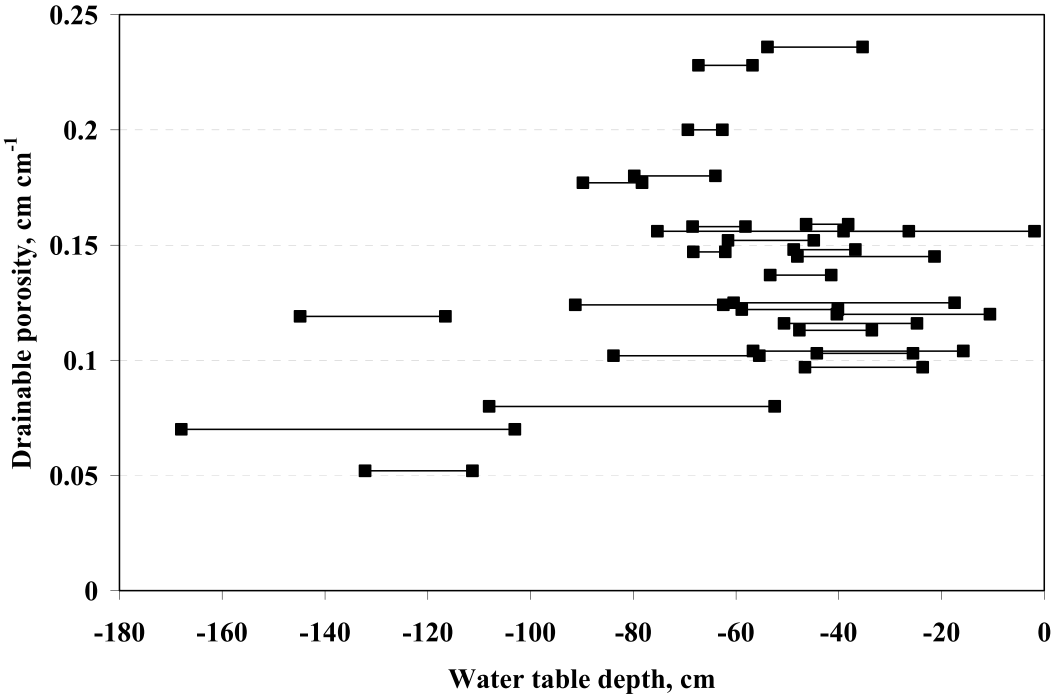

Figure 2.9: Estimates of drainable porosity from measured water table depth responses to precipitation events in 1996-1997 and 1999-2000 for F3.

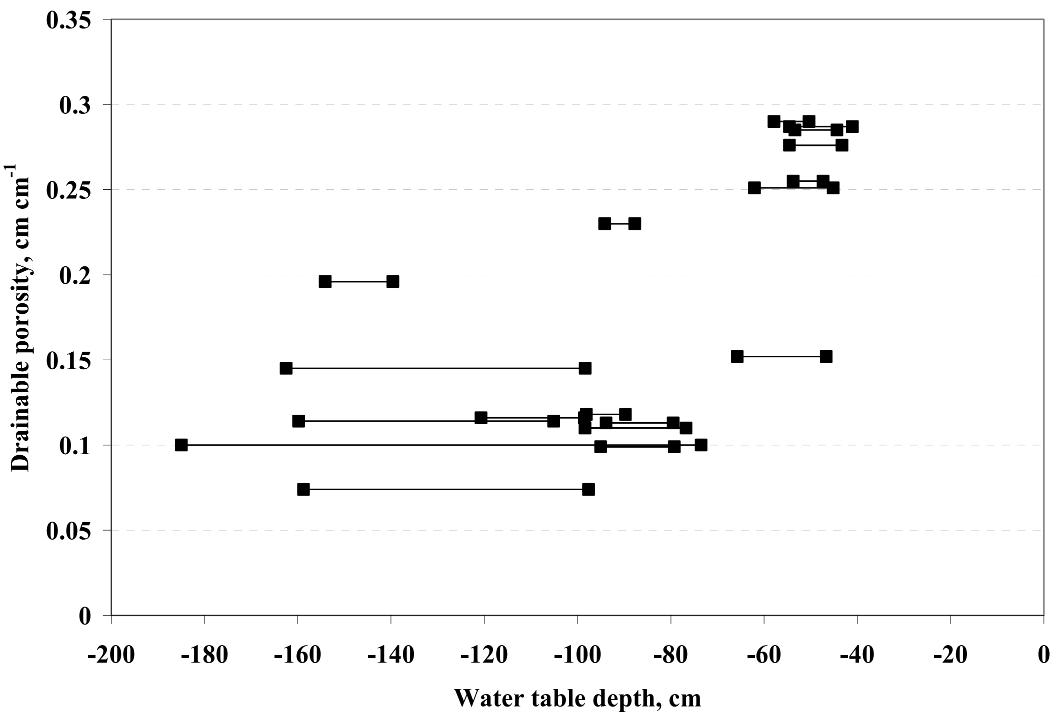

Figure 2.10: Estimates of drainable porosity from measured water table depth responses to precipitation events in 1996-1997 and 1999 for F5.

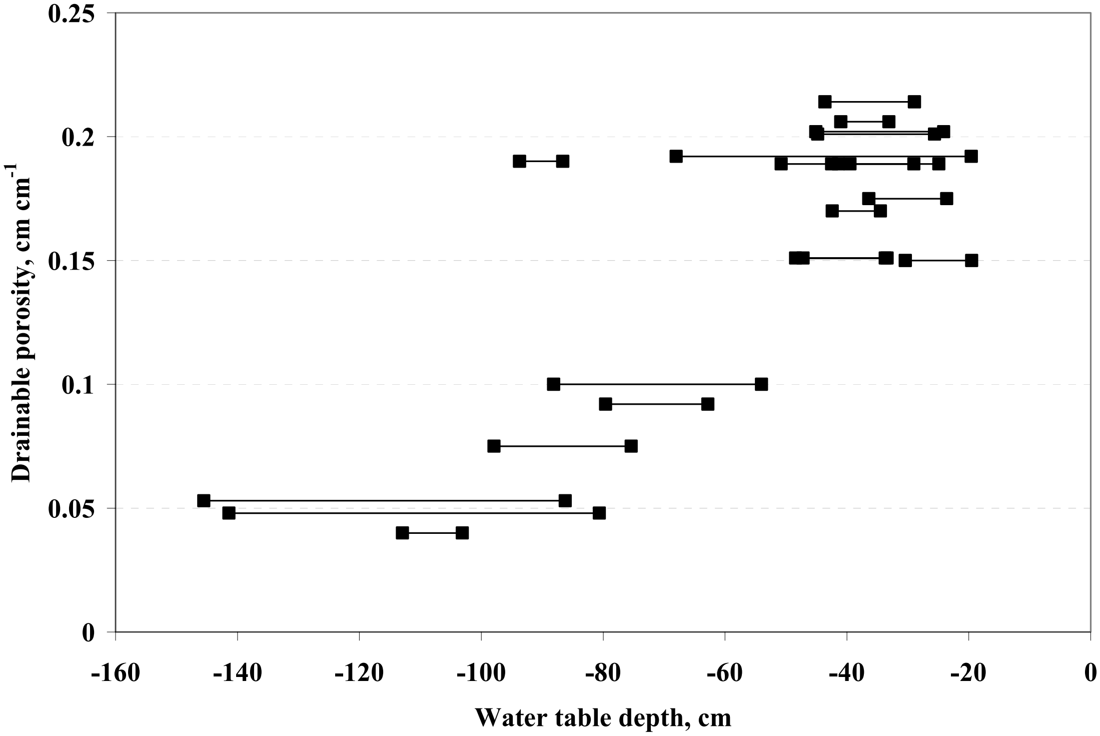

Figure 2.11: Estimates of drainable porosity from measured water table depth responses to precipitation events in 1996-1997 for F6.

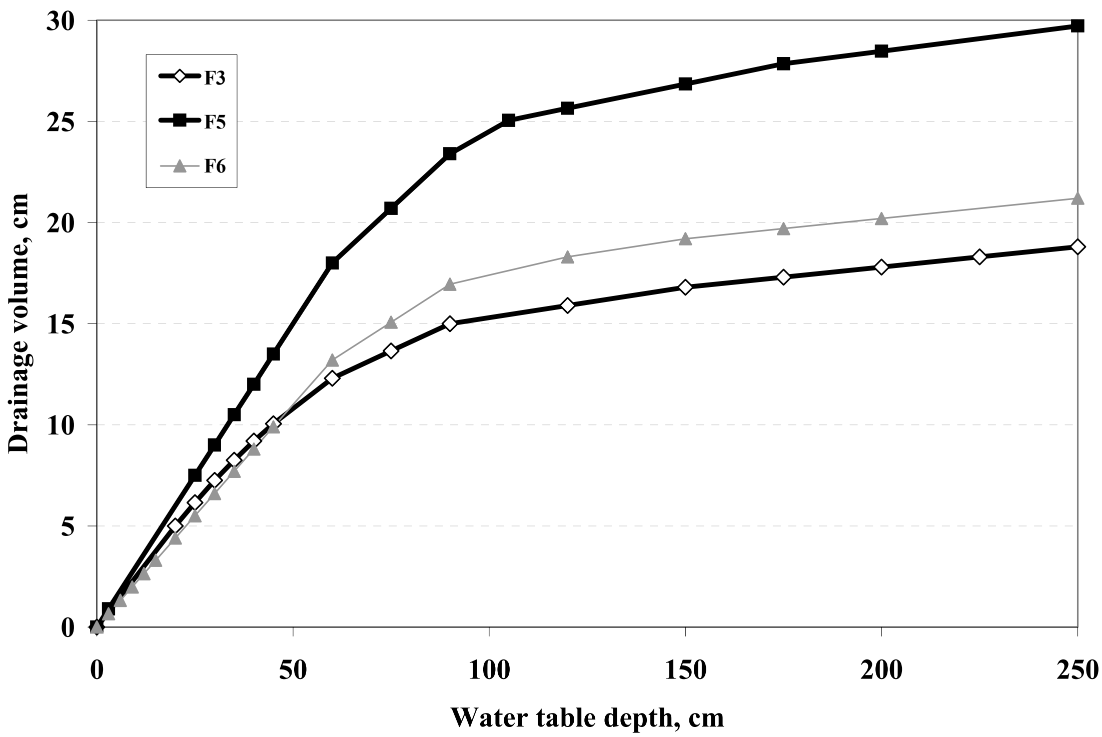

Figure 2.12: Calibrated volume drained – water table depth relationships for F3, F5, and F6.

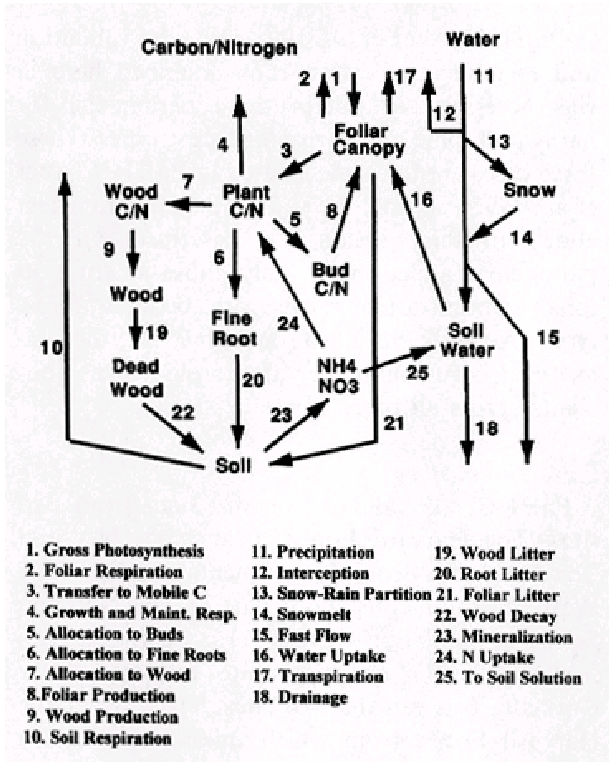

Figure 2.13: Structure of the *PnET-CN* model with C/N representing pools for carbon and nitrogen storage (taken from Aber et al., 1997).

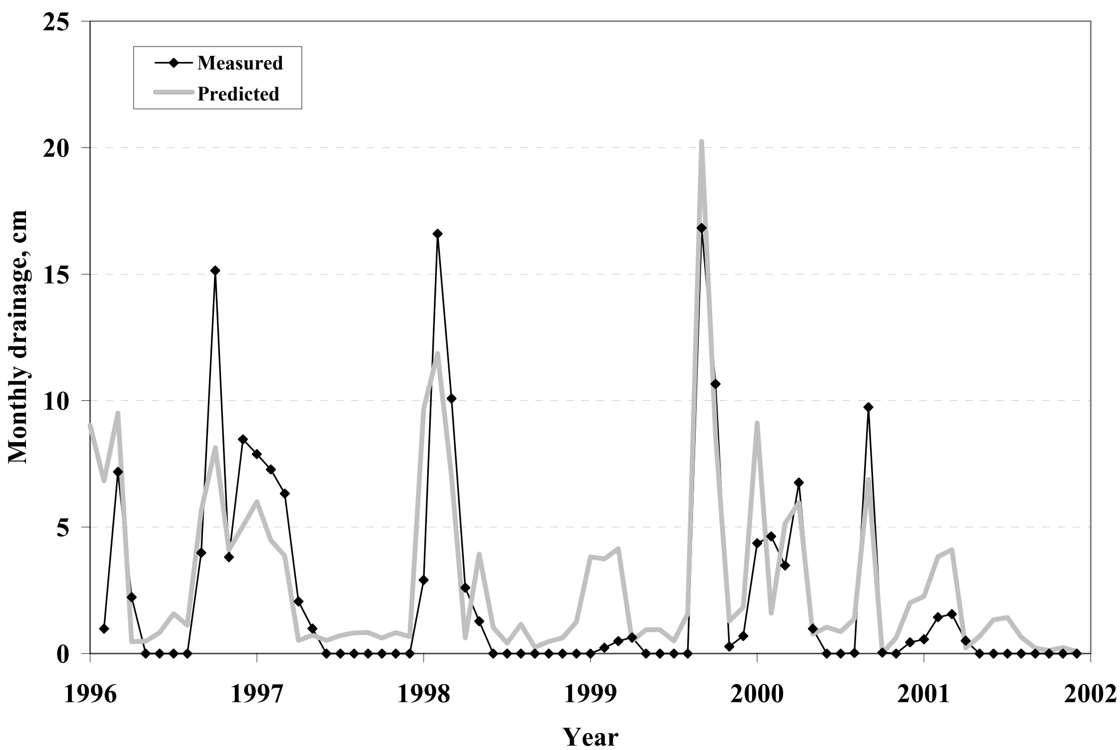

Figure 2.14: Monthly *PnET-CN* predicted drainage versus measured drainage for F3.

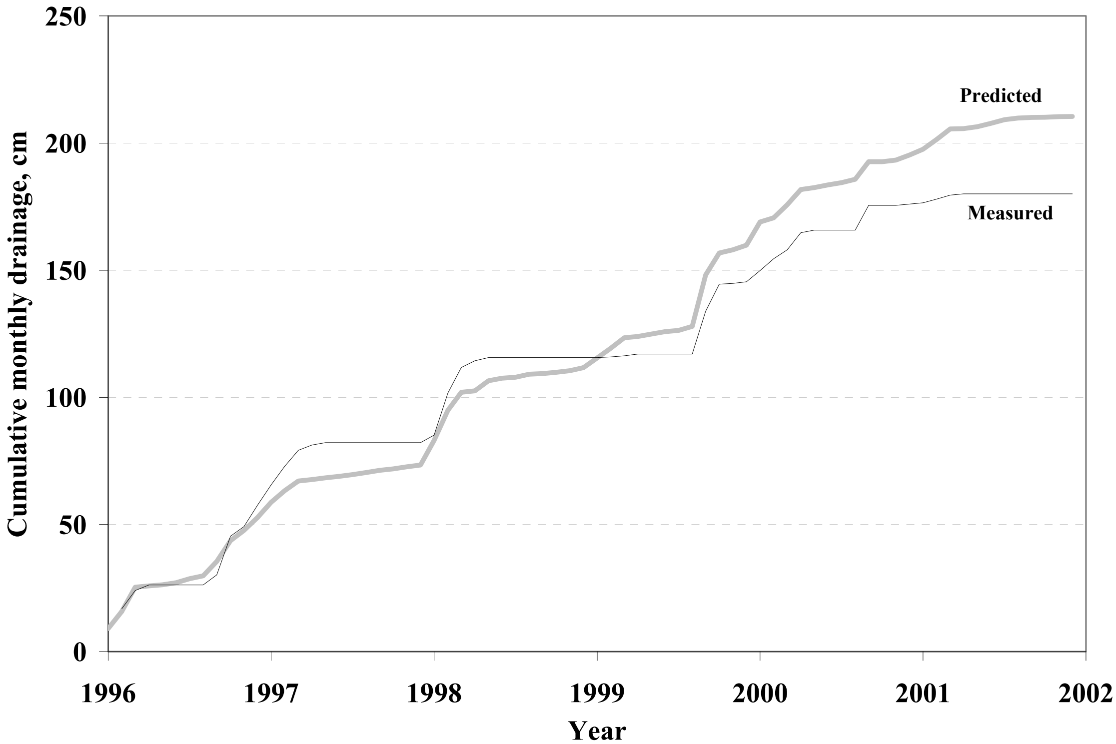

Figure 2.15: Cumulative monthly *PnET-CN* predicted drainage versus measured drainage for F3.

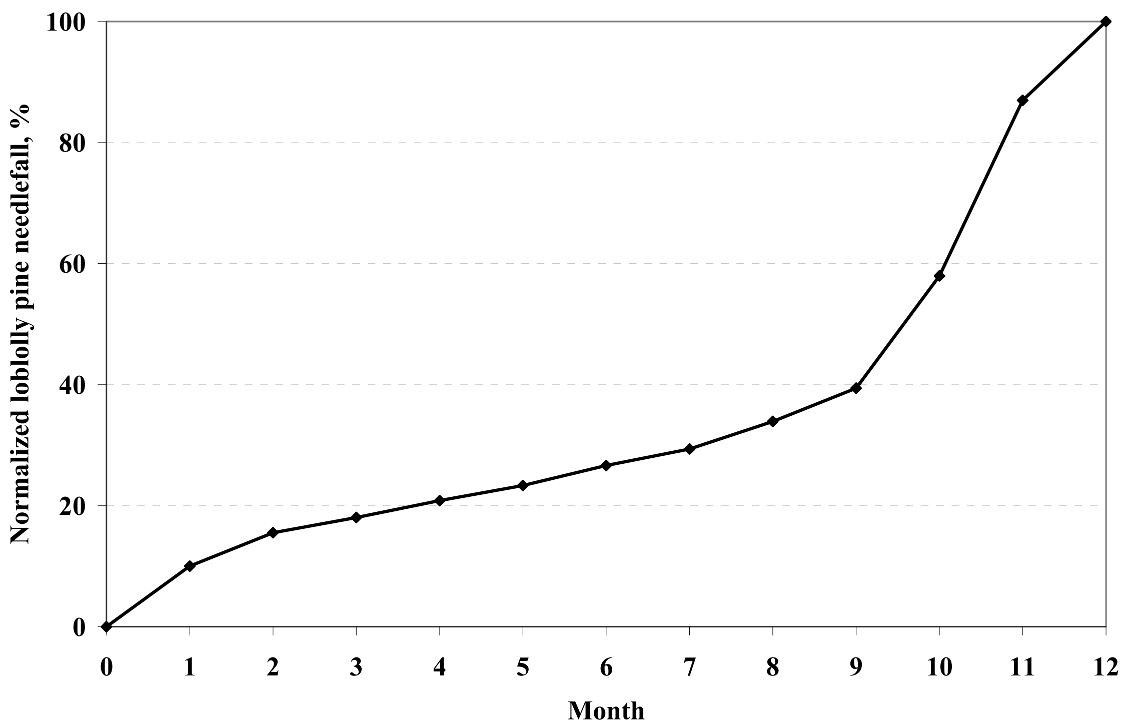

Figure 2.16: Normalized loblolly pine needlefall (from Dalla-Tea et al., 1991).

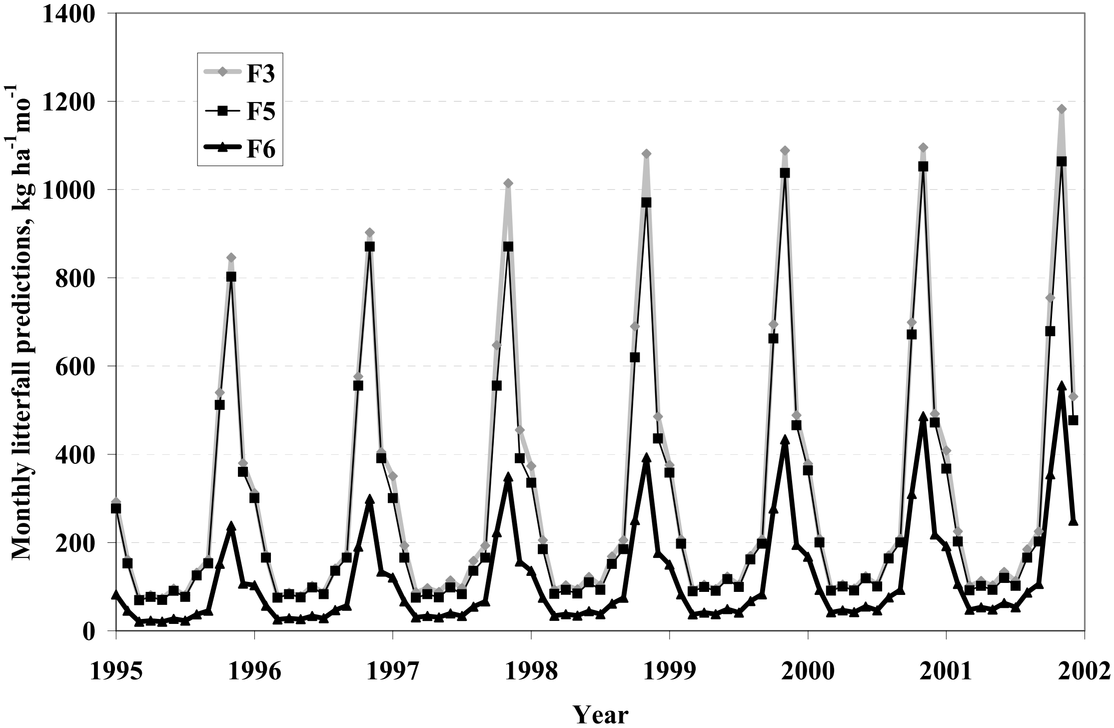

Figure 2.17: Monthly litterfall predictions for F3, F5, and F6.

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CHAPTER 3: RESULTS AND DISCUSSION

HYDROLOGY RESULTS

The results of the hydrology simulations using *DRAINMOD* are shown in Figures 3.1-3.48. Figures 3.1-3.6 show observations and predictions for the entire study period for each field, and Figures 3.7-3.48 show observations for 1995, 1996-1997, 1998-1999, and 2000-2001. Four types of plots are used to describe the results of the *DRAINMOD* hydrologic simulations for each field. The first plot type (Figures 3.1, 3.3, 3.5; and Figures 3.7, 3.11, …, 3.45) shows the measured versus simulated water table elevations for each field. The plot also shows the daily precipitation record that was used as an input in the simulation. The second plot type (Figures 3.2, 3.4, 3.6; and Figures 3.8, 3.10, …, 3.46) shows cumulative amounts of simulated and measured drainage, precipitation, and predicted evapotranspiration. The third type of plot (Figures 3.9, 3.13, …, 3.47) is of predicted versus measured water table elevations. The fourth type of plot (Figures 3.12, 3.16, …, 3.48) is of predicted versus measured daily drainage rates. A 1:1 line, which represents zero prediction error, was included in the third and fourth plot types to show model bias.

Several factors combined to make accurately simulating forest hydrology a challenge. *DRAINMOD* was originally developed for agricultural systems, and it was necessary to compensate for differences in forest soil structure and vegetation. The simulated forests in this study had very heterogeneous soils in the top layers, mainly because of extensive root systems. In addition, *DRAINMOD* was designed for flat, relatively uniform agricultural fields. Silvicultural management can greatly disturb the soil surface. Harvesting and planting preparation can create surface mounds and depressions and nonuniform soil surface compaction. These surface mounds and depressions become more level as the trees grow, which could change the soil properties.

Differences in vegetation between forested and agricultural systems also affected model accuracy. In agricultural fields, crops are planted uniformly across a given field. In forested fields, the system is more complex. Trees grow continuously from year to year, and understory vegetation grows seasonally at different locations throughout the field. As trees grow, their effect on evapotranspiration and water interception changes. Newly planted trees comprise a small portion of the total forest area. In addition, understory vegetation growth decreases as the growing trees block sunlight.

Fields F5 and F6 are both highly organic soils, with low bulk density and very high porosity in the top layers. F3 is a mineral soil, but also with high organic matter content. The amount of organic content in soil can affect the hydraulic conductivity (Chescheir et al., 2003); however, the effect of organic content can change with age. The top layers of these soils have extremely high lateral saturated conductivities, which were difficult to estimate with precision.

Highly organic soils can change significantly after the introduction of artificial drainage. There are two periods of subsidence, or shrinkage, which occur after drainage. Primary subsidence occurs simply because water is removed. Organic materials float in water, and when water is removed they settle under their own weight. Secondary subsidence is caused by oxidation of organic material and occurs over time. Since F3, F5, and F6 were drained in the 1970's, it is likely that primary subsidence occurred well before the 1995-2001 simulation period. Secondary subsidence likely occurred slowly during the simulation period. Secondary subsidence could have removed organic matter from the system and increased the porosity of the organic layers over time. However, the effect of subsidence on the soil properties over the simulation period is not completely understood.

Water table depth results

AADD values for the 1995-2001 simulation period showed fair agreement for F3 and F5 and good agreement for F6. The *AADD* of the 1995-2001 simulation period was 23.2, 28.4, and 13.0 cm for F3, F5, and F6 (Table 3.1). The *AADD* for individual years ranged from 6.5 to 34.4 cm for F3, 14.5 to 42.3 cm for F5, and 6.9 to 20.1 cm for F6. The minimum *AADD* value occurred in 1997 for F3 and F5 and in 1999 for F6. The maximum *AADD* value occurred in 1998 for F3, 1999 for F5, and 1997 for F6.

ADD values for the entire simulation period showed very good agreement for F3 and F5 and excellent agreement for F6 (Table 3.1). The *ADD* of the 1995-2001 simulation period was 4.0, 2.5, and 1.8 for F3, F5, and F6. The *ADD* for individual years ranged from -29.0 to 23.3 cm for F3, -42.3 to 26.1 cm for F5, and -6.5 to 12.4 cm for F6. Although there was significant bias for several individual years, the model only slightly overpredicted average water table depth for the entire simulation period for each field. For F3, the model overpredicted water table depth in four out of the seven simulated years. For F5, the model overpredicted water table depth in three out of seven simulated years. For F6, the model overpredicted five of the seven simulated years. Twelve out of 21 site-years for all fields had absolute *ADD* values less than 10.0 cm, with four under 5.0 cm. The *ADD* values show that for many individual years the model significantly over- or underpredicted water table elevations. However, throughout the entire simulation period, model underpredictions were countered by overpredictions, and the total *ADD* was very small.

R^2 values for the 1995-2001 simulation period demonstrated that the model had good agreement in water table depth predictions for F3, fair agreement for F5, and very good agreement for F6 (Table 3.1). The R^2 values for the entire simulation period were 0.72, 0.63, and 0.84 for F3, F5, and F6, respectively. Annual R^2 values ranged from 0.50 to 0.91 for F3, 0.61 to 0.96 for F5, and 0.54 to 0.96 for F6. The minimum R^2 value occurred in 2000 for F3 and in 1995 for F5 and F6. The maximum R^2 value occurred in 1997 for F3, in 1998 for F5, and in 1999 for F6. Four of the seven years had R^2 values higher than 0.75 for F3 and F5. Five of the seven years had R^2 values higher than 0.75 for F6.

The model efficiency, *E*, values for the 1995-2001 simulation period demonstrated that the model had good, fair, and very good agreement for F3, F5, and F6, respectively (Table 3.1). The model efficiency values for the entire period were 0.66, 0.59, and 0.82 for F3, F5, and F6, respectively. The model efficiency, *E*, values for individual years ranged from 0.27 to 0.86 for F3, 0.00 to 0.80 for F5, and -5.2 to 0.94 for F6. The minimum *E* value occurred in 1997 for F3, 1999 for F5, and 1996 for F6. The maximum *E* value occurred in 1996 for F3, 1997 for F5, and 1999 for F6. Three out of the seven years had *E* values above 0.6 for F3 and F5. Five out of the seven years had *E* values above 0.7 for F6.

Years in which the model had high R^2 values, but low *E* values (such as 1997 for F3 and 1999 for F5) demonstrate that the model consistently over- or underpredicted water table elevation during that year. Predicted values can have good association with measured values (i.e. high R^2 values) without accurately predicting water table elevations. Therefore, model efficiency is a more helpful descriptor of model accuracy than R^2.

Statistical parameters that show high errors could have resulted from temporal errors in water table predictions. These statistical parameters require the assumption that there are no errors in predicting the timing of the rise and fall of water table depth. In reality, the response of the water table, especially at greater depths, can be a day or two behind a given rainfall event. For example, in F3 there are significant rainfall events at the beginning of 1998 and 1999. The model predicts a faster response in water table depth rise than was measured. This difference could be attributed to the way that *DRAINMOD* assumes a drained to equilibrium profile in the unsaturated zone. In reality, a dry zone could exist between the wetting front and the water table, and the water table would not rise as fast as *DRAINMOD* predicts. Model errors in those situations can exceed 70 cm. Therefore, care should be taken when analyzing the statistical parameters to consider the effect of temporal errors.

By visual inspection of Figure 3.1, the model did well in predicting water table depths over the simulation period for F3. In summer to fall of both 1997 and 1998, model predictions of water table depth were higher than the measured observations. These summer seasons were very dry, and model error was probably due to underpredicting evapotranspiration. Errors in hydrology predictions compound over time, and in the beginning of 1999 the water table elevations were substantially higher than the measured values. Errors in predicted evapotranspiration were not consistent, however, because the model did reasonably well in predicting summer water table drawdown in 1996 and 1999.

By inspection of Figure 3.3, the model did reasonably well in predicting water table depths for F5 over the entire simulation period. There were no consistent model errors from 1995-2001. For example, although the model appears to underpredict evapotranspiration during the summer and fall of 1998, the model overpredicts evapotranspiration in 2001. Although the model fails to accurately simulate water table rise after rainfall in the summer of 1995, it does very well in simulating water table rise in the summer of 1996 and in the fall of 1999. These discrepancies in model performance could be attributed to the effect of lateral seepage on F5. Lateral seepage was estimated for each year by model calibration, but lateral seepage could be variable within a given year, based on the water elevation in the ditches or other unknown factors. Another possible explanation could be that the soil properties of F5 changed during 1995-2001. Significant 'curing' of the soil organic matter could have occurred, and the soil surface properties could have changed as the trees grew.

By inspection of Figure 3.5 for field F6, the model performed poorly during the summer months of 1995 and 1996 but did very well during the rest of the simulation period. The F6 stand was planted in 1992, and the trees grew significantly during the simulation period (1995-2001). Younger trees transpire less than older trees, and this contrast was simulated by using increasing rooting depths as F6 matured. As shown by Figures 3.5, 3.35, and 3.37, ET was greatly overestimated during the summer months of 1995 and 1996. This period of overestimated ET is the primary reason for the low R^2 and E values for F6 in 1995 and 1996. A 6-cm rooting depth was used for both of those years, but this change alone was not sufficient to reduce the ET enough to match predicted and observed values.

Drainage results

Although the three study sites were located in close proximity to each other, there were significant differences in the observed drainage from the fields. F6 had the largest volume of observed drainage with 203.3 cm. F3 had the second largest volume with 165.9 cm, and F5 had the least amount of drainage with 75.1 cm. F5 most likely had a small drainage volume because of lateral seepage throughout the study period. Most of the drainage from F6 occurred during 1996 to 1999. During this time, the trees on F6 were four to seven years old and did not remove as much water through transpiration as did trees in F3 and F5. Since transpiration was low, drainage volumes increased.

AADD values of drainage rate predictions for the 1996-2001 simulation period were 0.51, 0.23, and 0.53 mm d^{-1} for F3, F5, and F6, respectively (Table 3.2). The largest values of *AADD* occurred during the relatively wet years (1996, 1998, 1999, and 2000). In the relatively dry years, there were many days with zero-flows both in measured and predicted data, which caused low *AADD* values. The *AADD* of F5 was lower than F3 and F6 primarily because the drainage losses for F5 were lower than the other fields.

ADD values for the 1996-2001 simulation period were -0.10, 0.01, and -0.15 mm d^{-1} for F3, F5, and F6, respectively (Table 3.2). The model underpredicted drainage in five out of six years for F3 and four out of six years for F5 and F6. The model had two years of significant overpredictions for F5, which countered the underpredictions in the other four years.

R^2 values for the 1996-2001 simulation period showed good agreement for F3, very good agreement for F5, and fair agreement for F6 (Table 3.2). The R^2 values for the entire simulation period were 0.71, 0.85, and 0.69 for F3, F5, and F6, respectively. Annual R^2 values ranged from 0.54 to 0.88 for F3, 0.73 to 0.98 for F5, and 0.47 to 0.69 for F6. The minimum R^2 value occurred in 1996 for F3 and F5 and in 2000 for F6. The maximum R^2 value occurred in 1999 for F3 and F5 and in 1996 for F6. R^2 values were not reported in 2001 for F3 and F5 because no drainage was predicted.

E values for the 1996-2001 simulation period showed good agreement for each field (Table 3.2). *E* values for the entire simulation period were 0.70, 0.69, and 0.68 for F3, F5, and F6, respectively. Annual *E* values ranged from -2.3 to 0.72 for F3, 0.51 to 0.80 for F5, and -0.57 to 0.72 for F6. The minimum *E* value occurred in 1999 for F3, in 1996 for F5, and in 2000 for F6. The maximum *E* value occurred in 1998 for F3 and F6 and in 2000 for F5. Four of the five years with predicted drainage had *E* values greater than 0.5 for F3. Four out of five years with drainage had *E* values greater than 0.6 for F5, and four out of six years with drainage on F6 had *E* values greater than 0.5.

As shown by Figures 3.2, 3.4, and 3.6, the model did well in predicting cumulative drainage volumes for the entire simulation period for F3 and F6, and performed very well for F5. The model underpredicted cumulative drainage volume by 10.8 % and by 17.1 % for F3 and F6, respectively (Table 3.3). The model overpredicted cumulative drainage by 2.7 % for F5. There were substantial errors in predicting the cumulative drainage for individual years on all fields. However, there was no consistent bias, and years with overprediction were countered by years with underprediction over the entire simulation period.

For F3, *DRAINMOD* underpredicted drainage volume at the very end of 1996 and at the beginning of 1997 by about 15 cm. However, there were likely errors in drainage measurements during this period. From December 1996 to April 1997, the observed rainfall at station R1 was 35.9 cm. The observed drainage during this same period was 33.2 cm. It is unlikely that almost all of the rainfall was lost as drainage. Therefore, it is reasonable to conclude that there was either a measurement error or an unknown error source during this period. This uncertainty in the measured data means that the model probably performed better during this period in predicting drainage losses than the results indicate.

On F6, the model underpredicted cumulative drainage from 1996-1997 by about 40 cm. The primary reason for this underprediction is that the model overpredicted ET during both years. The trees were very small during those years, and there was likely very little ET taking place in the field. The trees comprised a small portion of the total land area and would have transpired very little water. After 1997 on F6, the model performs very well in predicting cumulative drainage.

Another source of error during the 1996-1997 periods for F3 and F6 could have been the use of submerged weirs to determine drainage flow rates from the fields. A submerged weir occurs when the downstream stage is above the V-notch weir, as was the case at the end of 1996 for F3 and at the end of 1996 and beginning of 1997 for F6. The weirs were designed so that the downstream stage is usually below the weir. However, during high flow events such as hurricanes or very wet periods, the weir can become submerged and lead to errors in measuring drainage rate.

NITROGEN RESULTS

Figures 3.49-3.58 show the results of the nitrate-nitrogen (NO_3-N) simulations for each field and calibration. Measured loads and concentrations of ammonium-nitrogen (NH_4-N) were much less than NO_3-N, and therefore figures with NH_4-N were not included. For field F6, there were very little differences in predicted NO_3-N loads and concentrations from the 1996-1998 and 1996-2001 calibrations. Therefore, only plots of NO_3-N loads and concentrations from the six-year calibration were included for F6. Figures 3.49-3.50, 3.53-3.54, and 3.57 show plots of cumulative NO_3-N loads and cumulative drainage volumes. Youssef (2003) reported that the accuracy of *DRAINMOD-N* II predictions was very dependent on the accuracy of the *DRAINMOD* hydrology predictions. Similar results were found in this study and plots of cumulative measured and predicted drainage show this dependency.

Figures 3.51-3.52, 3.55-3.56, and 3.58 show measured and predicted NO_3-N concentrations. Measured NO_3-N concentrations on each plot are from biweekly flow-proportional composite samples and from biweekly grab samples taken throughout the study. The version of the model used in this study did not report NO_3-N concentrations, although they were computed internally in the model. Predicted NO_3-N concentrations were determined from the *DRAINMOD*-predicted daily drainage and the *DRAINMOD-N* II-predicted daily NO_3-N loads. These computed concentrations represent the average NO_3-N concentration in drainage for each day. Therefore, care should be taken when comparing these average daily results with the measured composite and grab samples. Another consideration is that the predicted concentrations represent values at the field edge. The observed concentrations were measured at the outlet weir. Nitrate losses through denitrification could have occurred in the drainage system while traveling from the field edge to the weir.

Tables 3.4-3.9 show annual observed and predicted NO_3-N, NH_4-N, and dissolved inorganic nitrogen (DIN) losses. DIN is the sum of NO_3-N and NH_4-N, and it is reported to show the ability of the model to predict N losses regardless of the predicted distribution of N between the NO_3-N and NH_4-N forms. Tables 3.4-3.9 also show observed and predicted annual drainage rates and the ratio of predicted-to-observed drainage and N losses. These ratios provide a useful method of evaluating model accuracy. Since N predictions are highly dependent on predicted drainage losses, N predictions should reflect errors in hydrology predictions. For example, as shown in Table 3.5 for F3, the predicted-to-observed drainage ratio is 0.89 for the cumulative drainage from 1996-2001. The ratio of 0.89 shows that *DRAINMOD* underpredicted drainage over that period. Since drainage was underpredicted for that period, predicted N losses should also be less than measured losses. Therefore, the goal of *DRAINMOD-N* II calibration was to match the ratio of predicted-to-observed drainage losses with the predicted-to-observed ratio for N losses. The accuracy of *DRAINMOD-N* II should be evaluated by comparing the ratio of predicted-to-observed drainage losses with the ratio for N losses.

The accuracy of the complete modeling process using both the *DRAINMOD* and *DRAINMOD-N* II models would be evaluated by comparing the predicted to observed N losses directly. However, the purpose of this study was to evaluate the *DRAINMOD* and *DRAINMOD-N* II models separately to have a more rigorous evaluation of both models.

Since the objective of the *DRAINMOD-N* II calibration and modeling was to match the ratio of predicted-to-observed drainage losses with the predicted-to-observed ratio for N losses, it is unreasonable to compare predicted to observed N losses directly.

Field F3

Tables 3.4 and 3.5 show predicted and observed N losses from F3 for the 1996-1998 and 1996-2001 calibrations, respectively. In the 1996-1998 model calibration, input parameters were adjusted to match the predicted-to-observed ratio (error ratio) for N losses to the ratio for drainage losses, 0.79. After calibration, the error ratios of NO_3-N, NH_4-N, and DIN losses from 1996-1998 were 0.79, 0.78, and 0.79, respectively. The model overpredicted N loads considerably from 1996-2001, however. During that period, the error ratios for NO_3-N, NH_4-N, and DIN were 1.05, 1.96, and 1.17, which were much higher than the drainage error ratio of 0.89. Normalized error for the nitrogen validation, NE_N, is described by,

$$NE_N = \frac{N_{ER} - H_{ER}}{N_{ER}} * 100\ \% \tag{3.6}$$

where N_{ER} and H_{ER} are the predicted-to-observed error ratios for N and drainage losses, respectively. Normalized errors in predicted cumulative N loads for the 1996-2001 period after the 1996-1998 calibration were 15.2, 54.6, and 23.9 % for NO_3-N, NH_4-N, and DIN, respectively.

For the 1996-2001 calibration, the mineralization rate was decreased and the nitrification rate was increased. The error ratios for N from 1996-2001 were 0.91, 0.89, and 0.90 for NO_3-N, NH_4-N, and DIN, which were similar to the drainage error ratio of 0.89.

Although the model was calibrated to predict the six-year total losses accurately, there were substantial errors in predicting N losses for individual years as shown in Tables 3.4-3.5. The most significant error from both calibrations occurred with model underprediction of NO_3-N losses in end of 1996 and beginning of 1997. This underprediction caused there to be more NO_3-N available for transport in the beginning of 1998 and NO_3-N was overpredicted in 1998. However after 1998, predictions of cumulative nitrate load were more reasonable.

It is important to consider the amount of N that is lost from the field. Youssef (2003) found that model errors were likely to increase as the annual N loads decreased. That study was performed on an agricultural site with N losses much higher than from the three forested sites in this study. Since N losses from these forested sites were small (13 out of 18 site-years less than 5 kg DIN ha^{-1} yr^{-1}), it is understandable that percentage errors in annual N losses could be large.

Figures 3.51 and 3.52 show measured and predicted nitrate concentrations from F3 using the 1996-1998 and 1996-2001 calibrations, respectively. From inspection of these plots, it is evident that predicted NO_3-N concentrations decreased from the three-year to the six-year calibration. This decrease was because the mineralization rate was lowered. For unknown reasons, the model underpredicts NO_3-N concentrations in drainage in late 1996 and 1997 and then overpredicts NO_3-N concentrations in 1998.

The plots show a 'first flush' effect after the dry periods of 1997 and 1999 in both the predicted and measured concentrations. The 'first flush' effect happens because nitrification and mineralization occur during dry periods, and NO_3-N accumulates in the soil profile. After the dry period is over, the accumulated NO_3-N is released in the water that drains from the field immediately after the dry period, resulting in increased NO_3-N concentrations.

Field F5

Tables 3.6 and 3.7 show the predicted and observed N losses from F5 for the 1996-1998 and 1996-2001 calibrations, respectively. In the 1996-1998 calibration, input parameters were adjusted to match the error ratio for N losses to the ratio for drainage losses, 1.07. The error ratios for the 1996-1998 period after calibration for NO_3-N, NH_4-N, and DIN were 1.09, 1.03, and 1.09, respectively. However, as shown in Figure 3.53, the model substantially overpredicts cumulative NO_3-N losses from 1996-2001. During that period, the error ratios for NO_3-N, NH_4-N, and DIN were 1.45, 0.79, and 1.35, respectively, as compared to the drainage error ratio of 1.03. Normalized errors in predicted cumulative N loads for the 1996-2001 period after the 1996-1998 calibration were 28.9, -30.4, and 23.7 % for NO_3-N, NH_4-N, and DIN, respectively. Therefore, to account for these errors the mineralization and nitrification rates were decreased during the 1996-2001 calibration.

Model improvement from the three-year calibration to the six-year calibration was substantial. The error ratios for N from 1996-2001 were 1.00 for NO_3-N, NH_4-N, and DIN, which were similar to the drainage error ratio of 1.03. As with F3, there were several years for F5 with high errors of overprediction or underprediction for both calibrations. The model underpredicted NO_3-N losses during the winter of 1996-1997 and overpredicted NO_3-N losses in 1998, just as in F3.

Measured and predicted NO_3-N concentrations for F5 for both calibrations were higher than for F3 (Figures 3.55 and 3.56). F5 had a greater mineralization rate than F3 by about 10 kg ha^{-1} per year (Tables 3.10 and 3.11). More mineral N was available for loss in drainage from F5. In addition, F3 had predicted drainage of 148.0 cm compared with 75.1 cm for F5. F3 had a much greater drainage volume, and the NO_3-N was diluted.

Field F6

Tables 3.8 and 3.9 show the predicted and observed N losses from F6 for the 1996-1998 and 1996-2001 calibrations, respectively. For the three-year calibration, input parameters were adjusted to match the error ratio for N losses to the error ratio for drainage losses, 0.70. After calibration, the error ratios of NO_3-N, NH_4-N, and DIN losses from 1996-1998 were 0.70, 0.71, and 0.70, respectively. During 1996-2001, the error ratios for NO_3-N, NH_4-N, and DIN were 0.81, 0.56, and 0.78, respectively, as compared to the drainage error ratio of 0.83. Normalized errors in predicted cumulative N loads for the 1996-2001 period after the 1996-1998 calibration were -2.5, -48.2, and -6.4 % for NO_3-N, NH_4-N, and DIN, respectively. The model did very well in the validation period in predicting NO_3-N and DIN losses but considerably underpredicted NH_4-N losses (on a percentage basis). The model was calibrated during the 1996-2001 period by increasing the nitrification rate slightly and by decreasing the ammonium distribution coefficient, K_d. The model predicted cumulative NH_4-N loads more accurately after the six-year calibration, and the cumulative NO_3-N loads were unchanged from the three-year calibration (Figure 3.57). The error ratio for the 1996-2001 period was 0.82 for NH_4-N losses, as compared with 0.83 for drainage.

Figure 3.58 shows measured and predicted NO_3-N concentrations for F6 using the 1996-2001 calibration. Nitrate concentrations from F6 were higher than from F3 and lower than from F5. F6 had a predicted average annual mineralization rate about 8 kg ha^{-1} higher than F3 and F5 (Table 3.12). The predicted nitrification rate from F6 was also higher than F3 and F5, and more NO_3-N was available to be lost in drainage. However, F6 had 168.6 cm of predicted drainage from 1996-2001, which is 20.6 cm more than F3 and 91.4 cm more than F5. F6 had substantially lower NO_3-N concentrations than F5 because there was much more drainage from F6 than F5. Although the mineralization rate was higher for F6 than F3, NO_3-N concentrations were similar because of the difference in drainage.

Nitrogen transformation rates

Tables 3.10-3.12 show predicted annual N process rates for each field and both calibrations. Annual process rates of mineralization, nitrification, denitrification, and N uptake are reported. Proper modeling of mineralization rates is critical for accurately modeling N dynamics and turnover in forested systems. Topsoil is frequently replenished with organic matter due to litterfall and decomposition of surface volunteer vegetation. The average annual predicted mineralization rates for the 1996-2001 calibrations were 104.2, 115.0, and 113.4 kg NH_4-N ha^{-1} for F3, F5, and F6, respectively. Immobilization did not occur on any of the fields, and therefore all reported mineralization rates are both gross and net values. Simulated annual mineralization for the 1996-2001 calibrations ranged from 87.5 to 117.4 kg ha^{-1} for F3, 96.6 to 128.7 kg ha^{-1} for F5, and 97.6 to 127.5 kg ha^{-1} for F6. Table 3.13 shows measured mean annual mineralization values from the literature. The mineralization rates predicted by *DRAINMOD-N* II were higher than most of the values from the literature. Quality and quantity of litterfall, rainfall patterns, temperature, and water table management all have an effect on mineralization rates (Youssef, 2003). On-site measurements of N mineralization in these particular systems would be necessary to better evaluate the accuracy of the mineralization predictions.

Predicted average annual nitrification rates for the 1996-2001 calibrations were 71.8, 64.6, and 77.8 kg ha^{-1} for F3, F5, and F6, respectively. Nitrification rates ranged from 51.5 to 91.6 kg ha^{-1} for F3, 42.4 to 78.4 kg ha^{-1} for F5, and 52.9 to 101.4 kg ha^{-1} for F6. The maximum and minimum years for nitrification for all fields were 1997 and 2000, respectively. Annual nitrification rates were not found for similar forested conditions in the literature. Therefore, it would be necessary to measure nitrification from the field directly to evaluate nitrification predictions by *DRAINMOD-N* II.

Predicted average annual denitrification rates for the 1996-2001 calibrations were 20.5, 15.9, and 28.4 kg ha^{-1} for F3, F5, and F6, respectively. Denitrification rates ranged from 13.5 to 26.4 kg ha^{-1} for F3, from 3.5 to 30.5 kg ha^{-1} for F5, and from 8.1 to 41.4 kg ha^{-1} for F6. Lower rates of denitrification for individual years occurred during particularly dry years, since denitrification proceeds optimally under saturated conditions. F6, in general, had higher water table elevations than F3 and F5, which led to more saturated conditions and higher denitrification rates. Barton et al. (1999) performed an extensive literature review of annual denitrification rates from forested sites and found that rates varied from 0 to 40 kg ha^{-1} yr^{-1} with the majority of studies reporting rates less than 10 kg ha^{-1} yr^{-1}. However, most of the studies were performed on forested sites on well-drained upland soils. It is likely that denitrification rates would be higher on relatively flat soils with high water tables, such as those found at the study sites. Measurements of denitrification rates from the study sites would be required to further evaluate the rates predicted by *DRAINMOD-N* II.

Predicted average annual N uptake rates were 83.5, 95.2, and 80.7 kg ha^{-1} for F3, F5, and F6, respectively. Nitrogen uptake rates ranged from 71.8 to 93.4 kg ha^{-1} for F3, from 83.9 to 106.0 kg ha^{-1} for F5, and from 70.9 to 91.4 kg ha^{-1} for F6. Compared to the N uptake values predicted by *PnET-CN* as shown in Table 2.13, the model did well in predicting uptake rates from F3 and F5, but overpredicted uptake rates from F6.

Parker Tract N Losses

Chescheir et al. (2003) found that annual total nitrogen exports from selected forests in eastern North Carolina were typically less than 7.5 kg ha^{-1} yr^{-1}. However, maximum annual DIN losses from F3, F5, and F6 during 1996-2001 were 12.2, 14.1, and 23.4 kg ha^{-1} yr^{-1}, respectively. High mineralization rates coupled with very well-drained surface layers are most likely the primary reasons for high N losses from F3, F5, and F6 in comparison to other forests in the region. *DRAINMOD-N* II predicted average mineralization rates (using the six-year calibration) of 104.2, 115.0, and 113.4 kg ha^{-1} yr^{-1} for F3, F5, and F6, respectively. As expected, the mineralization rates from the organic soils of F5 and F6 were higher than the mineral soil of F3. These average mineralization rates are significantly higher than most of the values found in the literature (Table 3.11). These soils are very well drained because of the high conductivity of the top layers, and the drainage provides a pathway for the large amounts of mineralized N to be lost in drainage.

SUMMARY AND CONCLUSIONS

Hydrologic and N fate and transport modeling of three loblolly pine sites in the Lower Coastal Plain of North Carolina was conducted using the *DRAINMOD* water table management model and the *DRAINMOD-N* II nitrogen model. *DRAINMOD* was developed to simulate the performance of artificial drainage on flat, agricultural soils. *DRAINMOD-N* II was developed to simulate N dynamics and turnover in the soil-water-plant system under different management practices and soil and environmental conditions.

The three forested sites, F3, F5, and F6, are comprised of a highly organic mineral soil (F3) and two organic soils (F5 and F6). Trees on F3, F5, and F6 were planted in 1983, 1984, and 1992, respectively. Water table depth midway between drains and meteorological data were automatically collected and recorded from 1995-2001. Drainage flow rate and drainage water quality samples were recorded from 1996-2001.

The results of the hydrologic simulations showed fair to good agreement between predicted and observed water table depths. The *AADD* of the water table depth predictions from 1995-2001 were 23.2, 28.4, and 13.0 cm for F3, F5, and F6, respectively. The R^2 values for the 1995-2001 simulation period were 0.70, 0.63, and 0.84 for F3, F5, and F6, respectively. The E values for the entire period were 0.66, 0.59, and 0.83 for F3, F5, and F6, respectively.

The agreement between predicted and observed drainage rates was fair to good. The R^2 values for daily drainage rate predictions from 1996-2001 were 0.71, 0.85, and 0.69 for F3, F5, and F6, respectively. The E values were 0.70, 0.69, and 0.68 for F3, F5, and F6, respectively. The normalized errors for the cumulative drainage predictions from 1996-2001 were -10.8, 2.7, and -17.1 % for F3, F5, and F6, respectively. Hydrology predictions from individual years varied considerably in accuracy, but there was no consistent model bias in model predictions.

Predictions of N loads by *DRAINMOD-N* II were highly dependent on hydrology predictions. Therefore, it was necessary to consider errors in hydrologic modeling when evaluating model N load predictions. The model was initially calibrated from 1996-1998 by comparing the ratio of predicted-to-measured N loads with the ratio of predicted-to-measured drainage losses. For F3, normalized errors in predicted cumulative N loads for the 1996-2001 period after the 1996-1998 calibration were 15.2, 54.6, and 23.9 % for NO_3-N, NH_4-N, and DIN, respectively. For F5, normalized errors were 28.9, -30.4, and 23.7 % for NO_3-N, NH_4-N, and DIN, respectively. For F6, normalized errors were -2.5, -48.2, and -6.4 % for NO_3-N, NH_4-N, and DIN, respectively. The model was calibrated again from 1996-2001 to improve model accuracy and to determine more accurate input parameters for future studies. Although the model predicted cumulative N loads from 1996-2001 after the six-year calibration, there were significant errors for individual years on all fields. These errors were not systematic however, and the years of model overprediction were countered by years of underprediction.

Predicted N transformation rates of mineralization and denitrification matched well with values from the literature. Predicted N uptake rates from F3 and F5 agreed well with values predicted by *PnET-CN,* but uptake rates were overpredicted for F6. The model was also able to simulate the 'first flush' occurrence of increased N losses in storm events after long dry periods that was observed in the field.

Model predictions of process rates, particularly N mineralization, were useful in developing a better understanding of N losses from F3, F5, and F6. N losses from these fields were significantly higher than from other forests in the eastern North Carolina region. The study showed that high mineralization rates coupled with very well-drained soils were a significant factor in high N losses from these fields.

The results of this study showed the reliability of *DRAINMOD* as a water table management model and the potential of *DRAINMOD-N* II for simulating N fate and transport in forested systems. The study also showed the dependence of *DRAINMOD-N* II nitrogen predictions on *DRAINMOD* hydrology predictions. Most of the input parameters for *DRAINMOD-N* II were determined from the literature or by calibration. A more accurate evaluation of *DRAINMOD-N* II would require more field and/or laboratory measurements to determine model inputs.

Table 3.1: Statistical comparison between observed and predicted water table depth for F3, F5, and F6.

	n			AADD, cm			ADD, cm			R^2			E		
	F3	**F5**	**F6**	**F3**	**F5**	**F6**	**F3**	**F5**	**F6**	**F3**	**F5**	**F6**	**F3**	**F5**	**F6**
1995	272	364	365	32.8	23.6	17.9	23.3	12.0	11.5	0.56	0.61	0.54	0.32	0.54	0.17
1996	267	256	357	14.2	20.4	14.5	5.8	-5.1	12.4	0.88	0.65	0.57	0.85	0.63	-5.2
1997	100	146	361	6.5	14.5	20.1	6.4	-1.0	9.4	0.91	0.88	0.80	0.27	0.80	0.76
1998	86	87	259	34.4	24.7	9.5	-29.0	-24.7	-6.5	0.76	0.96	0.95	0.37	0.65	0.93
1999	354	286	364	26.2	42.3	6.9	-8.4	-42.3	0.2	0.72	0.77	0.96	0.61	0.00	0.94
2000	248	291	291	23.9	15.4	12.5	-16.2	1.9	-6.1	0.50	0.83	0.77	0.34	0.74	0.74
2001	327	342	286	17.4	29.4	12.9	4.6	26.1	8.6	0.88	0.65	0.89	0.85	0.37	0.86
1995-2001	**1654**	**1772**	**2283**	**23.2**	**28.4**	**13.0**	**4.0**	**2.5**	**1.8**	**0.70**	**0.63**	**0.84**	**0.66**	**0.59**	**0.83**

Table 3.2: Average observed drainage and statistical comparison between observed and predicted drainage for F3, F5, and F6.

	Average Observed Drainage mm d^{-1}			AADD, mm d^{-1}			ADD, mm d^{-1}			R^2			E		
				F3	**F5**	**F6**	**F3**	**F5**	**F6**	**F3**	**F5**	**F6**	**F3**	**F5**	**F6**
1996	1.138	0.568	2.208	0.97	0.47	0.96	-0.10	-0.08	-0.91	0.54	0.73	0.78	0.54	0.51	0.70
1997	0.684	0.203	0.623	0.36	0.10	0.40	-0.36	-0.10	-0.26	0.82	0.88	0.63	0.60	0.71	0.54
1998	0.915	0.282	1.124	0.44	0.23	0.67	-0.17	0.23	-0.07	0.78	0.97	0.72	0.72	0.64	0.72
1999	0.815	0.413	1.022	0.77	0.22	0.67	0.72	0.20	0.16	0.88	0.98	0.74	-2.3	0.76	0.71
2000	0.86	0.502	0.516	0.65	0.23	0.45	-0.11	-0.13	0.13	0.59	0.84	0.47	0.52	0.80	-0.57
2001	0.123	0.086	0.064	0.12	0.09	0.06	-0.12	-0.09	-0.06	na	na	0.58	na	na	0.11
1996-2001	**0.757**	**0.343**	**0.927**	**0.51**	**0.21**	**0.53**	**-0.10**	**0.01**	**-0.15**	**0.71**	**0.85**	**0.69**	**0.70**	**0.69**	**0.68**

Table 3.3: Observed and predicted annual subsurface drainage for F3, F5, and F6 in 1996-2001, with normalized error.

	F3			F5			F6		
	Observed	**Predicted**	**NE, %**	**Observed**	**Predicted**	**NE, %**	**Observed**	**Predicted**	**NE, %**
1996	41.7	40.2	-3.6	20.8	18.5	-11.2	80.8	49.5	-38.8
1997	25.0	11.7	-53.2	7.4	3.9	-47.4	22.7	13.2	-42.0
1998	33.5	27.1	-19.0	10.3	18.7	81.1	41.1	38.6	-6.1
1999	29.8	41.3	38.6	15.1	22.5	48.6	37.4	43.2	15.6
2000	31.5	27.7	-11.9	18.4	13.6	-25.7	18.9	23.8	26.0
2001	4.5	0.0	na	3.1	0.0	na	2.3	0.3	-89.0
Total	**165.9**	**148.0**	**-10.8**	**75.1**	**77.2**	**2.7**	**203.3**	**168.6**	**-17.1**

Table 3.4: Predicted and observed N losses from F3 using 1996-1998 calibration. Cumulative annual drainage, and predicted:observed ratios of drainage, NO_3, NH_4, and DIN losses.

	Observed			**Predicted**					**Predicted : Observed Ratio**			
	NO_3 Loss kg ha^{-1}	**NH_4 Loss** kg ha^{-1}	**DIN Loss** kg ha^{-1}	**NO_3 Loss** kg ha^{-1}	**NH_4 Loss** kg ha^{-1}	**DIN Loss** kg ha^{-1}	**Observed Drainage** cm	**Predicted Drainage** cm	**Drainage**	**NO_3 Loss**	**NH_4 Loss**	**DIN Loss**
1995	na	na	na	0.7	0.1	1.0	na	13.4	na	na	na	na
1996	11.2	1.0	12.2	4.2	1.0	5.6	41.7	40.2	0.96	0.37	1.01	0.42
1997	3.9	0.6	4.5	1.2	0.1	0.5	25.0	11.7	0.47	0.30	0.12	0.28
1998	3.0	0.7	3.7	8.9	0.7	7.4	33.5	27.1	0.81	2.99	1.01	2.61
1999	2.0	0.8	2.8	6.0	4.2	6.2	29.8	41.3	1.39	2.99	5.53	3.68
2000	1.0	0.3	1.3	2.0	0.5	2.6	31.5	27.7	0.88	1.99	1.86	1.96
2001	0.1	0.0	0.1	0.0	0.0	0.0	4.5	0.0	0.00	0.32	0.00	0.30
1996-1998	**18.1**	**2.3**	**20.4**	**14.3**	**1.8**	**13.4**	**100.1**	**79.0**	**0.79**	**0.79**	**0.78**	**0.79**
1996-2001	**21.3**	**3.3**	**24.6**	**22.3**	**6.5**	**22.3**	**165.9**	**148.0**	**0.89**	**1.05**	**1.96**	**1.17**

Table 3.5: Predicted and observed N losses from F3 using 1996-2001 calibration. Cumulative annual drainage, and predicted:observed ratios of drainage, NO_3, NH_4, and DIN losses.

	Observed			**Predicted**					**Predicted : Observed Ratio**			
	NO_3 Loss kg ha^{-1}	**NH_4 Loss** kg ha^{-1}	**DIN Loss** kg ha^{-1}	**NO_3 Loss** kg ha^{-1}	**NH_4 Loss** kg ha^{-1}	**DIN Loss** kg ha^{-1}	**Observed Drainage cm**	**Predicted Drainage cm**	**Drainage**	**NO_3 Loss**	**NH_4 Loss**	**DIN Loss**
1995	na	na	na	0.7	0.1	0.8	na	13.4	na	na	na	na
1996	11.2	1.0	12.2	4.0	0.4	4.4	41.7	40.2	0.96	0.35	0.44	0.36
1997	3.9	0.6	4.5	1.0	0.0	1.0	25.0	11.7	0.47	0.25	0.05	0.22
1998	3.0	0.7	3.7	8.2	0.3	8.4	33.5	27.1	0.81	2.73	0.38	2.28
1999	2.0	0.8	2.8	4.6	2.0	6.6	29.8	41.3	1.39	2.28	2.59	2.37
2000	1.0	0.3	1.3	1.5	0.3	1.8	31.5	27.7	0.88	1.52	0.91	1.39
2001	0.1	0.0	0.1	0.0	0.0	0.0	4.5	0.0	0.00	0.24	0.00	0.23
Total	**21.3**	**3.3**	**24.6**	**19.3**	**2.9**	**22.2**	**165.9**	**148.0**	**0.89**	**0.91**	**0.89**	**0.90**

Table 3.6: Predicted and observed N losses from F5 using 1996-1998 calibration. Cumulative annual drainage, and predicted:observed ratios of drainage, NO_3, NH_4, and DIN losses.

	Observed			Predicted					Predicted : Observed Ratio			
	NO_3 Loss kg ha^{-1}	NH_4 Loss kg ha^{-1}	DIN Loss kg ha^{-1}	NO_3 Loss kg ha^{-1}	NH_4 Loss kg ha^{-1}	DIN Loss kg ha^{-1}	Observed Drainage cm	Predicted Drainage cm	Drainage	NO_3 Loss	NH_4 Loss	DIN Loss
1995	na	na	na	0.2	0.1	0.3	na	9.5	na	na	na	na
1996	13.4	0.8	14.1	6.7	0.7	7.3	20.8	18.5	0.89	0.50	0.82	0.52
1997	1.7	0.2	1.9	0.2	0.0	0.2	7.4	3.9	0.53	0.14	0.05	0.13
1998	2.1	0.3	2.5	11.9	0.7	12.6	10.3	18.7	1.81	5.56	2.10	5.08
1999	2.0	1.2	3.1	10.4	1.6	12.0	15.1	22.5	1.49	5.27	1.38	3.83
2000	1.8	1.3	3.1	1.7	0.1	1.8	18.4	13.6	0.74	0.97	0.06	0.58
2001	0.3	0.0	0.3	0.0	0.0	0.0	3.1	0.0	0.00	0.00	0.00	0.00
1996-1998	**17.2**	**1.3**	**18.5**	**18.8**	**1.4**	**20.2**	**38.5**	**41.1**	**1.07**	**1.09**	**1.03**	**1.09**
1996-2001	**21.3**	**3.9**	**25.1**	**30.9**	**3.1**	**34.0**	**75.1**	**77.2**	**1.03**	**1.45**	**0.79**	**1.35**

Table 3.7: Predicted and observed N losses from F5 using 1996-2001 calibration. Cumulative annual drainage, and predicted:observed ratios of drainage, NO_3, NH_4, and DIN losses.

	Observed			Predicted					Predicted : Observed Ratio			
	NO_3 Loss kg ha^{-1}	NH_4 Loss kg ha^{-1}	DIN Loss kg ha^{-1}	NO_3 Loss kg ha^{-1}	NH_4 Loss kg ha^{-1}	DIN Loss kg ha^{-1}	Observed Drainage cm	Predicted Drainage cm	Drainage	NO_3 Loss	NH_4 Loss	DIN Loss
1995	na	na	na	0.1	0.1	0.2	na	9.5	na	na	na	na
1996	13.4	0.8	14.1	4.1	0.8	4.9	20.8	18.5	1.13	0.31	0.97	0.35
1997	1.7	0.2	1.9	0.1	0.0	0.1	7.4	3.9	1.90	0.06	0.05	0.06
1998	2.1	0.3	2.5	8.5	1.0	9.6	10.3	18.7	0.55	3.98	2.99	3.84
1999	2.0	1.2	3.1	7.5	1.9	9.4	15.1	22.5	0.67	3.79	1.68	3.01
2000	1.8	1.3	3.1	1.2	0.1	1.3	18.4	13.6	1.35	0.66	0.08	0.41
2001	0.3	0.0	0.3	0.0	0.0	0.0	3.1	0.0	0.00	0.00	0.00	0.00
Total	**21.3**	**3.9**	**25.1**	**21.4**	**3.9**	**25.2**	**75.1**	**77.2**	**1.03**	**1.00**	**1.00**	**1.00**

Table 3.8: Predicted and observed N losses from F6 using 1996-1998 calibration. Cumulative annual drainage, and predicted:observed ratios of drainage, NO_3, NH_4, and DIN losses.

	Observed			**Predicted**					**Predicted : Observed Ratio**			
	NO_3 Loss kg ha^{-1}	**NH_4 Loss** kg ha^{-1}	**DIN Loss** kg ha^{-1}	**NO_3 Loss** kg ha^{-1}	**NH_4 Loss** kg ha^{-1}	**DIN Loss** kg ha^{-1}	**Observed Drainage** cm	**Predicted Drainage** cm	**Drainage**	**NO_3 Loss**	**NH_4 Loss**	**DIN Loss**
1995	na	na	na	2.0	0.2	2.2	na	29.8	na	na	na	na
1996	21.6	1.8	23.4	9.1	1.2	10.3	80.8	49.5	0.61	0.42	0.65	0.44
1997	3.9	0.3	4.2	2.0	0.1	2.1	22.7	13.2	0.58	0.50	0.29	0.49
1998	7.6	0.5	8.1	12.2	0.6	12.8	41.1	38.6	0.94	1.60	1.20	1.57
1999	9.0	1.6	10.6	9.5	1.2	10.7	37.4	43.2	1.16	1.05	0.77	1.01
2000	1.2	1.8	3.0	2.3	0.2	2.5	18.9	23.8	1.26	1.92	0.14	0.85
2001	0.1	0.0	0.1	0.0	0.0	0.0	2.3	0.3	0.11	0.00	0.00	0.00
1996-1998	**33.1**	**2.6**	**35.8**	**23.3**	**1.9**	**25.1**	**144.7**	**101.3**	**0.70**	**0.70**	**0.71**	**0.70**
1996-2001	**43.5**	**6.0**	**49.4**	**35.0**	**3.3**	**38.3**	**203.3**	**168.6**	**0.83**	**0.81**	**0.56**	**0.78**

Table 3.9: Predicted and observed N losses from F6 using 1996-2001 calibration. Cumulative annual drainage, and predicted:observed ratios of drainage, NO_3, NH_4, and DIN losses.

	Observed			**Predicted**					**Predicted : Observed Ratio**			
	NO_3 Loss kg ha^{-1}	**NH_4 Loss** kg ha^{-1}	**DIN Loss** kg ha^{-1}	**NO_3 Loss** kg ha^{-1}	**NH_4 Loss** kg ha^{-1}	**DIN Loss** kg ha^{-1}	**Observed Drainage** cm	**Predicted Drainage** cm	**Drainage**	**NO_3 Loss**	**NH_4 Loss**	**DIN Loss**
1995	na	na	na	1.9	0.2	2.1	na	29.8	na	na	na	na
1996	21.6	1.8	23.4	8.9	1.7	10.5	80.8	49.5	0.61	0.41	0.94	0.45
1997	3.9	0.3	4.2	1.9	0.1	2.1	22.7	13.2	0.58	0.49	0.45	0.49
1998	7.6	0.5	8.1	12.0	1.0	13.0	41.1	38.6	0.94	1.58	1.92	1.60
1999	9.0	1.6	10.6	9.4	1.7	11.1	37.4	43.2	1.16	1.04	1.10	1.05
2000	1.2	1.8	3.0	2.2	0.4	2.6	18.9	23.8	1.26	1.86	0.20	0.87
2001	0.1	0.0	0.1	0.0	0.0	0.0	2.3	0.3	0.11	0.00	0.00	0.00
Total	**43.5**	**6.0**	**49.4**	**34.4**	**4.9**	**39.3**	**203.3**	**168.6**	**0.83**	**0.79**	**0.82**	**0.79**

Table 3.10: Annual predicted nitrogen process rates for the 1996-1998 and the 1996-2001 calibration periods for F3.

	1996-1998 Calibration				1996-2001 Calibration			
	Mineral-ization kg ha^{-1}	**Nitrif-ication** kg ha^{-1}	**Denitrif-ication** kg ha^{-1}	**N Uptake** kg ha^{-1}	**Mineral-ization** kg ha^{-1}	**Nitrif-ication** kg ha^{-1}	**Denitrif-ication** kg ha^{-1}	**N Uptake** kg ha^{-1}
1995	130.2	37.5	9.5	77.3	117.4	51.1	11.9	79.5
1996	114.1	48.9	21.0	90.6	102.7	55.3	21.4	88.9
1997	129.3	64.9	21.9	86.3	116.3	70.4	20.7	83.6
1998	125.6	58.3	24.3	93.8	112.9	62.1	21.7	89.8
1999	106.6	49.1	20.3	100.2	95.6	49.0	17.0	93.4
2000	97.6	35.5	12.2	76.4	87.4	37.7	10.4	71.8
2001	107.5	51.3	15.0	82.2	96.1	54.9	13.7	77.7
Avg.	**115.8**	**49.4**	**17.8**	**86.7**	**104.0**	**54.4**	**16.7**	**83.5**

Table 3.11: Annual predicted nitrogen process rates for the 1996-1998 and the 1996-2001 calibration periods for F5.

	1996-1998 Calibration				1996-2001 Calibration			
	Mineral-ization kg ha^{-1}	**Nitrif-ication** kg ha^{-1}	**Denitrif-ication** kg ha^{-1}	**N Uptake** kg ha^{-1}	**Mineral-ization** kg ha^{-1}	**Nitrif-ication** kg ha^{-1}	**Denitrif-ication** kg ha^{-1}	**N Uptake** kg ha^{-1}
1995	128.4	61.9	6.1	83.7	128.4	61.0	7.3	83.9
1996	110.4	70.5	26.1	106.1	110.4	68.4	30.5	105.7
1997	128.7	80.7	4.0	93.6	128.7	78.4	4.1	92.7
1998	123.5	77.2	25.3	106.3	123.5	74.5	29.7	104.7
1999	105.6	66.0	25.2	107.3	105.6	63.5	29.8	106.0
2000	96.6	44.9	4.4	90.6	96.6	42.4	6.3	88.5
2001	111.6	65.6	2.8	85.9	111.6	63.8	3.5	84.5
Average	**115.0**	**66.7**	**13.4**	**96.2**	**115.0**	**64.6**	**15.9**	**95.2**

Table 3.12: Annual predicted nitrogen process rates for the 1996-1998 and the 1996-2001 calibration periods for F6.

	1996-1998 Calibration				**1996-2001 Calibration**			
	Mineral-ization kg ha^{-1}	**Nitrif-ication** kg ha^{-1}	**Denitrif-ication** kg ha^{-1}	**N Uptake** kg ha^{-1}	**Mineral-ization** kg ha-1	**Nitrif-ication** kg ha-1	**Denitrif-ication** kg ha-1	**N Uptake** kg ha-1
1995	120.6	88.6	37.2	71.2	120.6	84.4	36.2	71.2
1996	104.2	72.2	42.0	70.7	104.2	68.8	41.4	70.9
1997	127.5	103.9	37.2	74.8	127.5	101.4	37.2	74.8
1998	121.7	80.3	34.6	87.8	121.7	77.1	34.5	87.8
1999	104.9	66.6	30.1	91.4	104.9	63.7	30.0	91.4
2000	97.6	57.0	12.1	83.0	97.6	52.9	11.7	83.4
2001	117.2	99.8	8.3	85.4	117.2	96.7	8.1	85.4
Avg	**113.4**	**81.2**	**28.8**	**80.6**	**113.4**	**77.8**	**28.4**	**80.7**

Table 3.13: Annual net mineralization rates from the literature.

Source	**Forest type**	**Location**	**Age**	**Mean Annual Mineralization kg ha^{-1}**	**Range kg ha^{-1}**
Li et al., 2003	Loblolly	Lower Coastal Plain, NC	2	125.5	103-143
Li et al., 2003	Loblolly	Lower Coastal Plain, NC	5	21.7	16.3-26.1
Piatek and Allen, 1999	Loblolly	Piedmont, NC	1	68.1	18-100
Piatek and Allen, 1999	Loblolly	Piedmont, NC	2	55.1	19-85
Piatek and Allen, 1999	Loblolly	Piedmont, NC	15	22.6	2.6-34.3
Reich et al., 1997	Conifer	Wisconsin, Minnesota	mature	58	20-120
Frazer et al., 1990	Conifer	Northern California	5	49	
Frazer et al., 1990	Conifer	Northern California	17	31	
Frazer et al., 1990	Conifer	Northern California	100	12	
Persson and Wiren, 1995	Norway Spruce	Sweden and Denmark	mature	70	35-105
Carlyle and Nambiar, 2001	*Pinus Radiata*	Australia	25-60	55	30-80

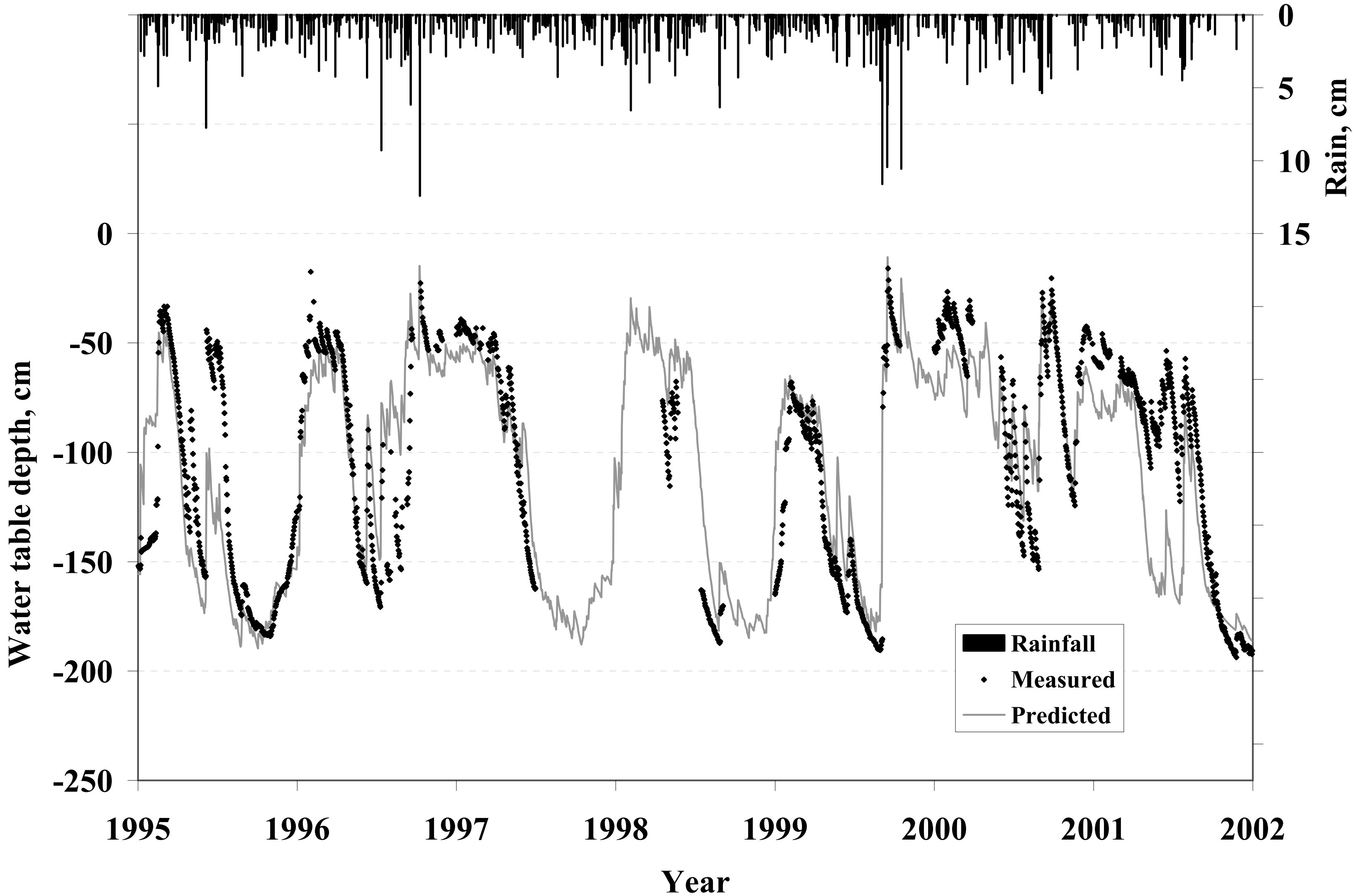

Figure 3.1: Rainfall and predicted and measured water table depths at F3 from 1995-2001.

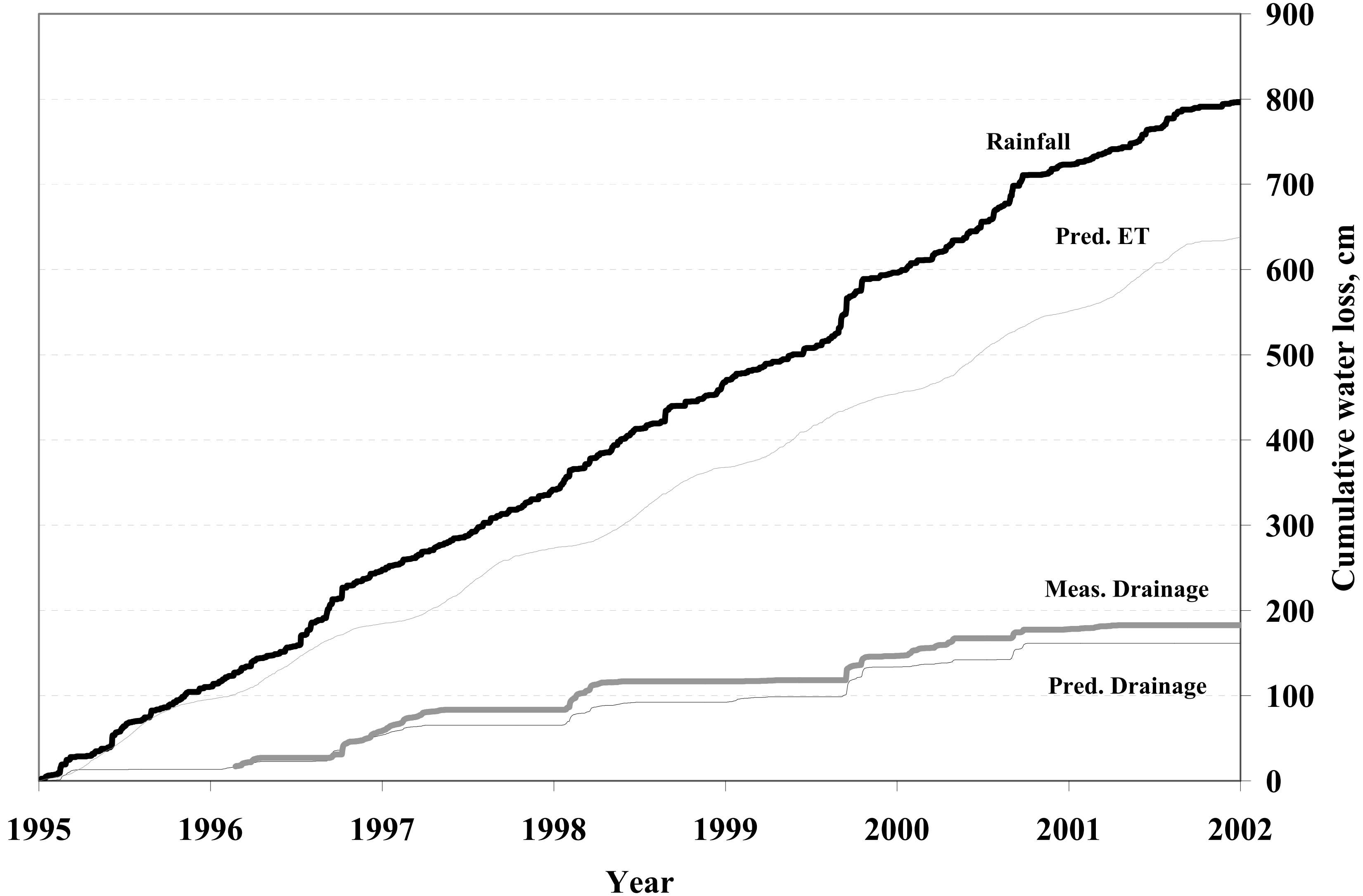

Figure 3.2: Cumulative rainfall, predicted ET, and measured and predicted drainage at F3 from 1995-2001.

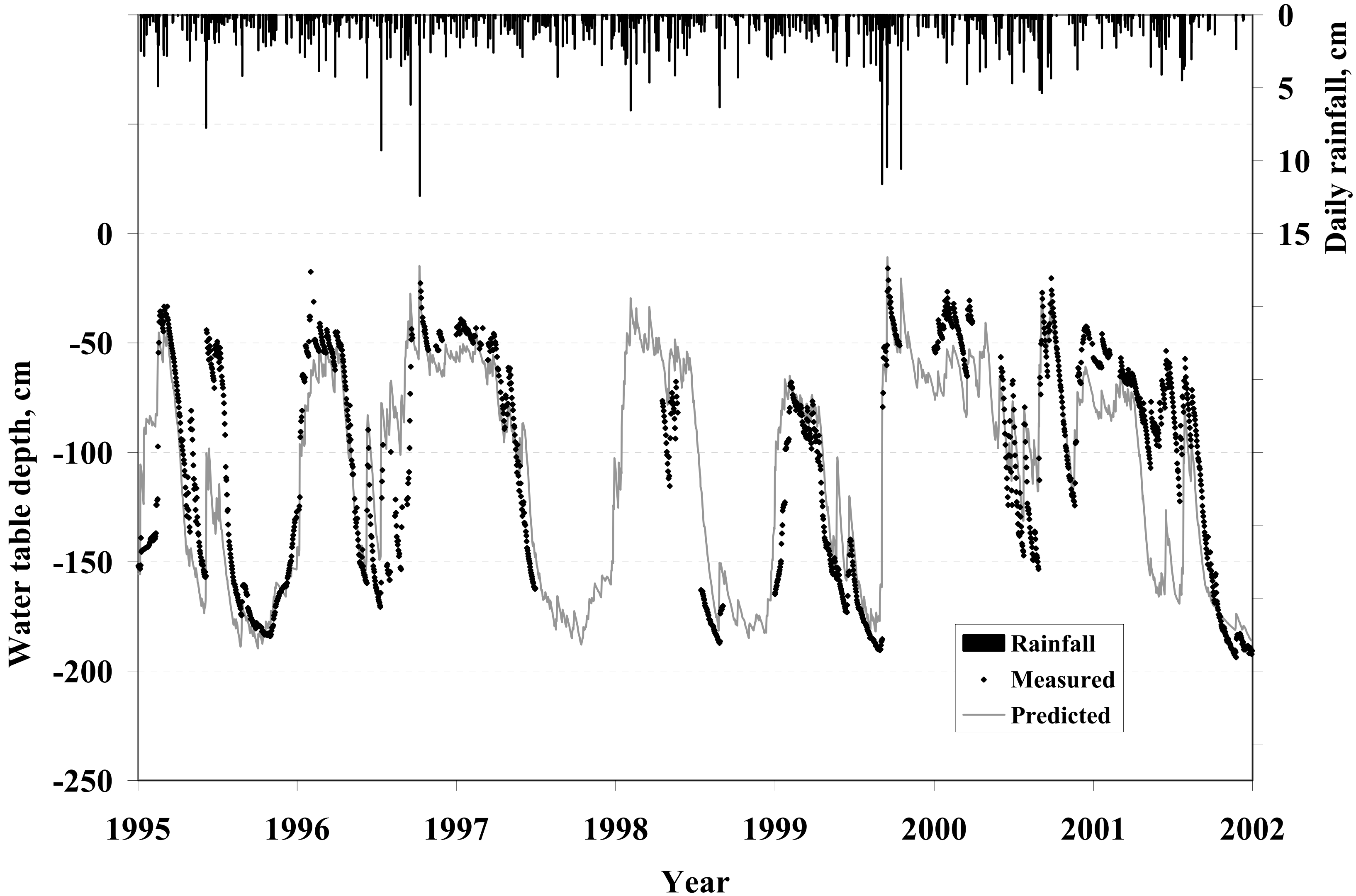

Figure 3.3: Rainfall and predicted and measured water table depths at F5 from 1995-2001.

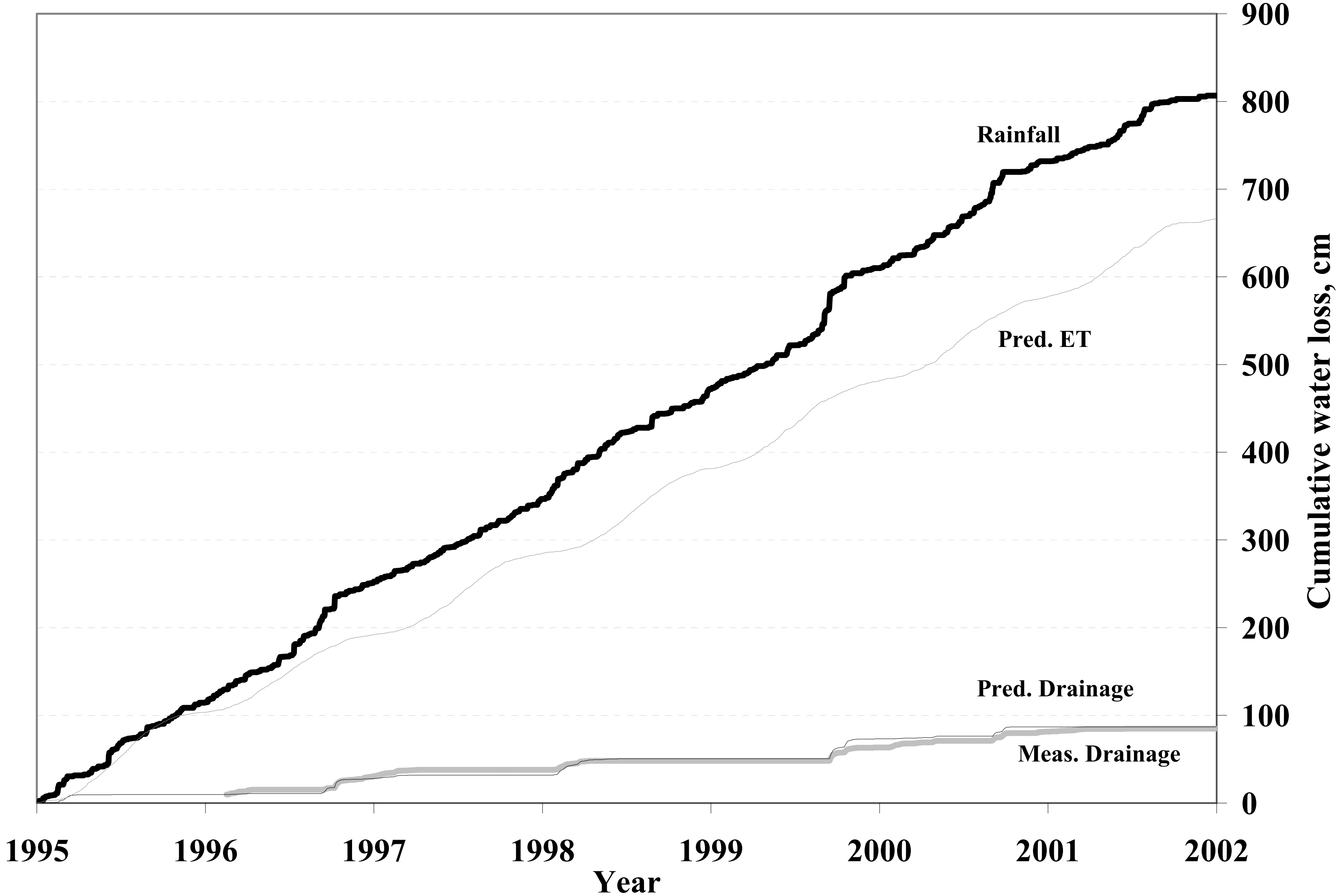

Figure 3.4: Cumulative rainfall, predicted ET, and measured and predicted drainage at F5 from 1995-2001.

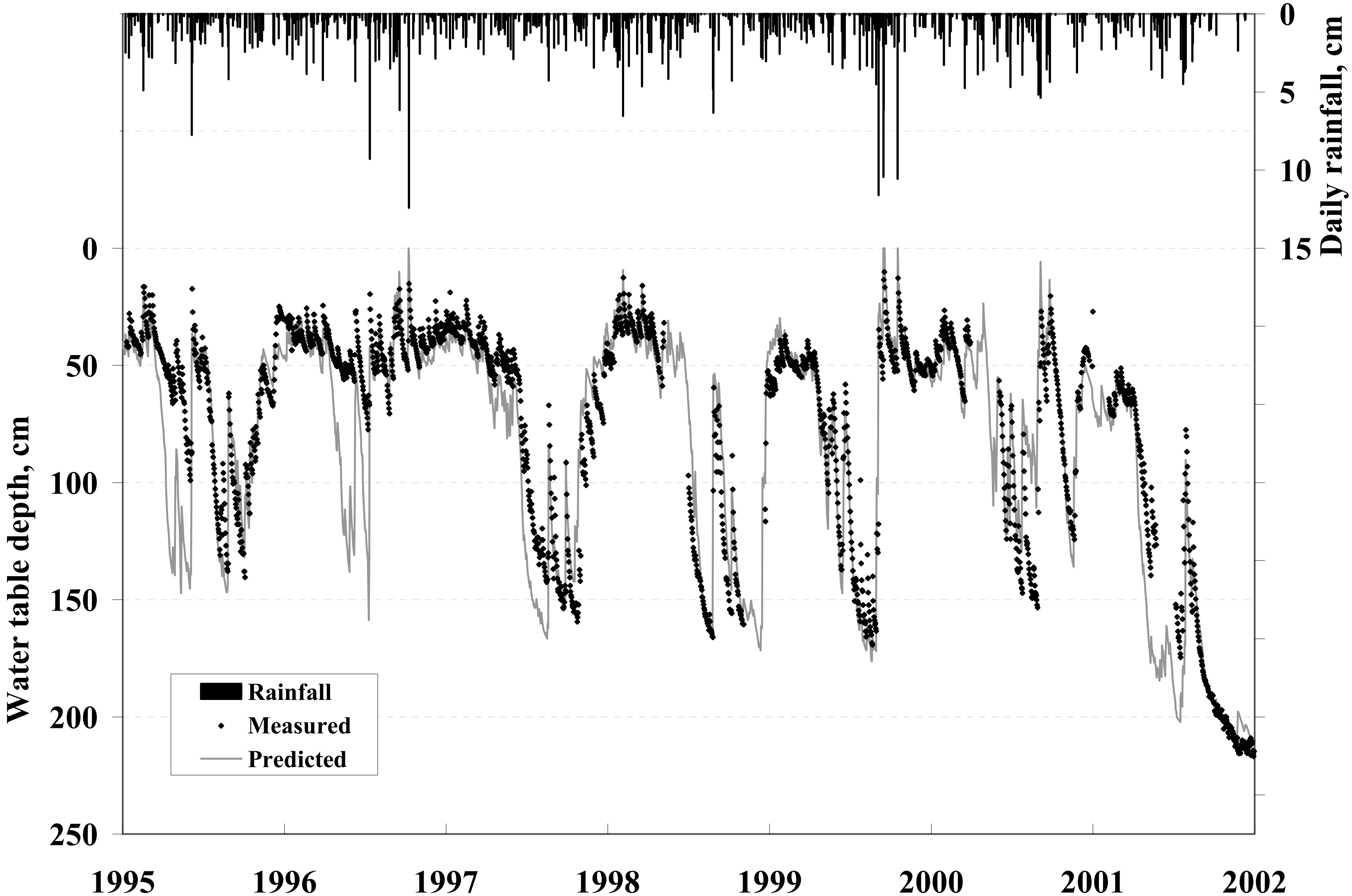

Figure 3.5: Rainfall and predicted and measured water table depths at F6 from 1995-2001.

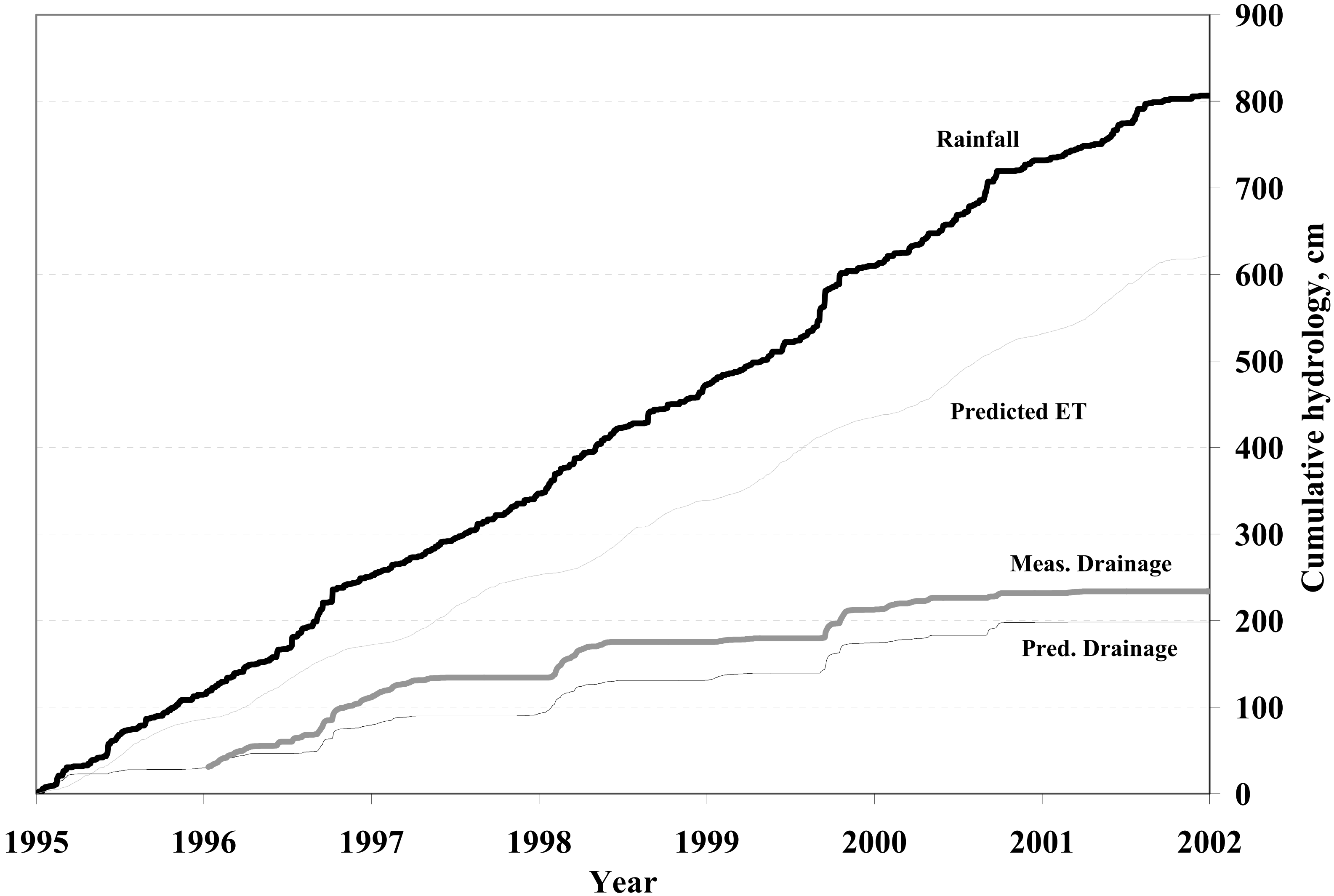

Figure 3.6: Cumulative rainfall, predicted ET, and measured and predicted drainage at F6 from 1995-2001.

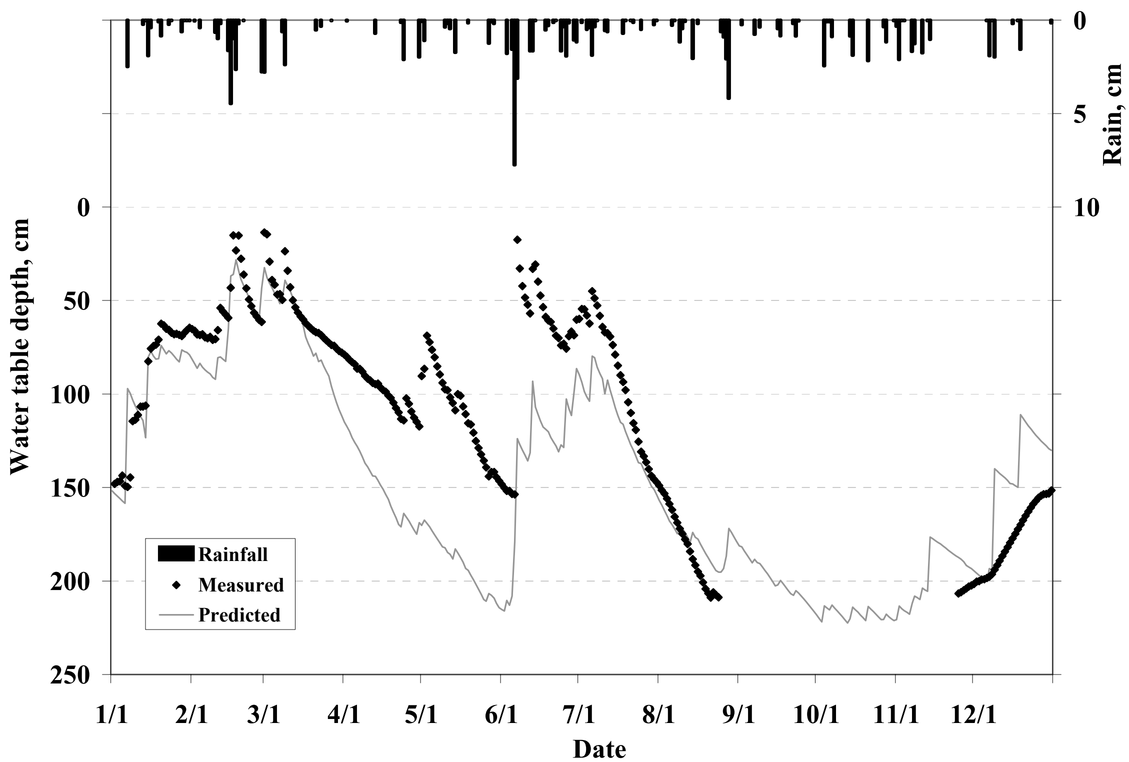

Figure 3.7: Rainfall and predicted and measured water table depths at F3 from 1995.

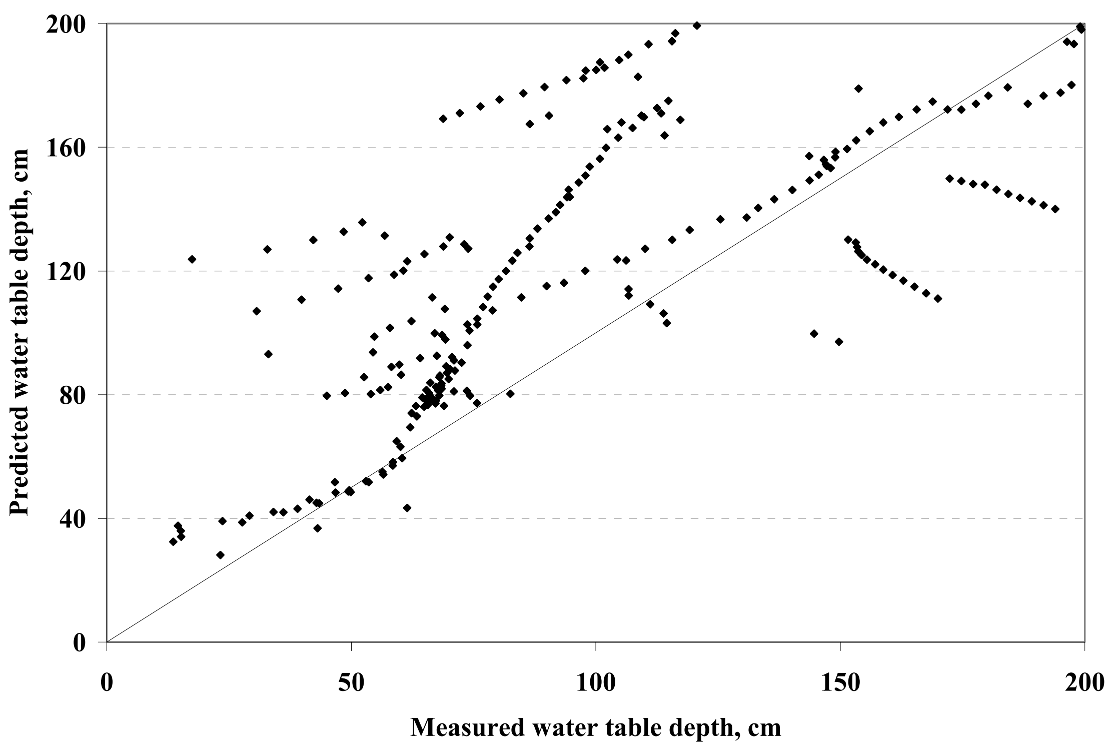

Figure 3.8: Predicted versus measured water table depths at F3 from 1995.

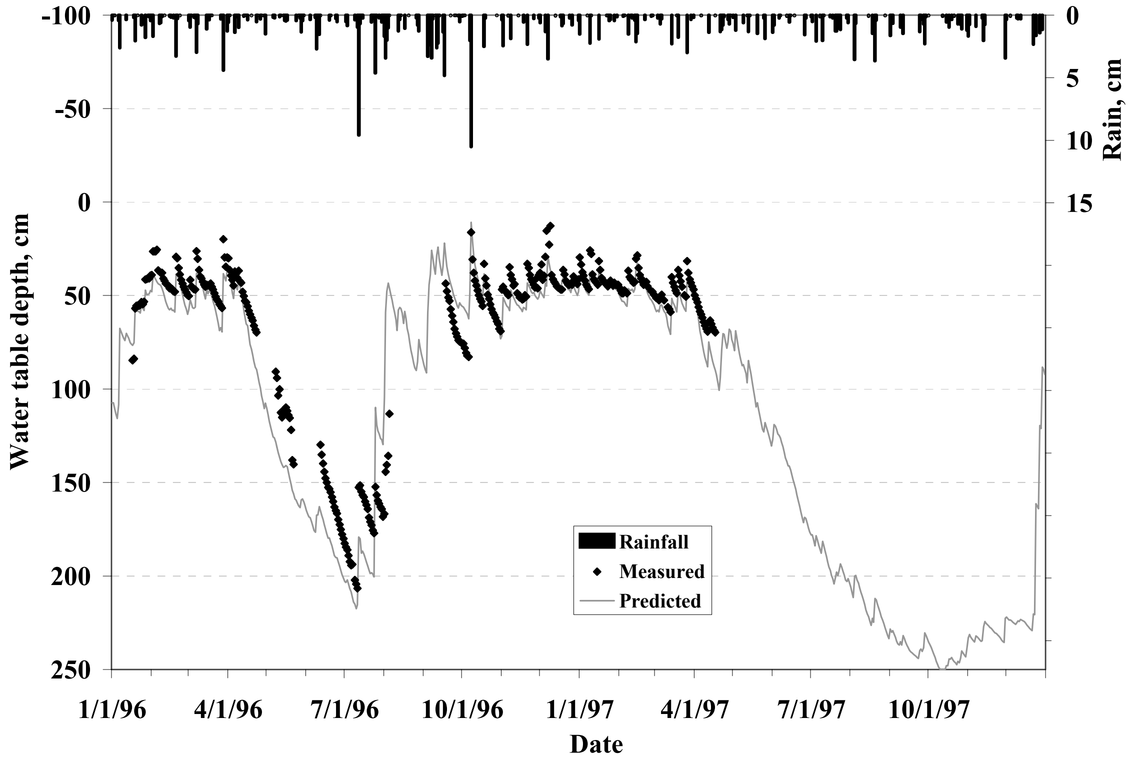

Figure 3.9: Rainfall and predicted and measured water table depths at F3 from 1996-1997.

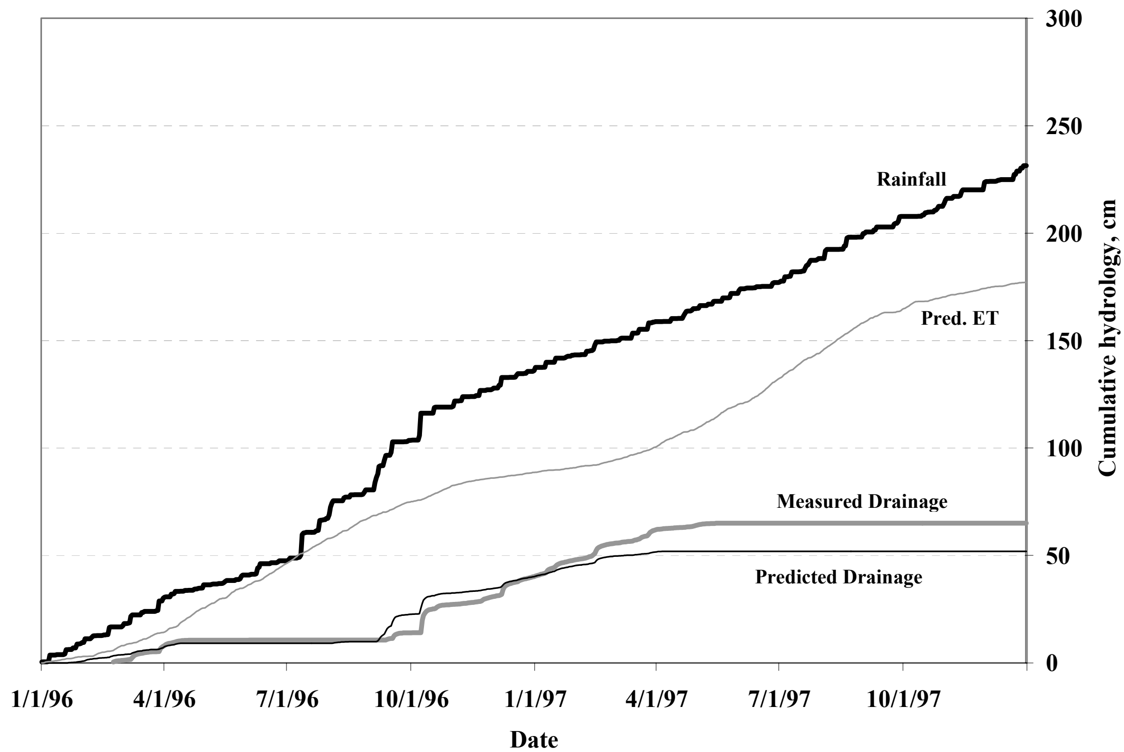

Figure 3.10: Cumulative rainfall, predicted ET, and measured and predicted drainage at F3 from 1996-1997.

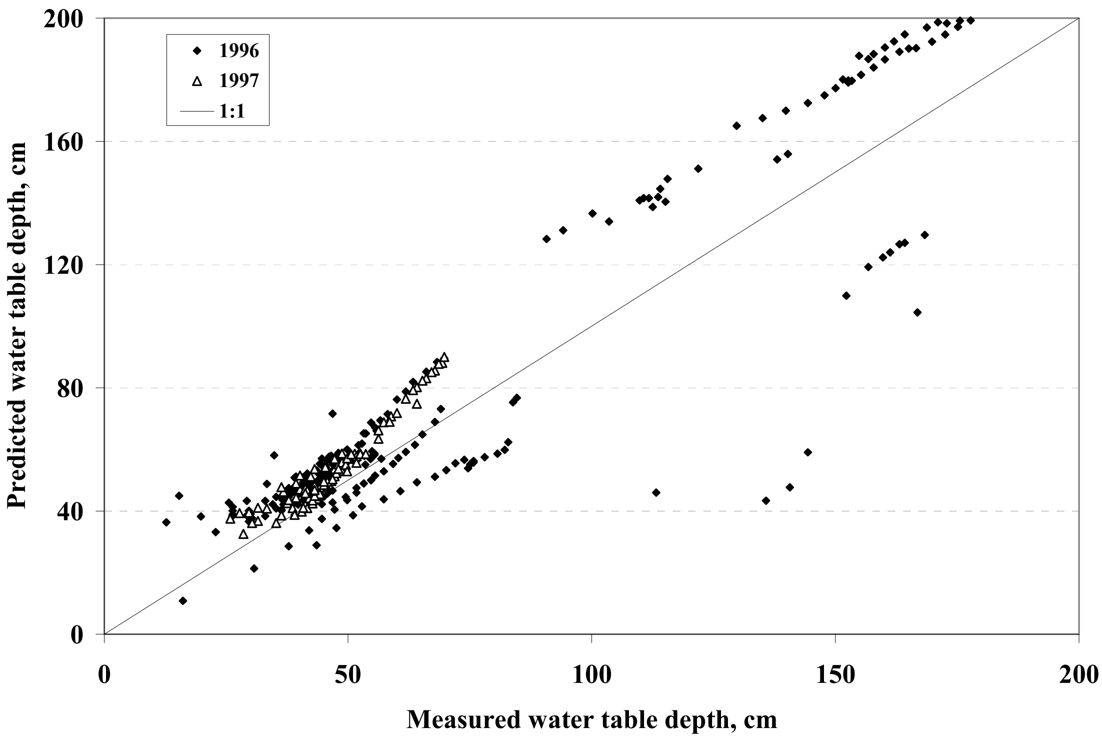

Figure 3.11: Predicted versus measured water table depths at F3 from 1996-1997.

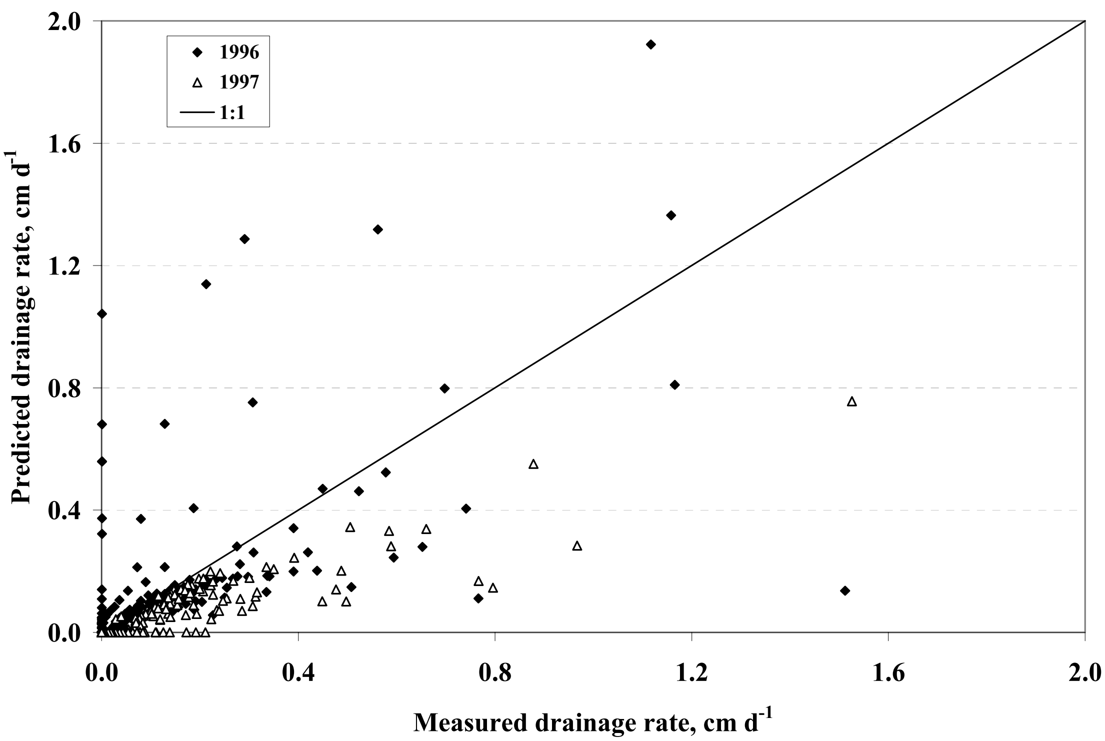

Figure 3.12: Predicted versus measured drainage rates at F3 from 1996-1997.

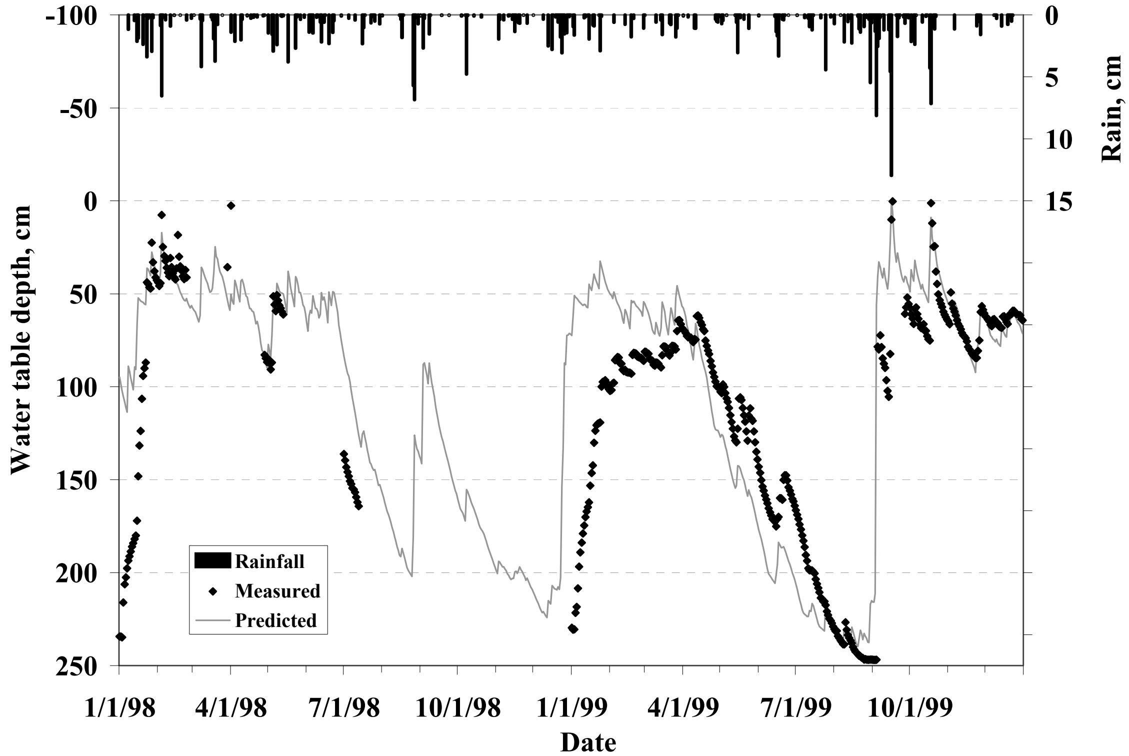

Figure 3.13: Rainfall and predicted and measured water table depths at F3 from 1998-1999.

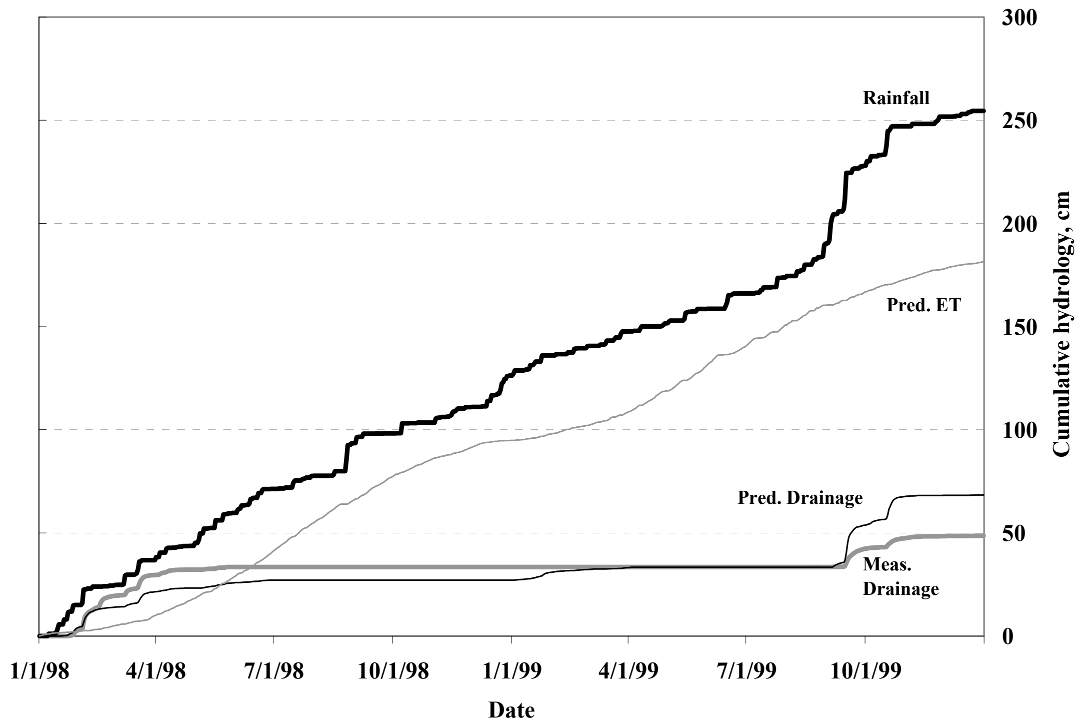

Figure 3.14: Cumulative rainfall, predicted ET, and measured and predicted drainage at F3 from 1998-1999.

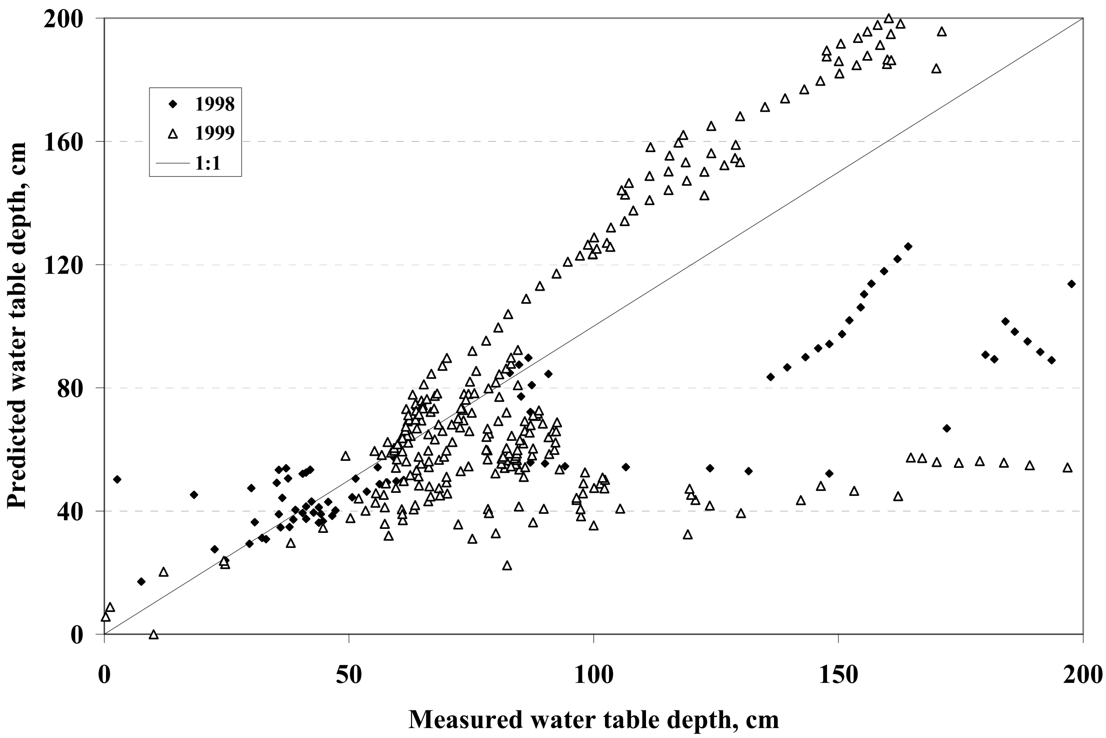

Figure 3.15: Predicted versus measured water table depths at F3 from 1998-1999.

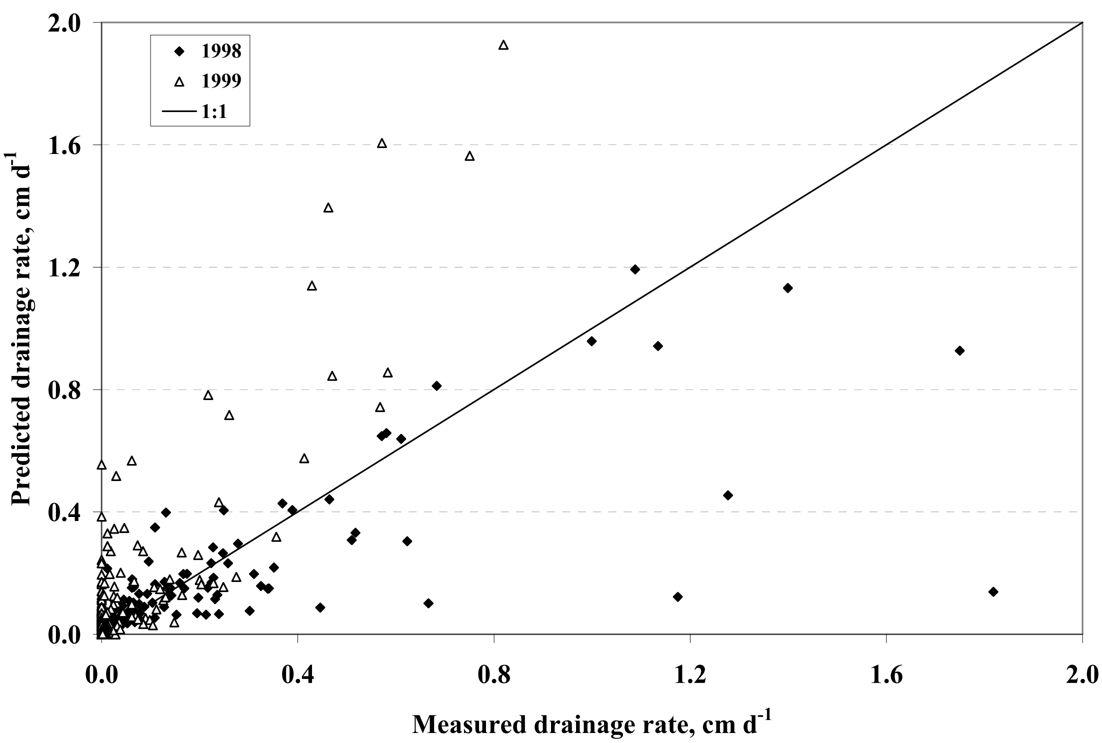

Figure 3.16: Predicted versus measured drainage rates at F3 from 1998-1999.

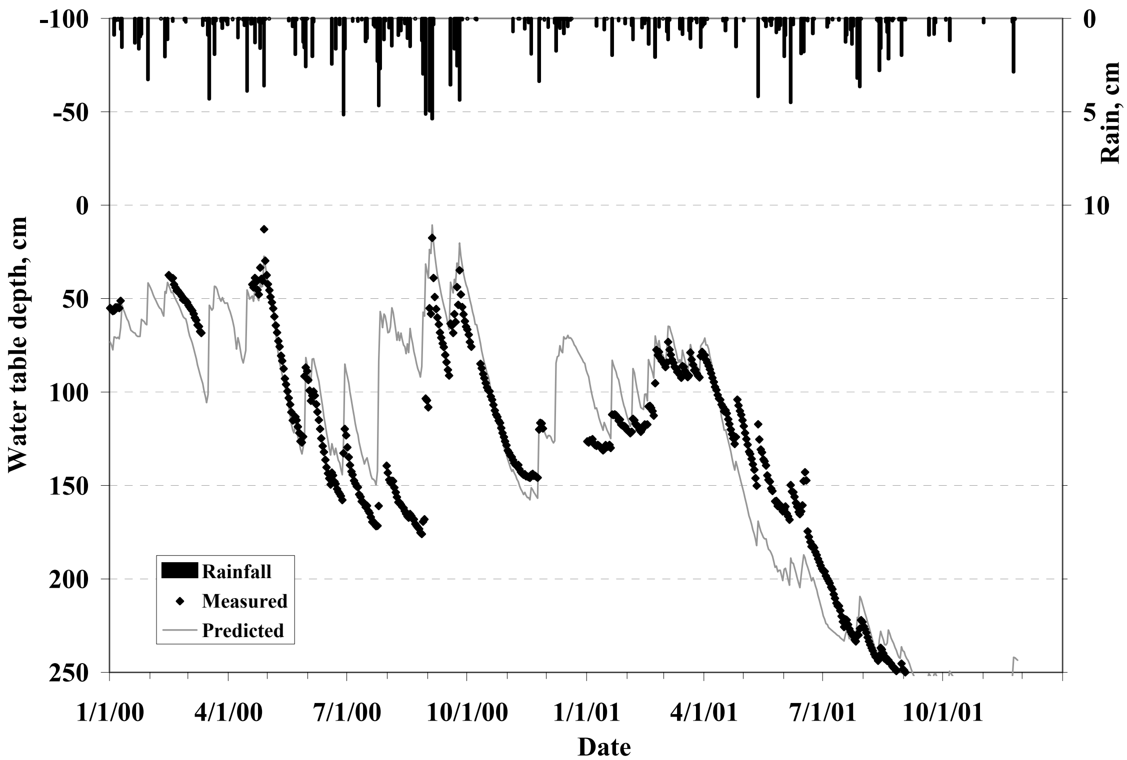

Figure 3.17: Rainfall and predicted and measured water table depths at F3 from 2000-2001

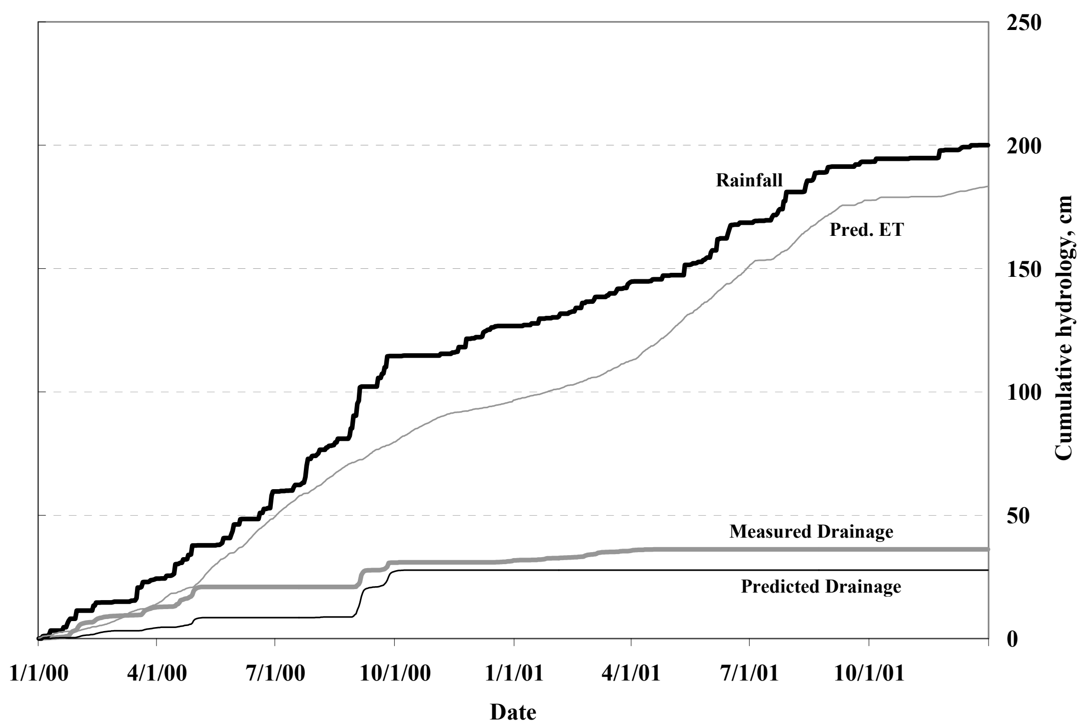

Figure 3.18: Cumulative rainfall, predicted ET, and measured and predicted drainage at F3 from 2000-2001.

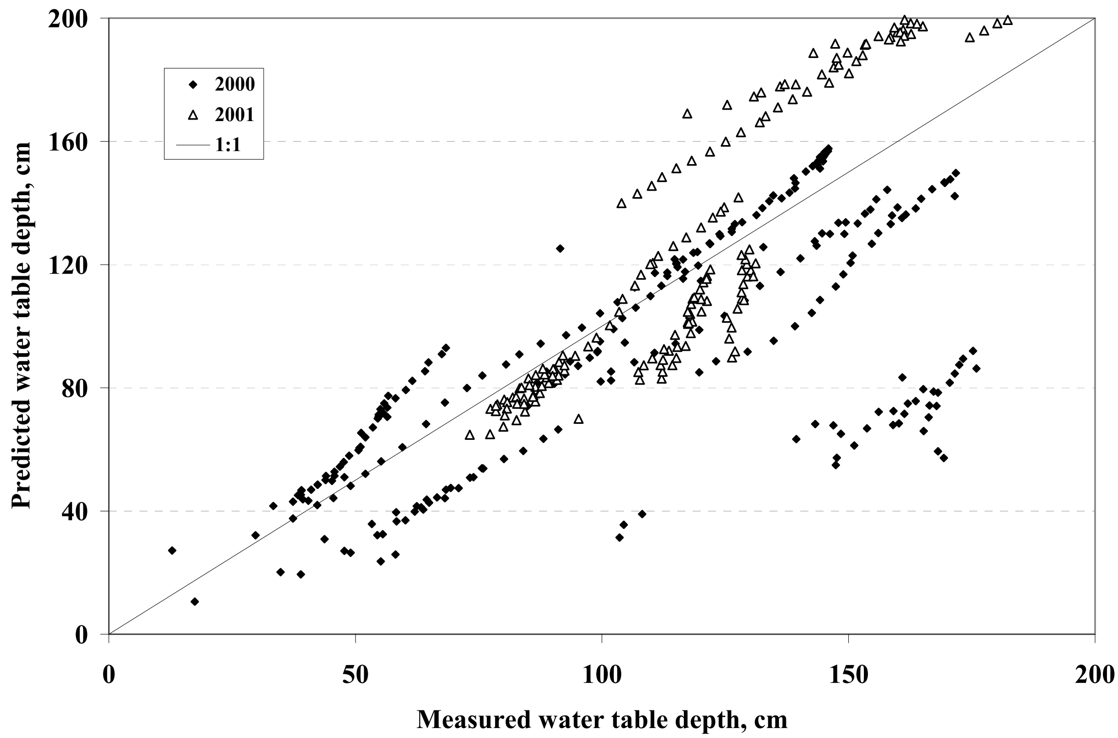

Figure 3.19: Predicted versus measured water table depths at F3 from 2000-2001.

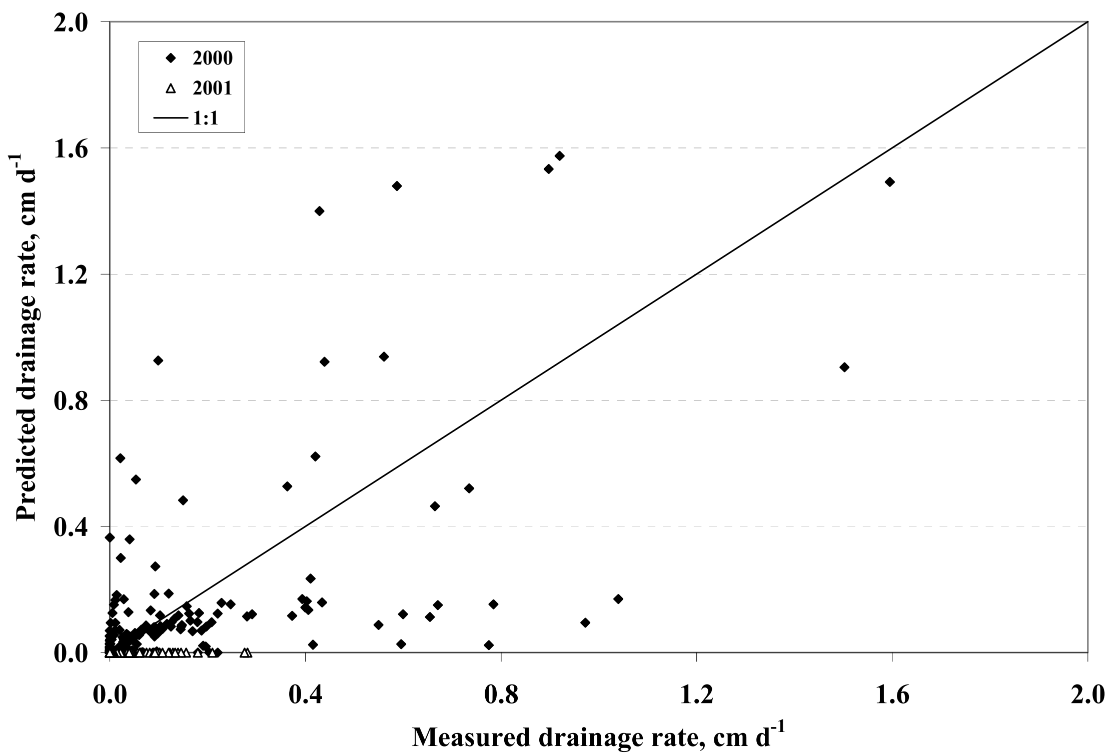

Figure 3.20: Predicted versus measured drainage rates at F3 from 2000-2001.

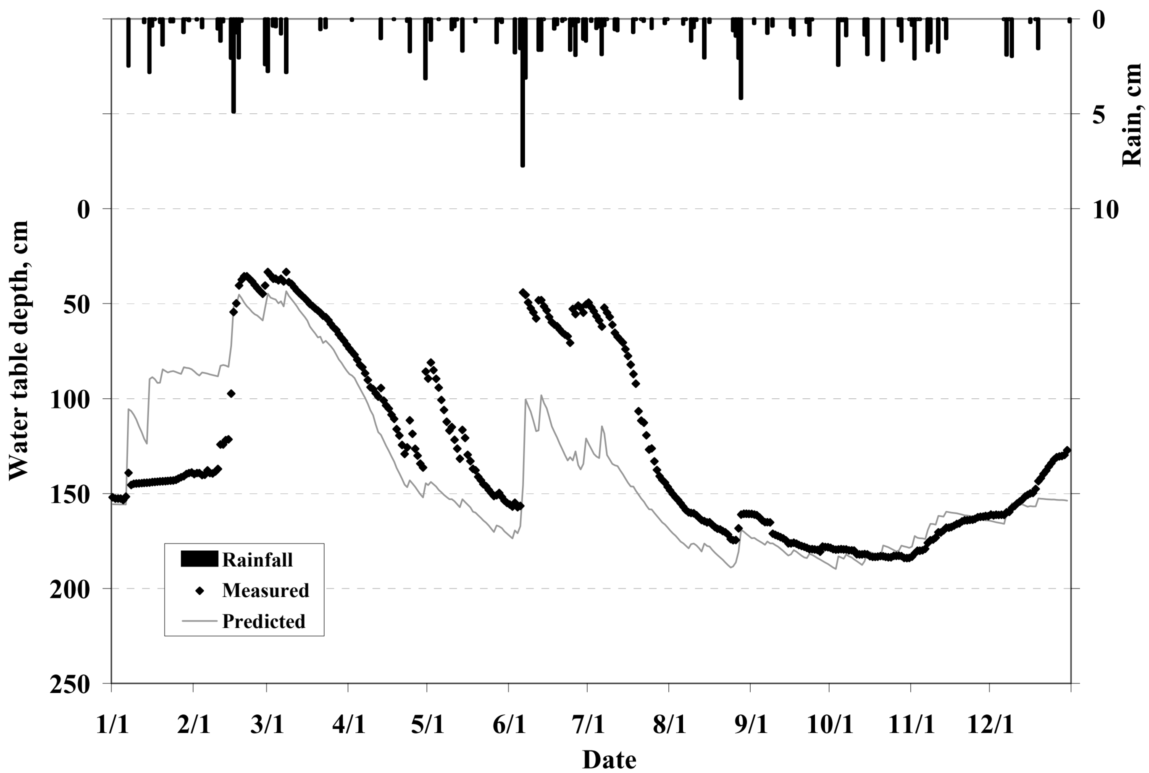

Figure 3.21: Rainfall and predicted and measured water table depths at F5 from 1995.

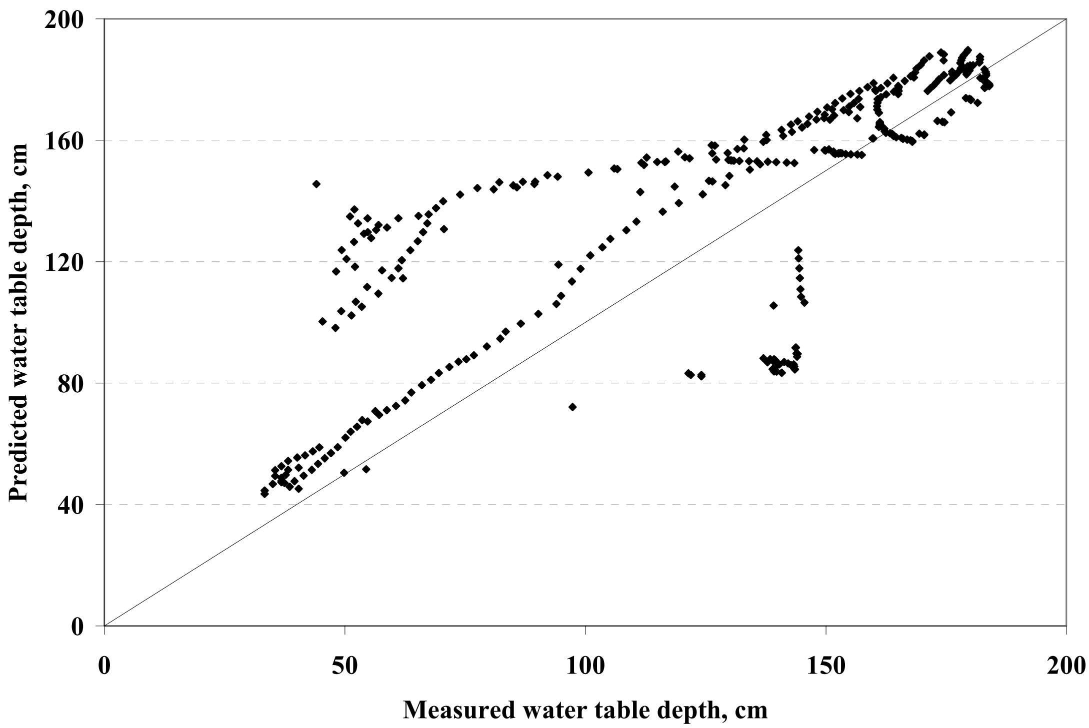

Figure 3.22: Predicted versus measured water table depths at F5 from 1995.

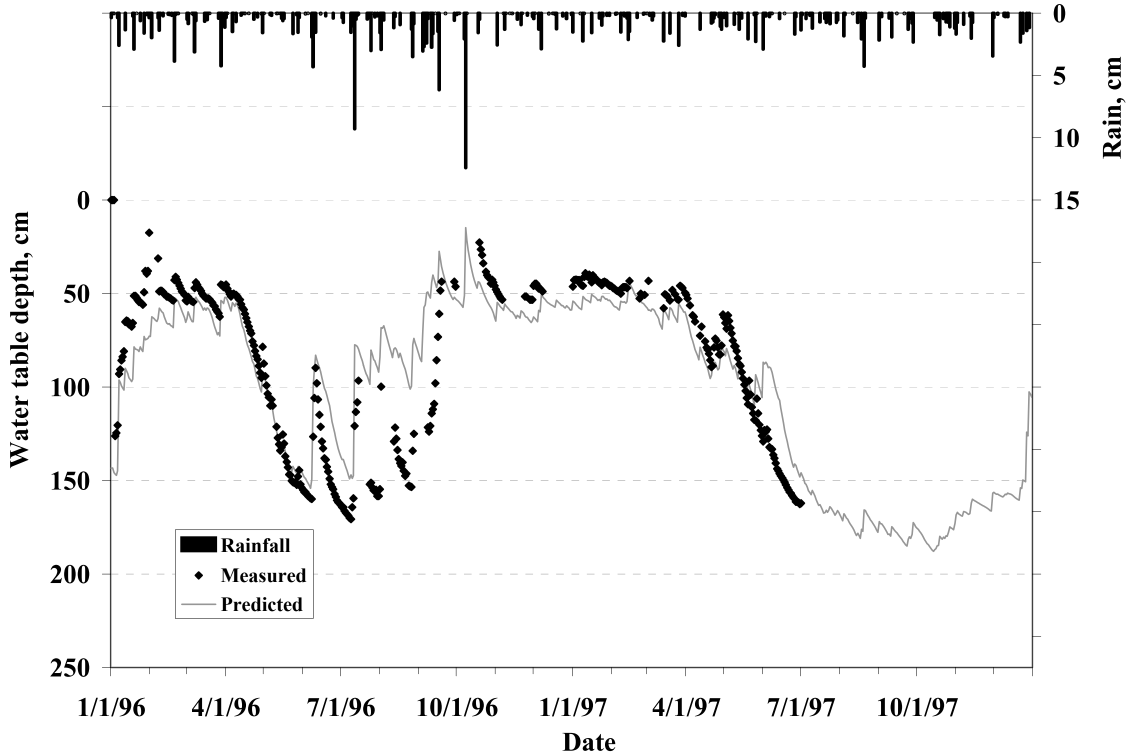

Figure 3.23: Rainfall and predicted and measured water table depths at F5 from 1996-1997.

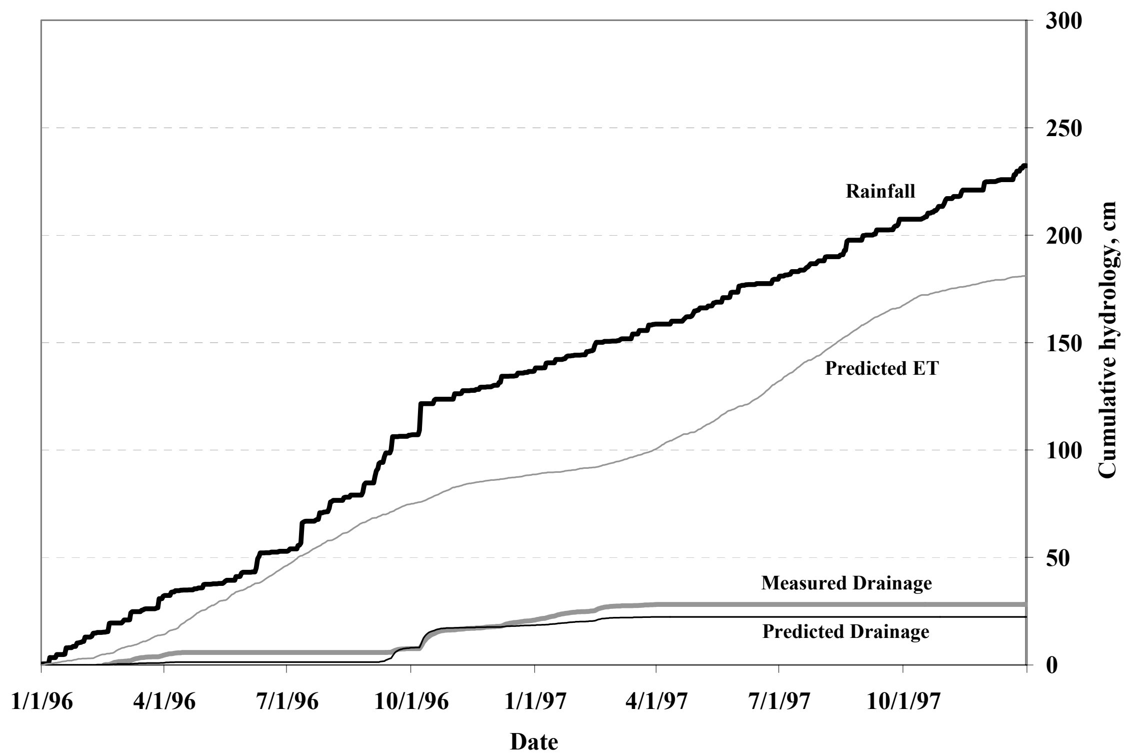

Figure 3.24: Cumulative rainfall, predicted ET, and measured and predicted drainage at F5 from 1996-1997.

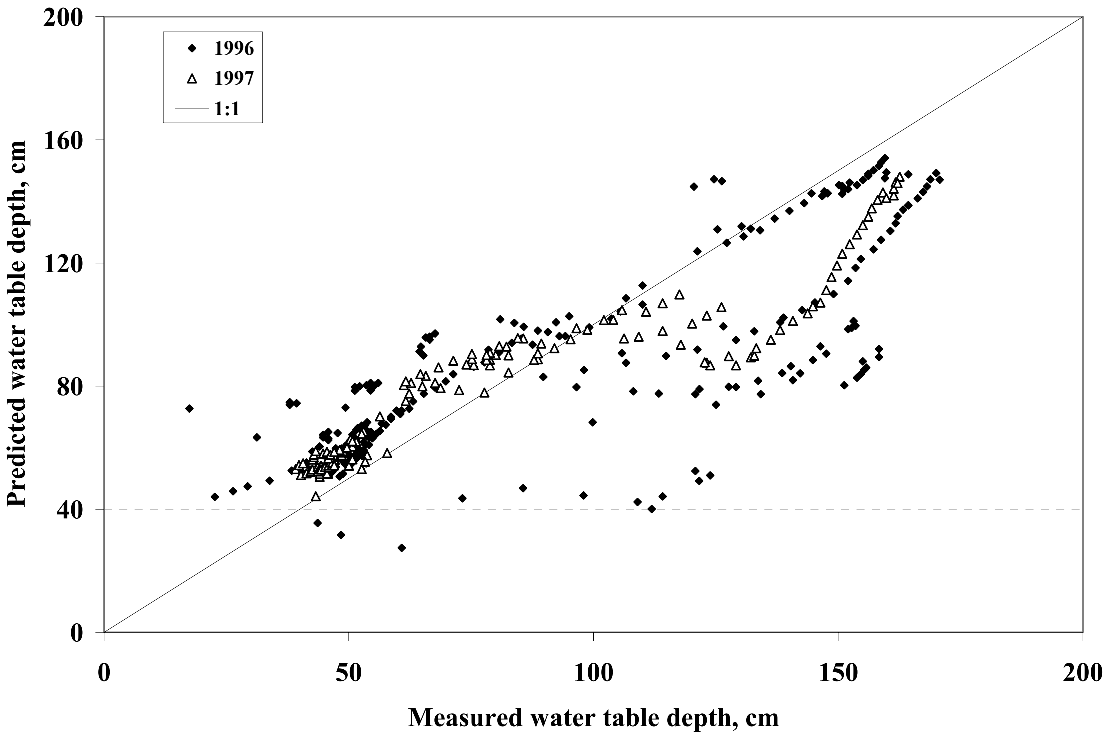

Figure 3.25: Predicted versus measured water table depths at F5 from 1996-1997.

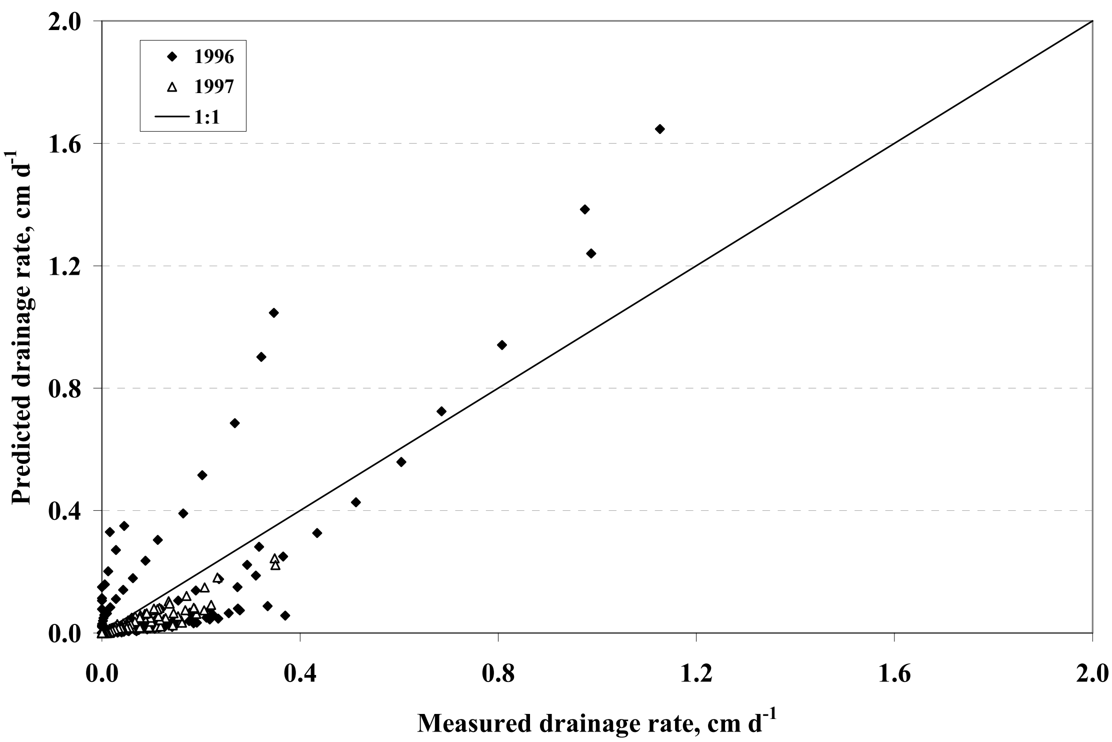

Figure 3.26: Predicted versus measured drainage rates at F5 from 1996-1997.

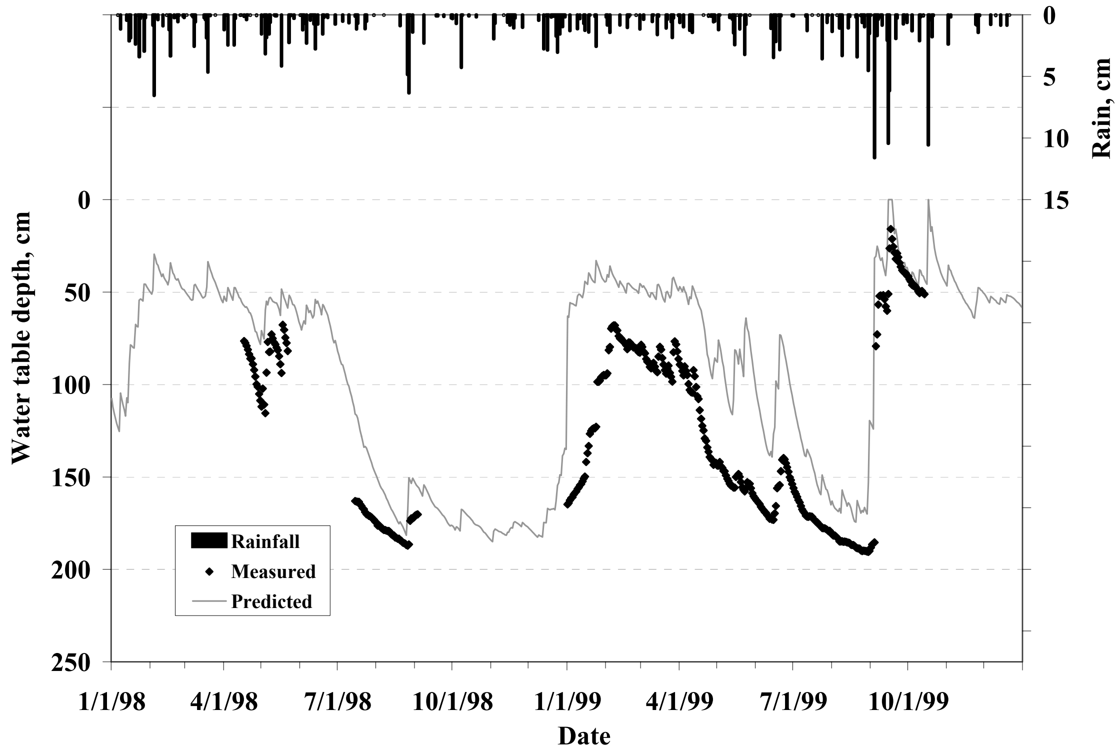

Figure 3.27: Rainfall and predicted and measured water table depths at F5 from 1998-1999.

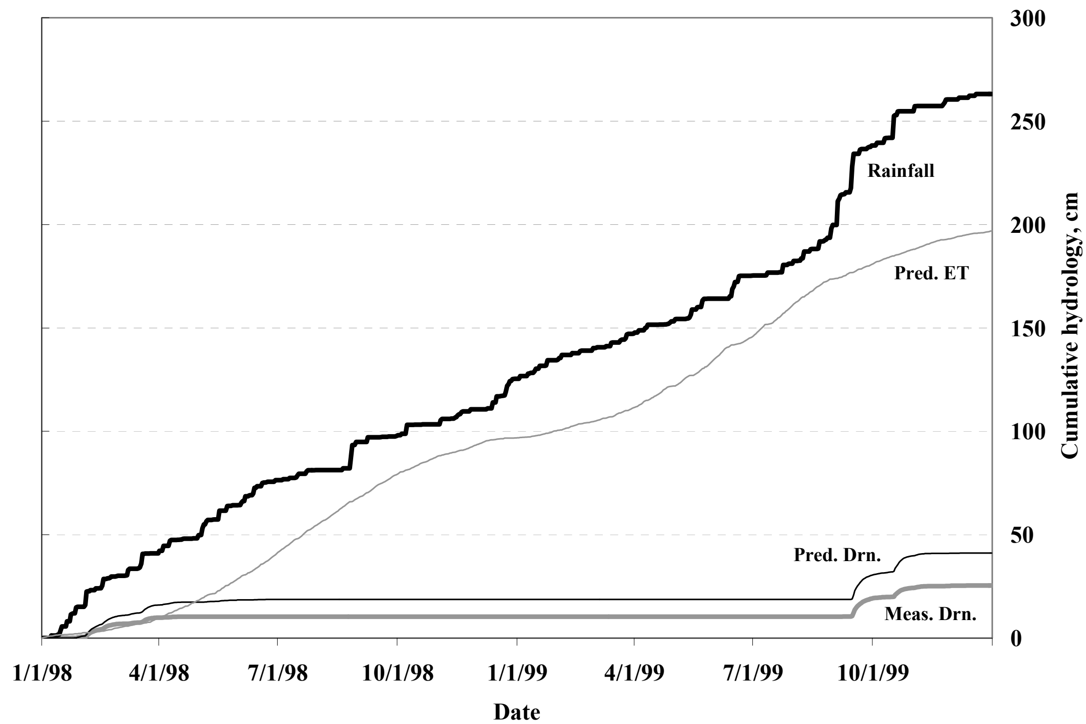

Figure 3.28: Cumulative rainfall, predicted ET, and measured and predicted drainage at F5 from 1998-1999.

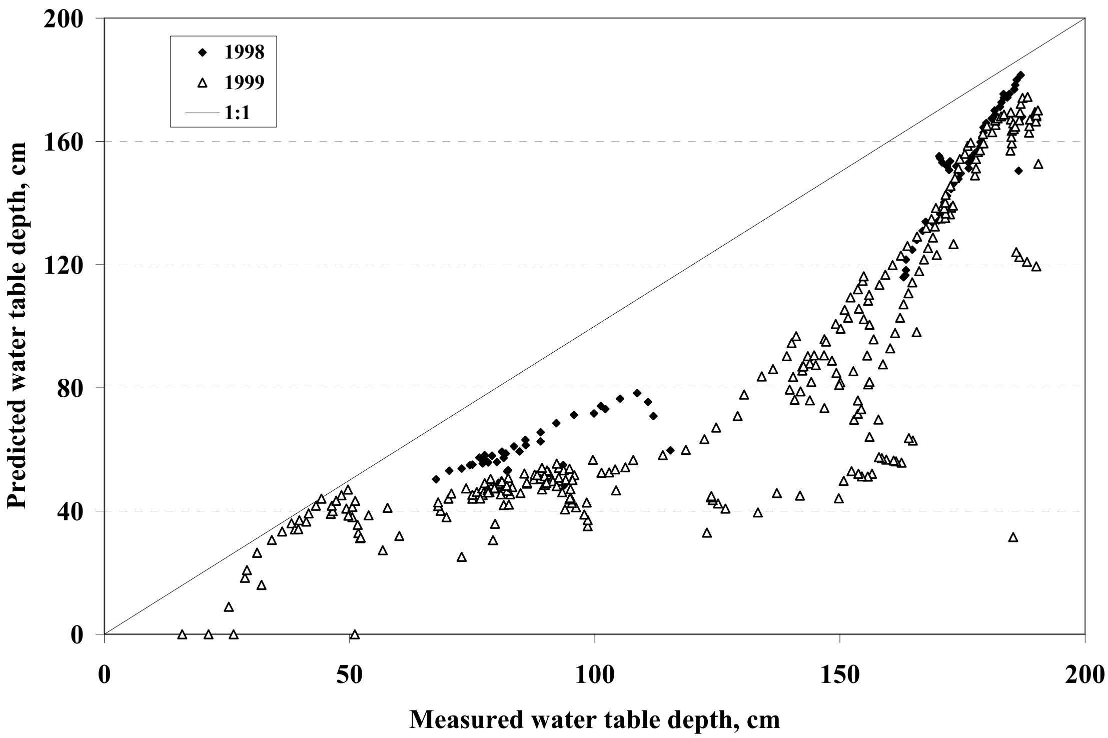

Figure 3.29: Predicted versus measured water table depths at F5 from 1998-1999.

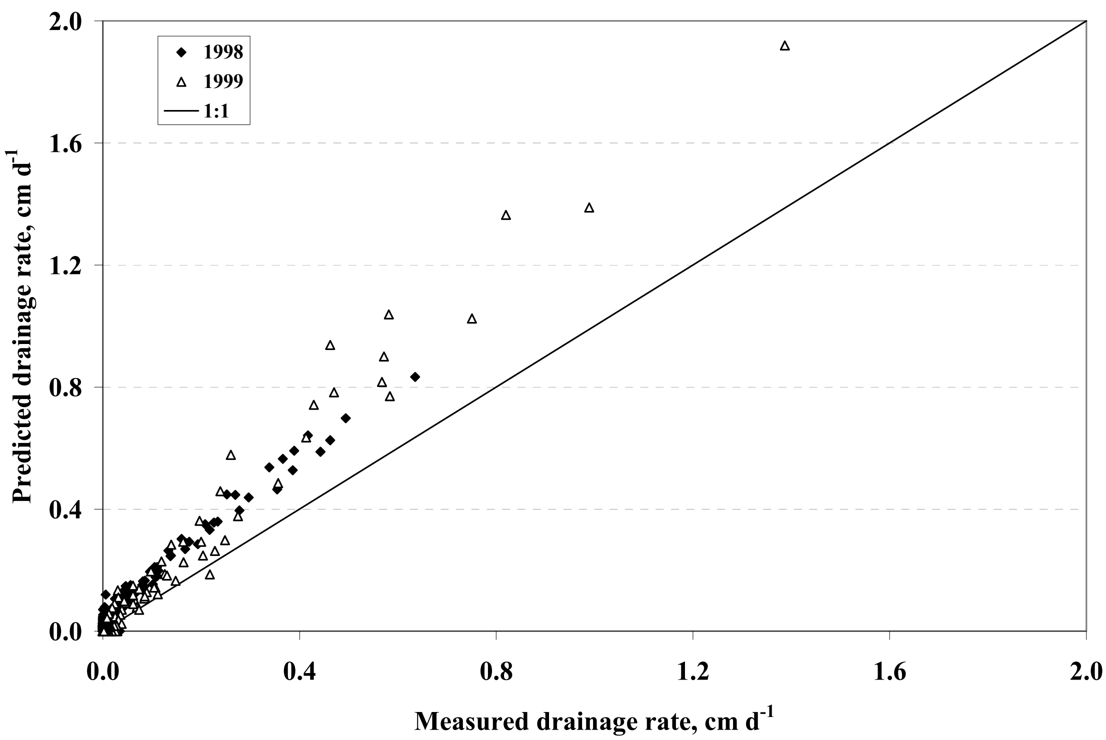

Figure 3.30: Predicted versus measured drainage rates at F5 from 1998-1999.

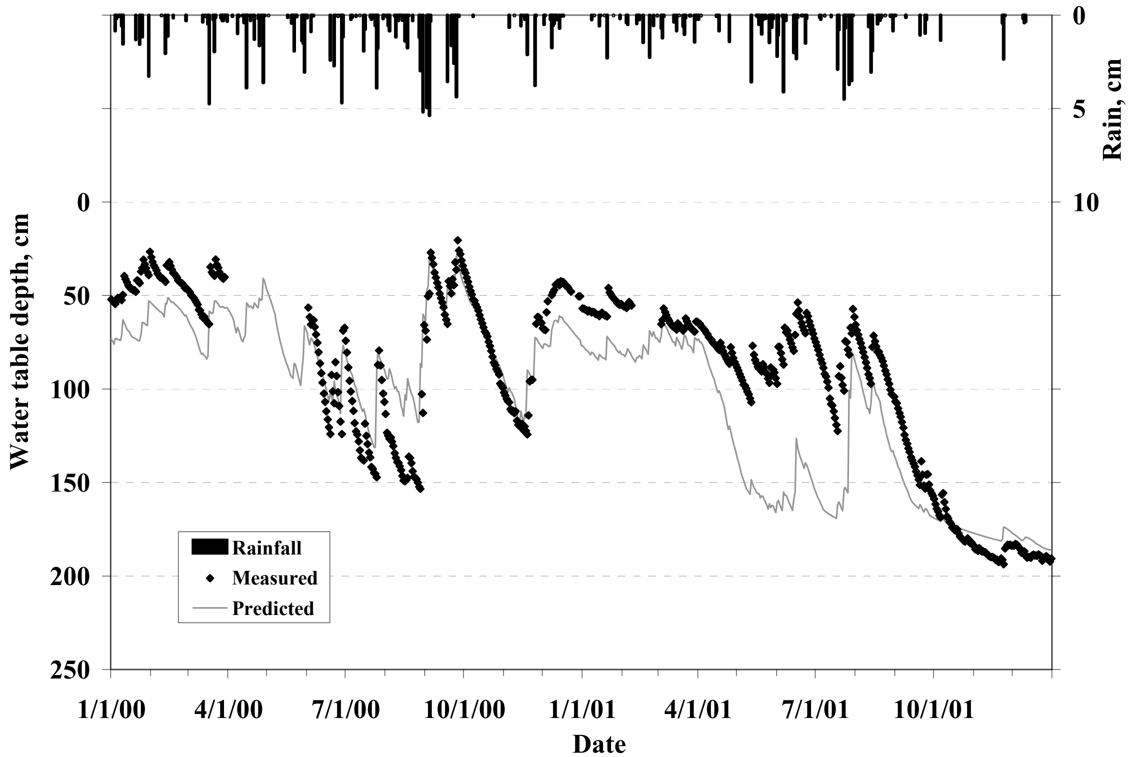

Figure 3.31: Rainfall and predicted and measured water table depths at F5 from 2000-2001.

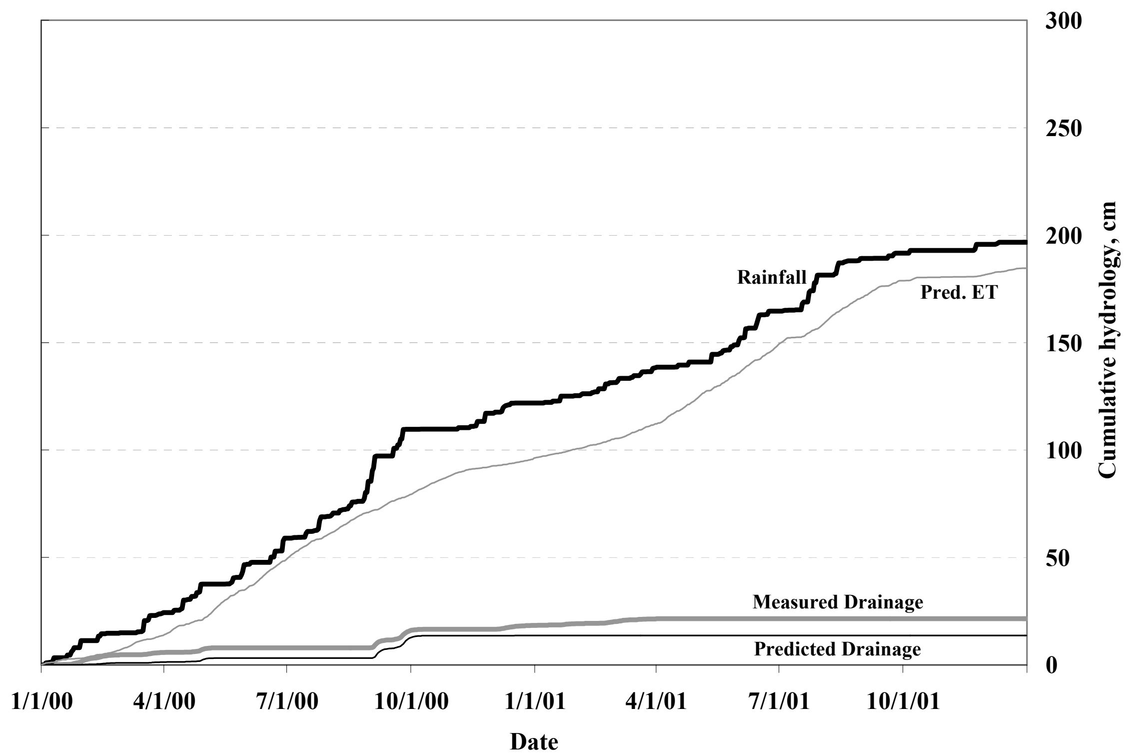

Figure 3.32: Cumulative rainfall, predicted ET, and measured and predicted drainage at F5 from 2000-2001.

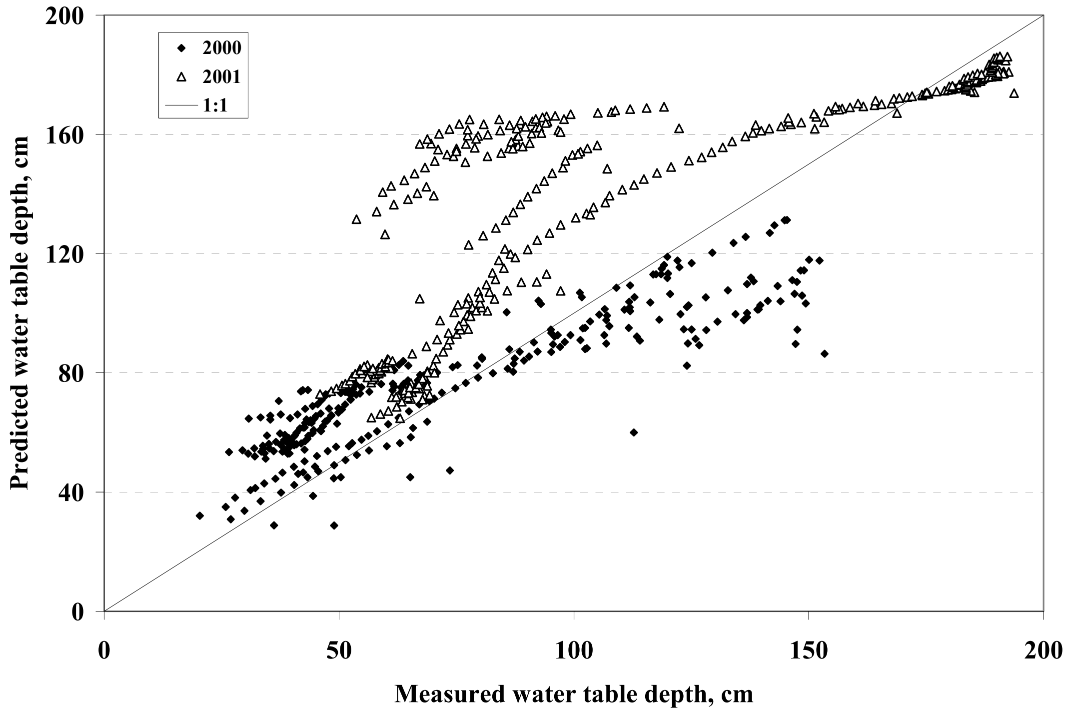

Figure 3.33: Predicted versus measured water table depths at F5 from 2000-2001.

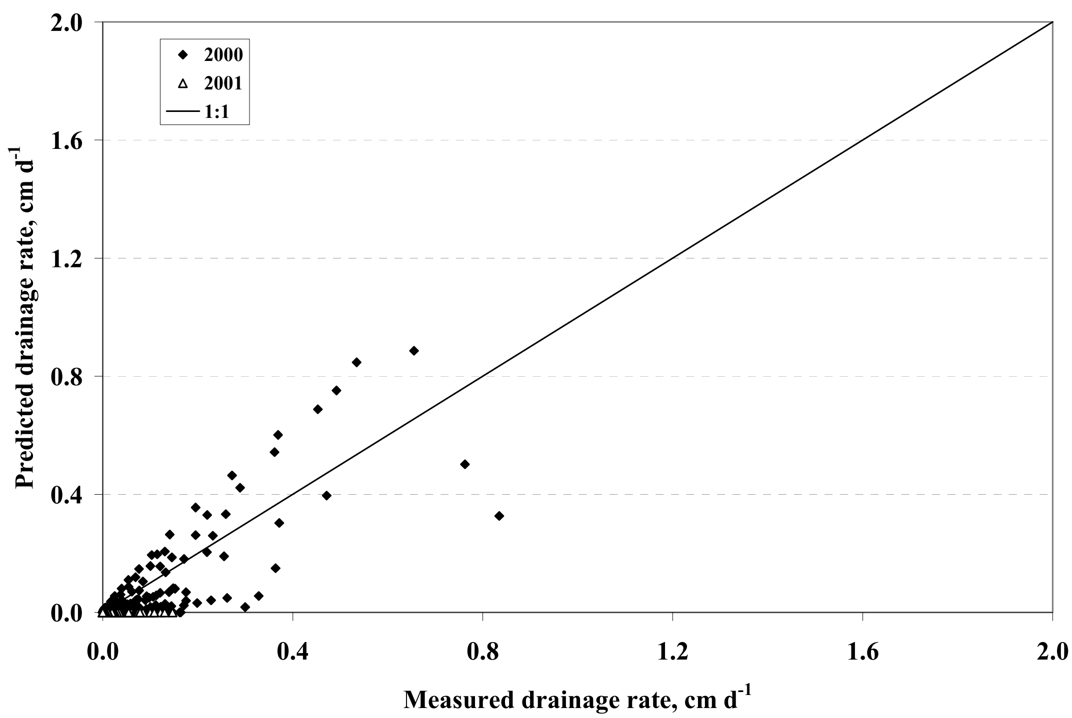

Figure 3.34: Predicted versus measured drainage rates at F5 from 2000-2001.

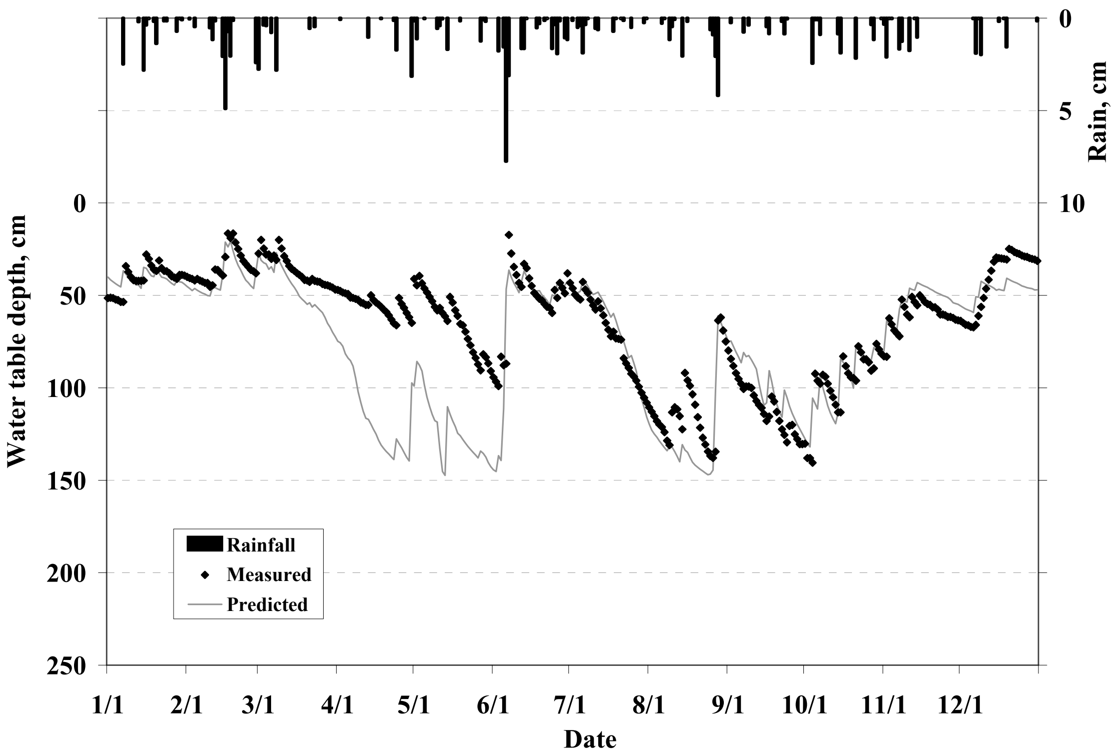

Figure 3.35: Rainfall and predicted and measured water table depths at F6 from 1995.

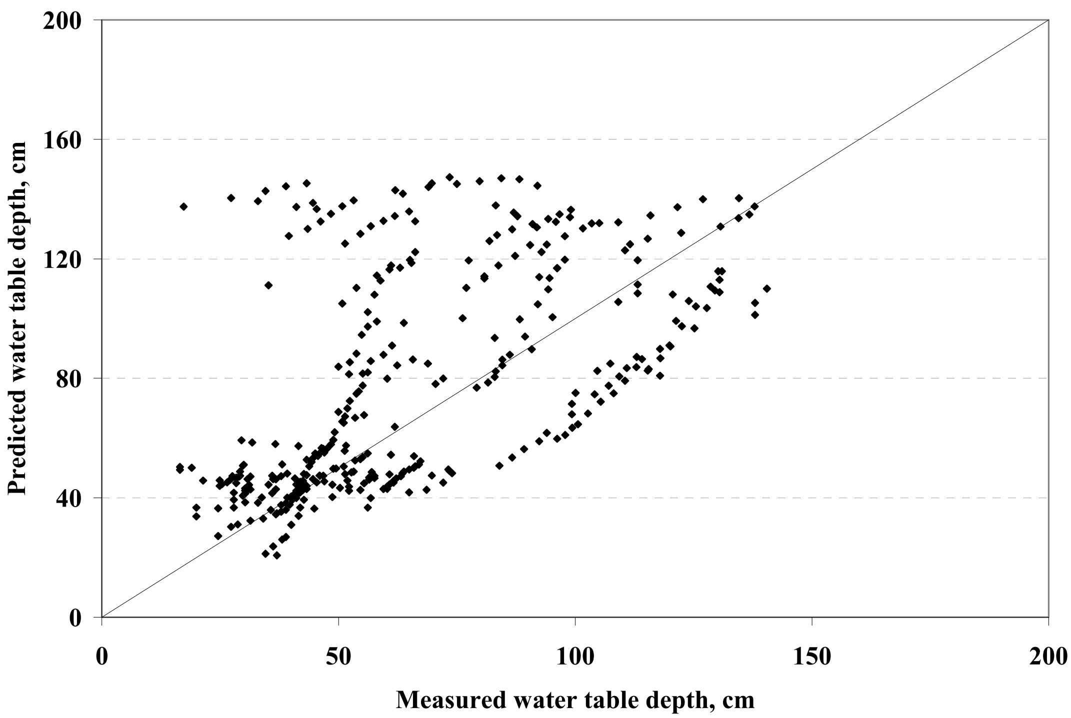

Figure 3.36: Predicted versus measured water table depths at F6 from 1995.

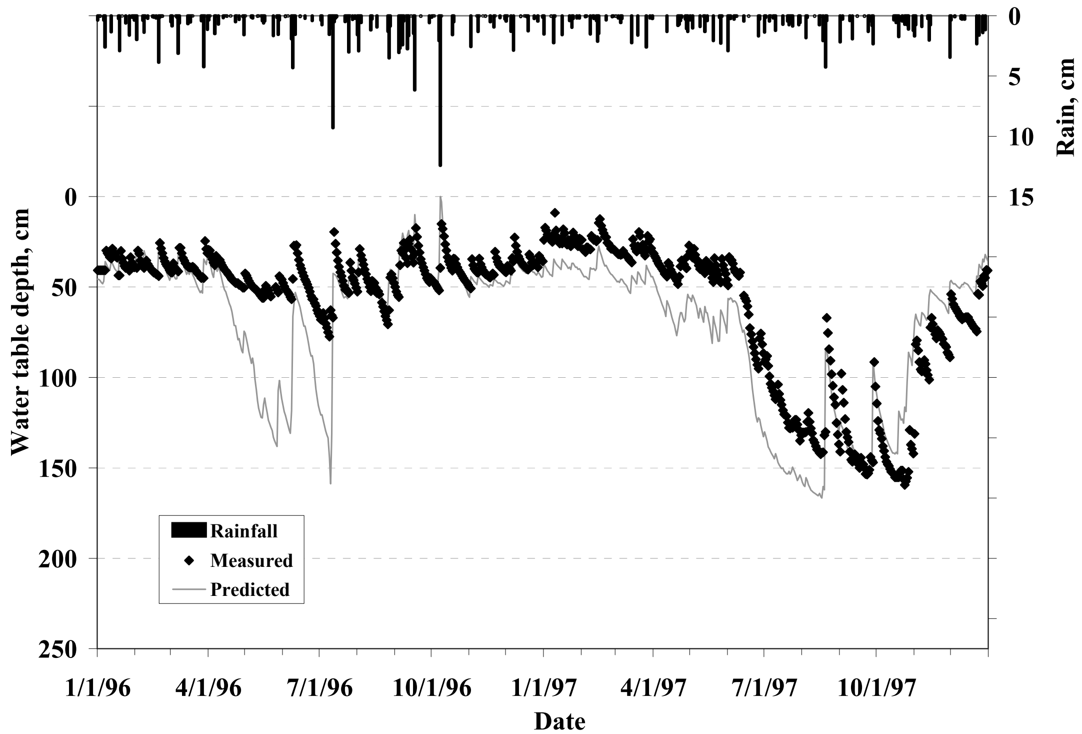

Figure 3.37: Rainfall and predicted and measured water table depths at F6 from 1996-1997.

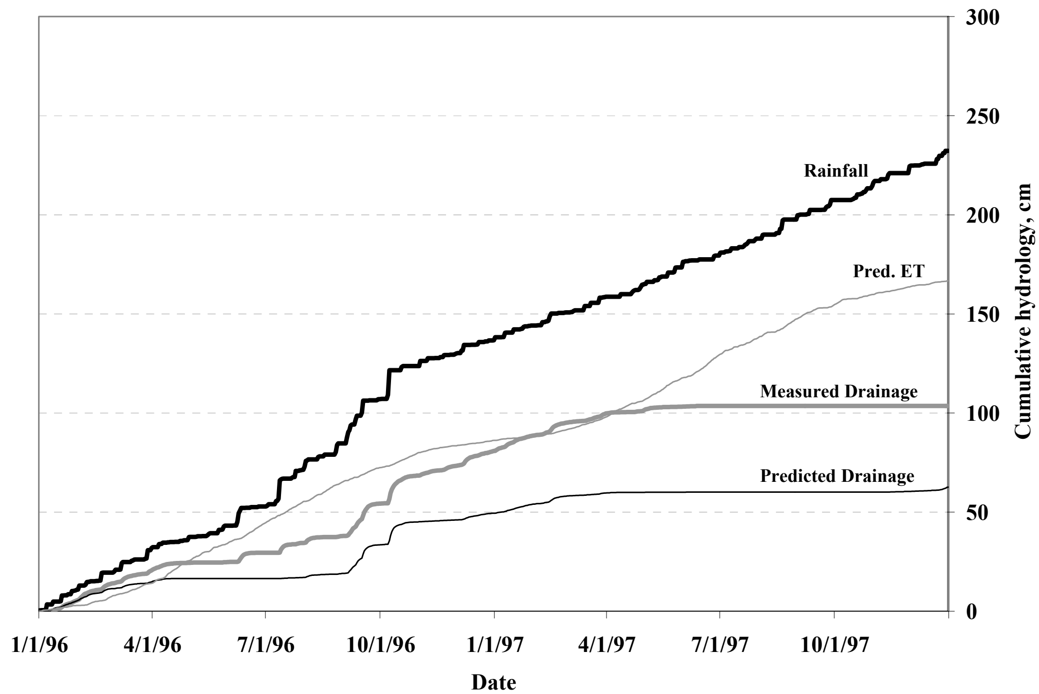

Figure 3.38: Cumulative rainfall, predicted ET, and measured and predicted drainage at F6 from 1996-1997.

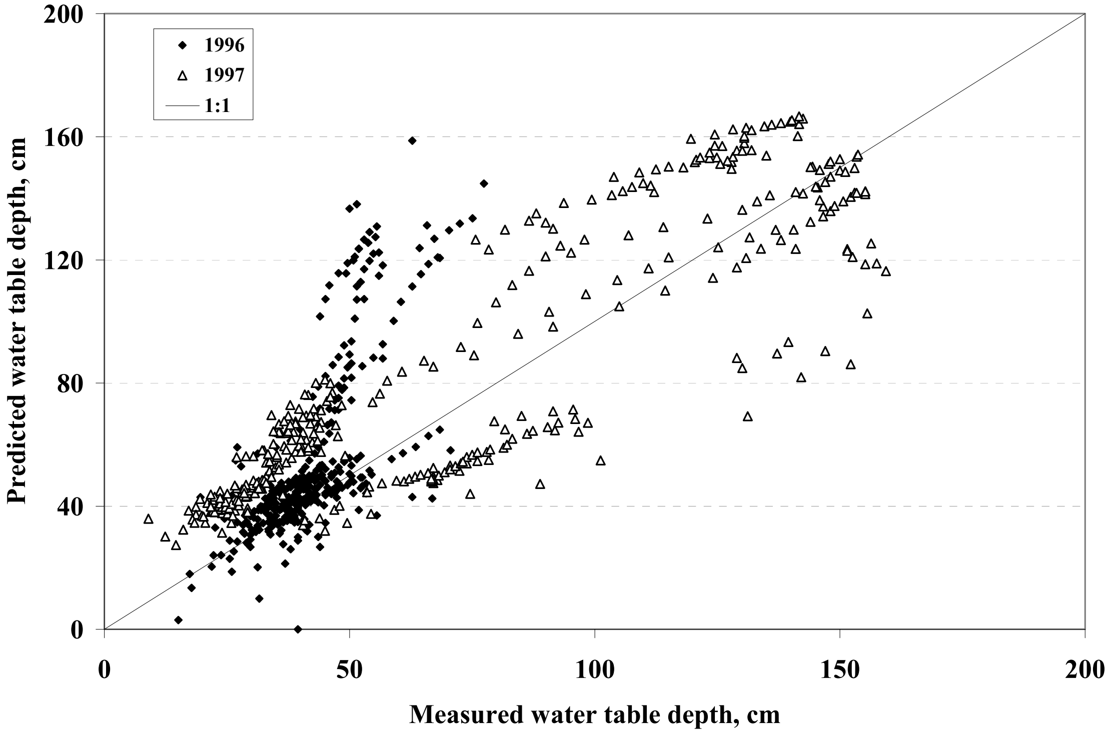

Figure 3.39: Predicted versus measured water table depths at F6 from 1996-1997.

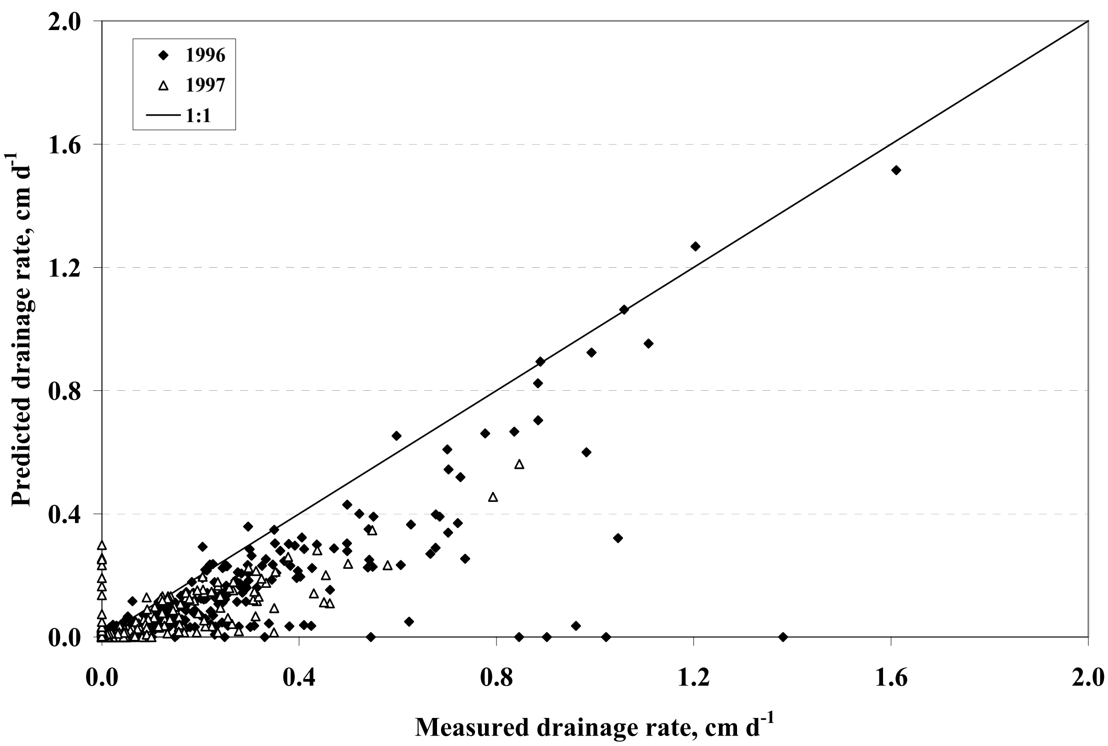

Figure 3.40: Predicted versus measured drainage rates at F6 from 1996-1997.

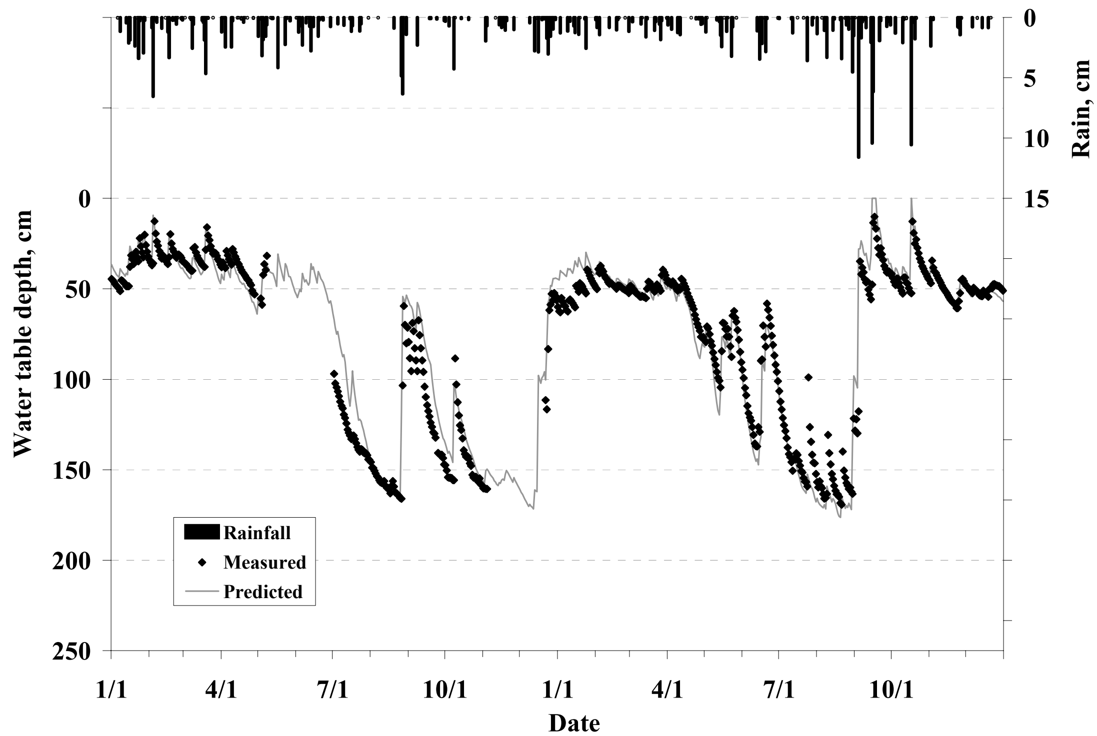

Figure 3.41: Rainfall and predicted and measured water table depths at F6 from 1998-1999.

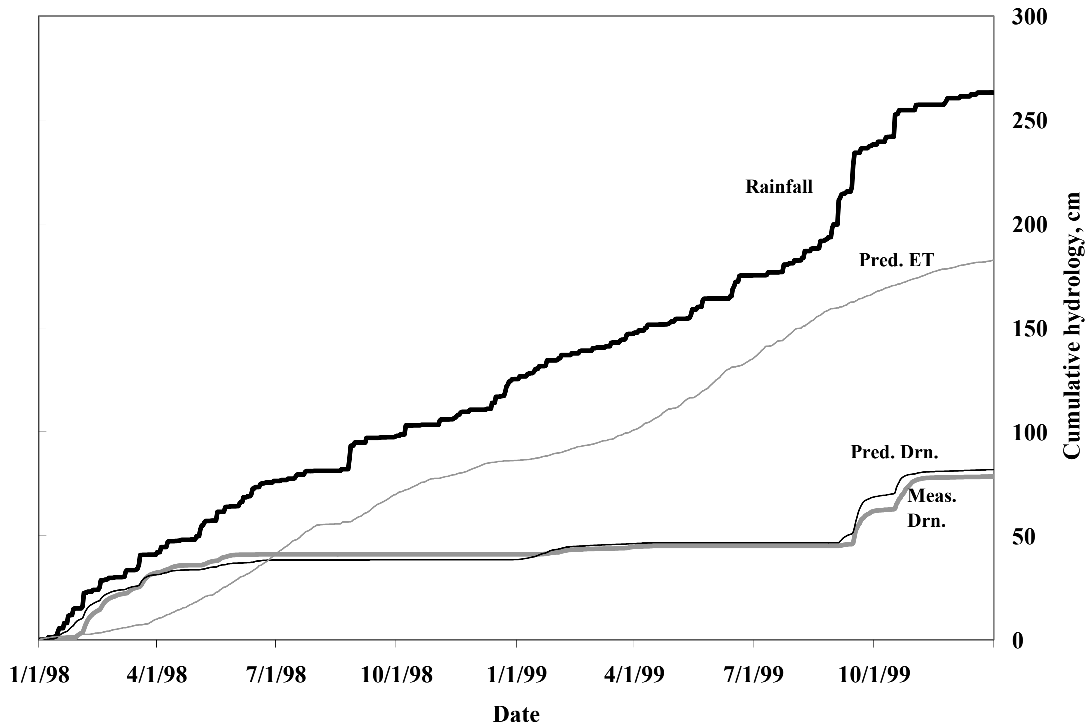

Figure 3.42: Cumulative rainfall, predicted ET, and measured and predicted drainage at F6 from 1998-1999.

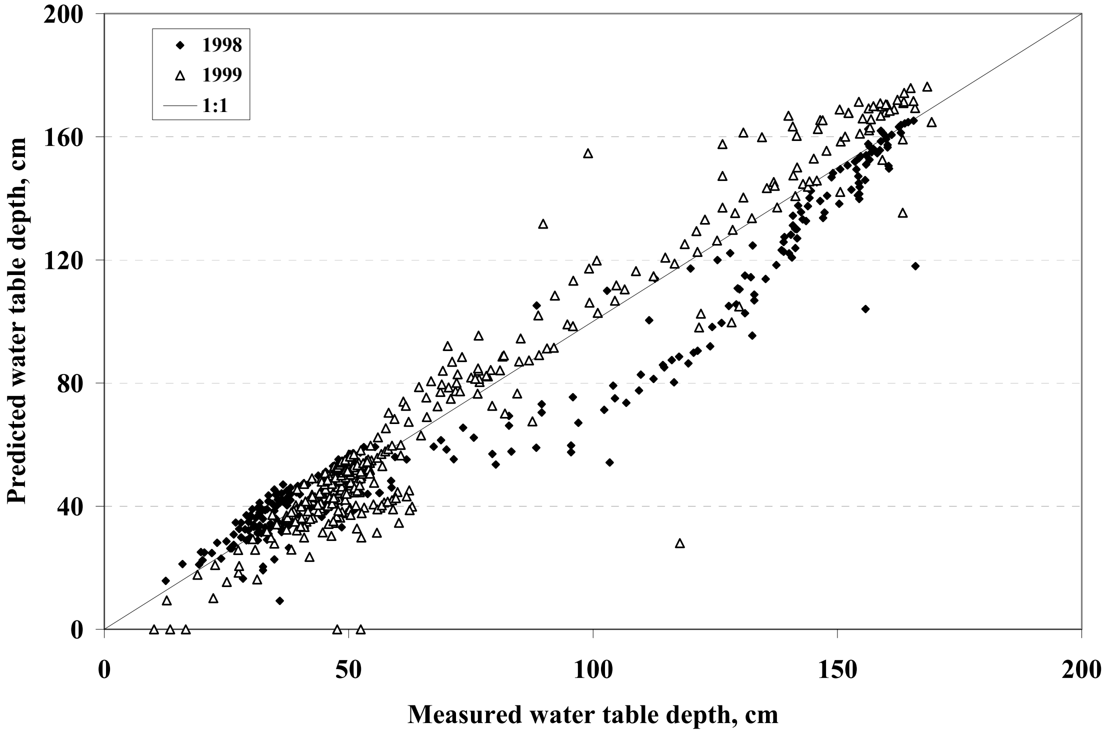

Figure 3.43: Predicted versus measured water table depths at F6 from 1998-1999.

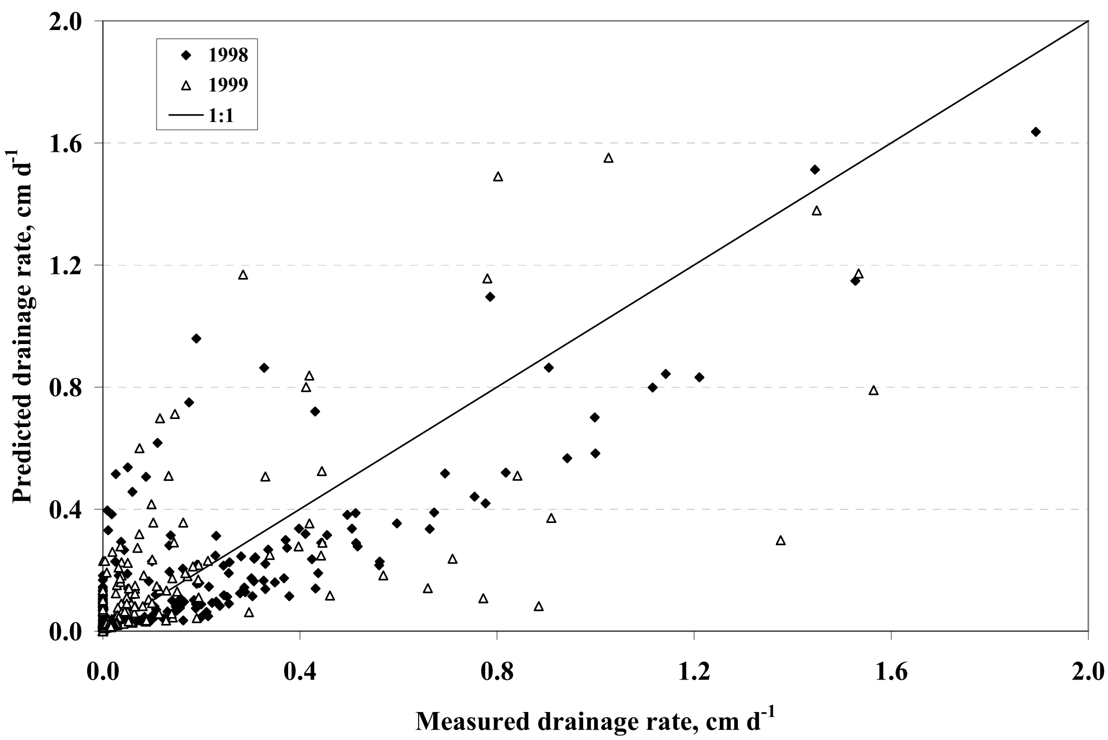

Figure 3.44: Predicted versus measured drainage rates at F6 from 1998-1999.

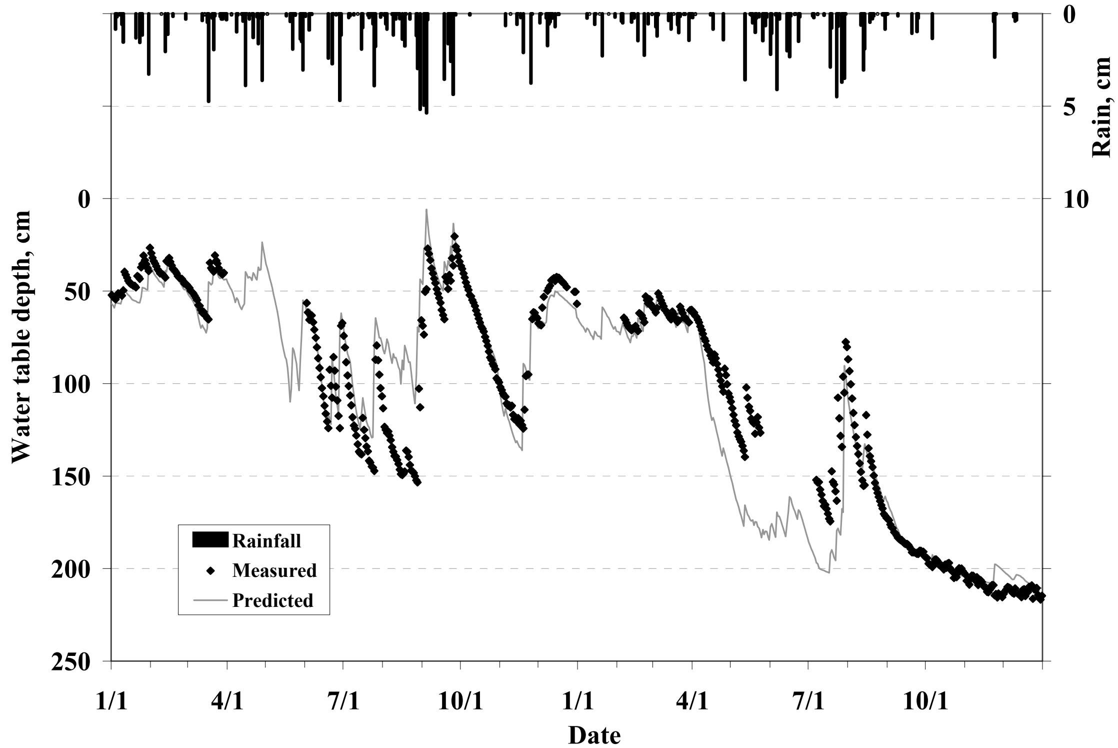

Figure 3.45: Rainfall and predicted and measured water table depths at F6 from 2000-2001.

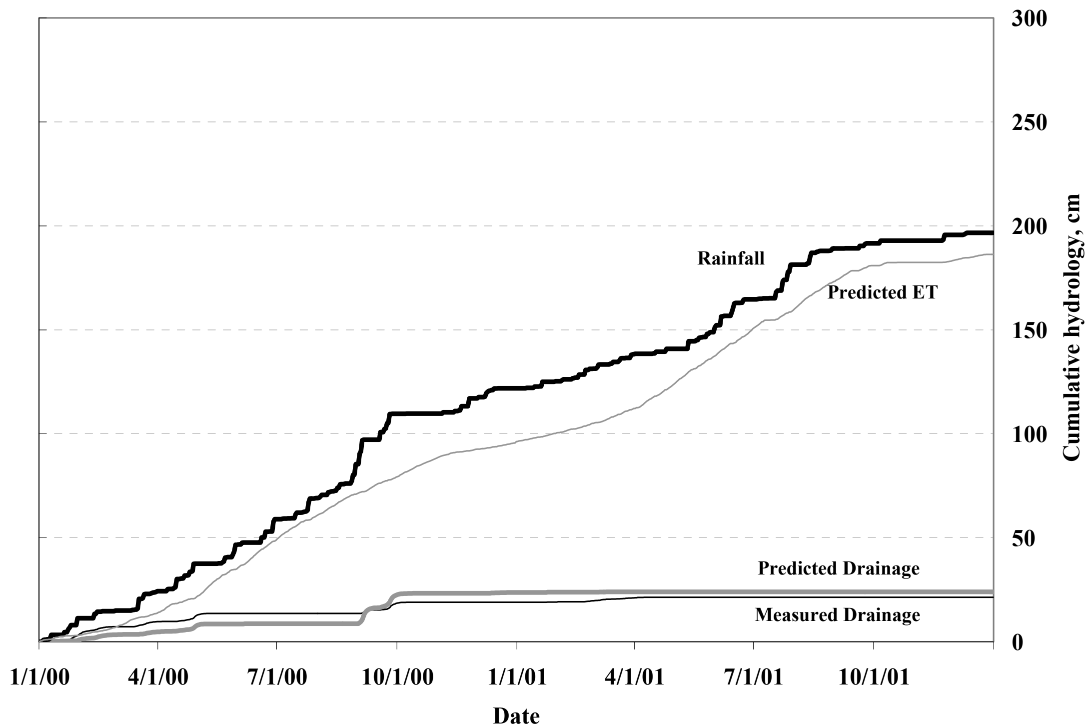

Figure 3.46: Cumulative rainfall, predicted ET, and measured and predicted drainage at F6 from 2000-2001.

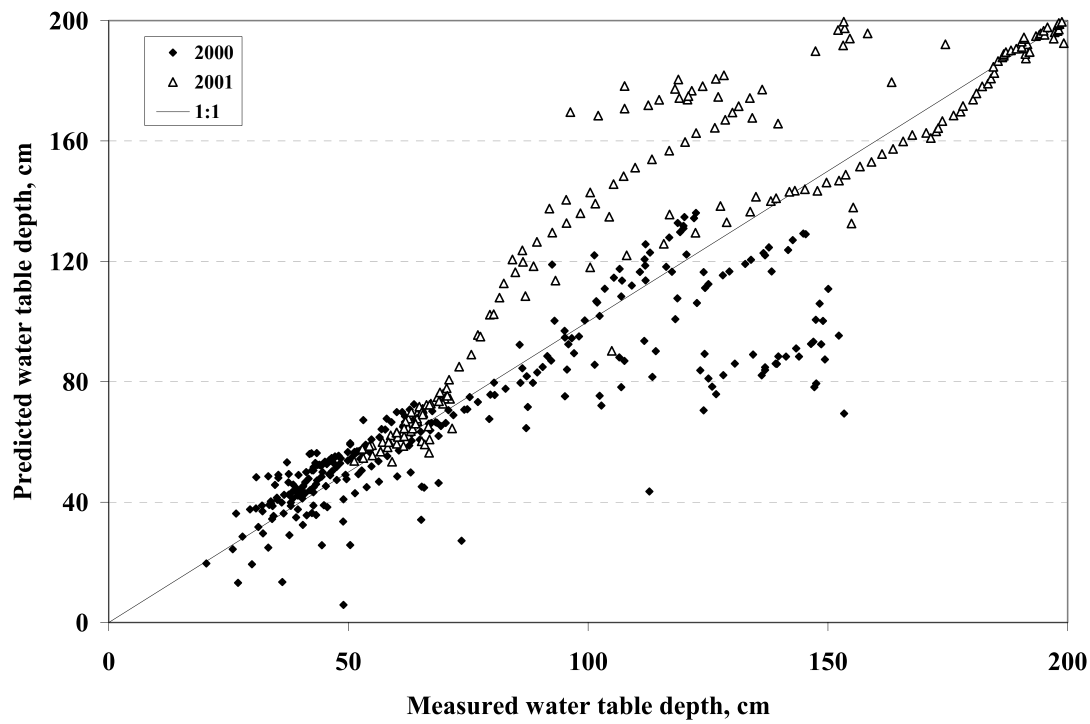

Figure 3.47: Predicted versus measured water table depths at F6 from 2000-2001.

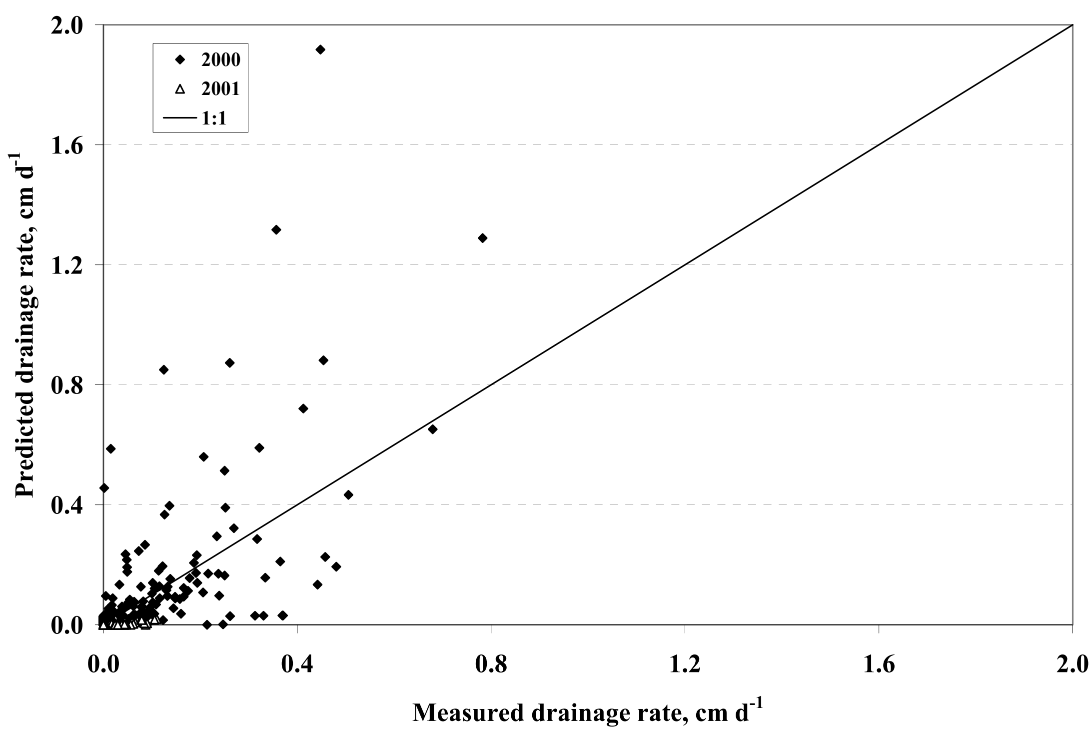

Figure 3.48: Predicted versus measured drainage rates at F6 from 2000-2001.

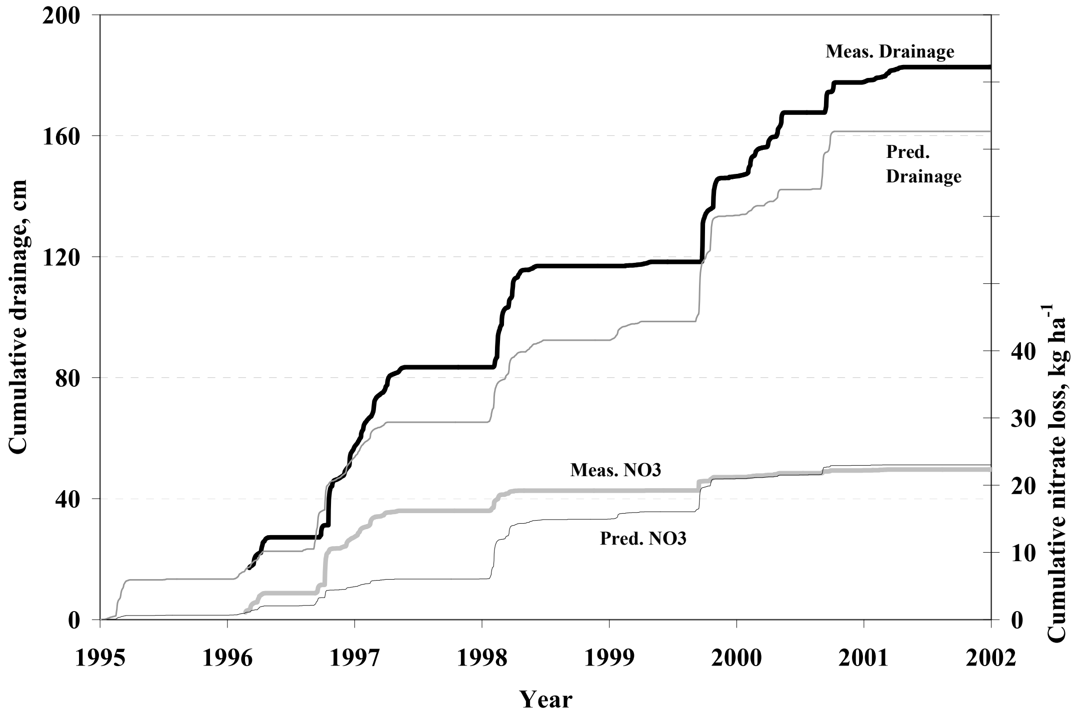

Figure 3.49: Measured and predicted cumulative drainage and nitrate loads for F3 using 1996-1998 calibration.

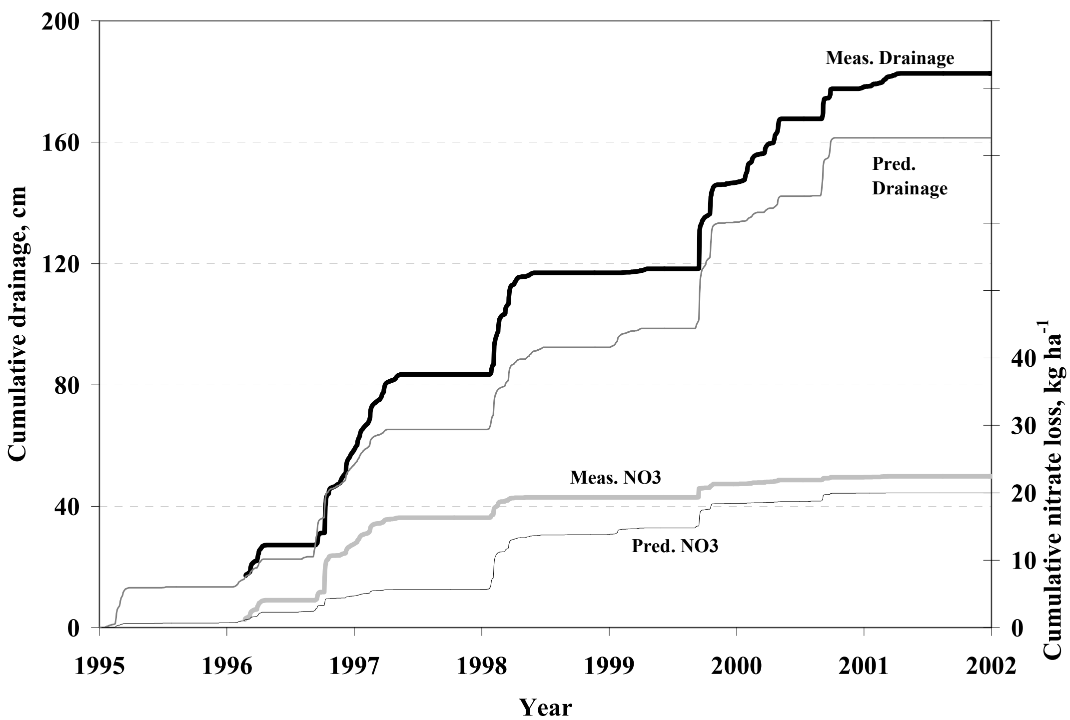

Figure 3.50: Measured and predicted cumulative drainage and nitrate loads for F3 using 1996-2001 calibration.

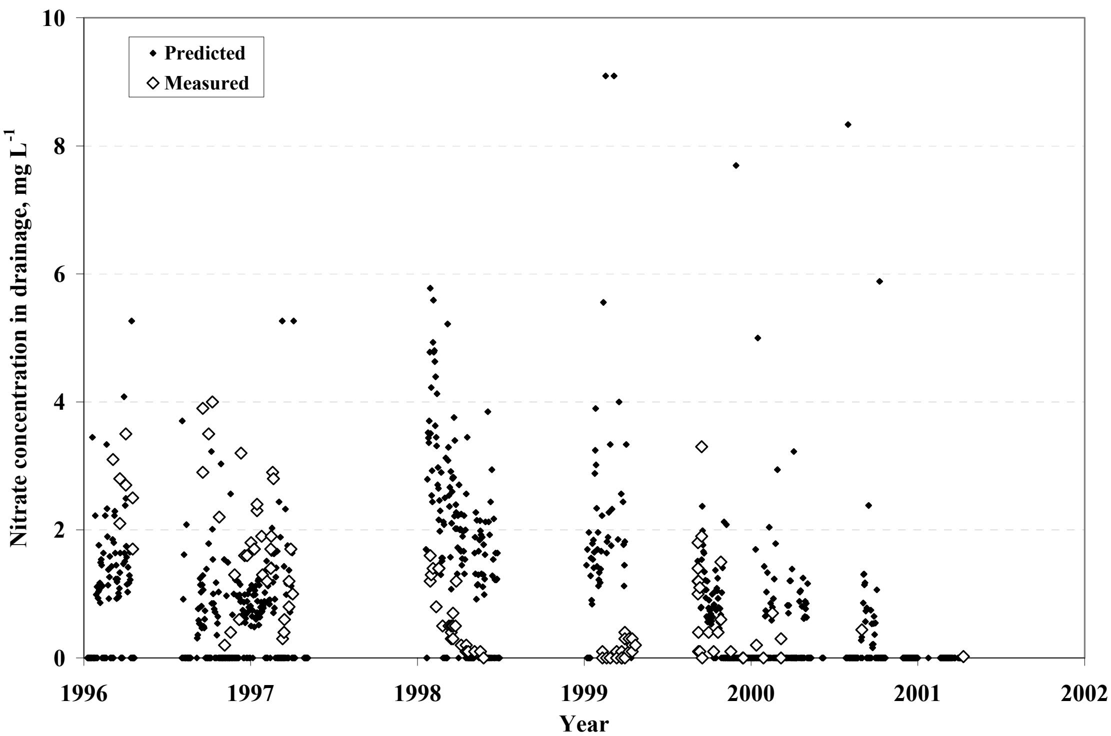

Figure 3.51: Measured and predicted nitrate concentrations for F3 using 1996-1998 calibration.

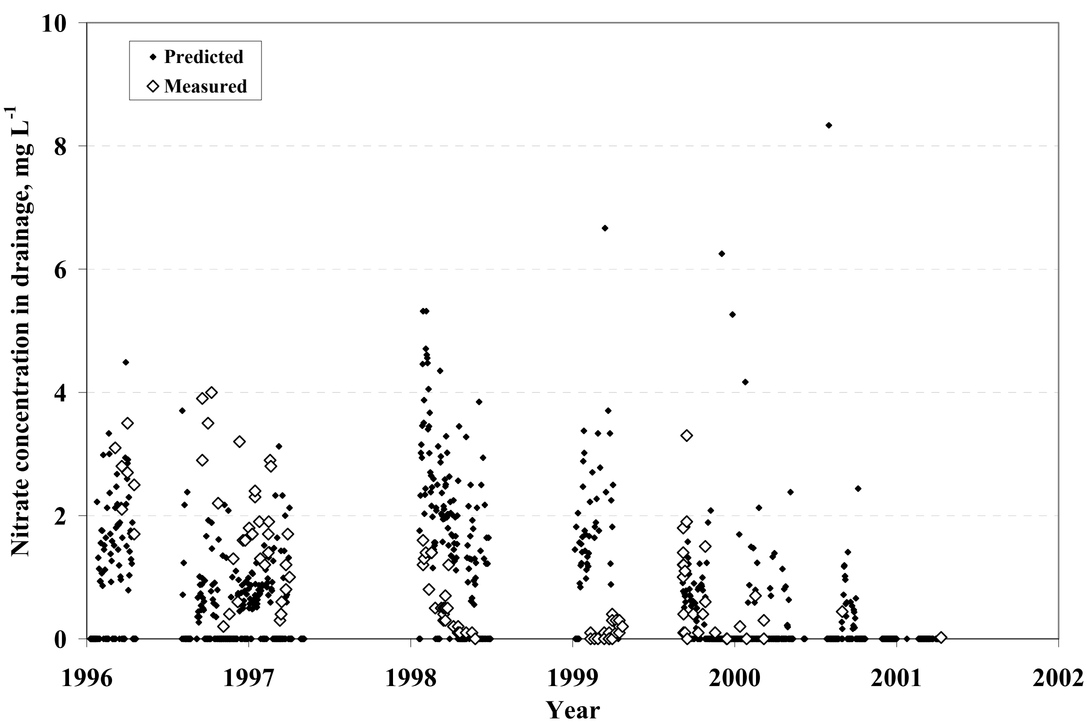

Figure 3.52: Measured and predicted nitrate concentrations for F3 using 1996-2001 calibration.

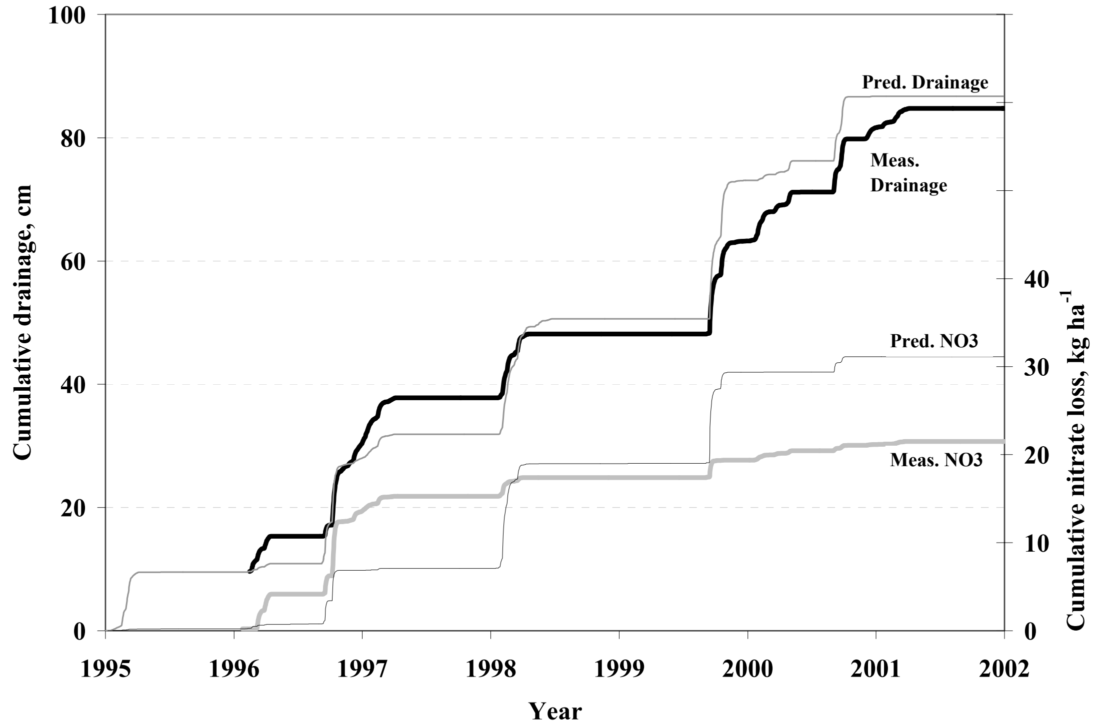

Figure 3.53: Measured and predicted cumulative drainage and nitrate loads for F5 using 1996-1998 calibration.

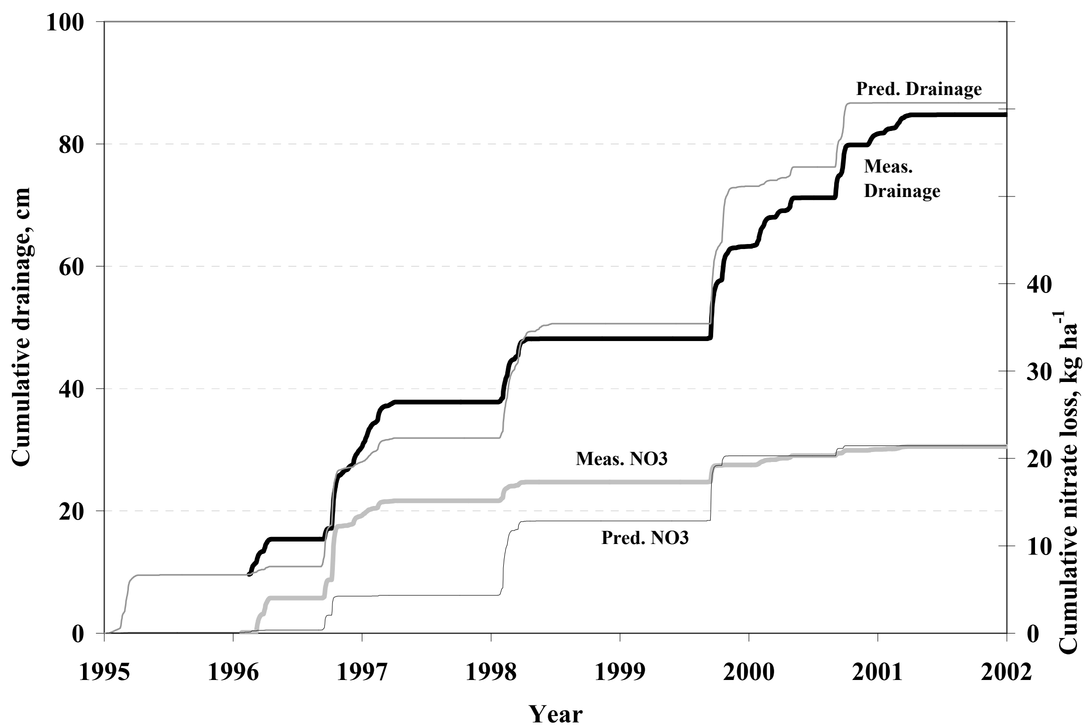

Figure 3.54: Measured and predicted cumulative drainage and nitrate loads for F5 using 1996-2001 calibration.

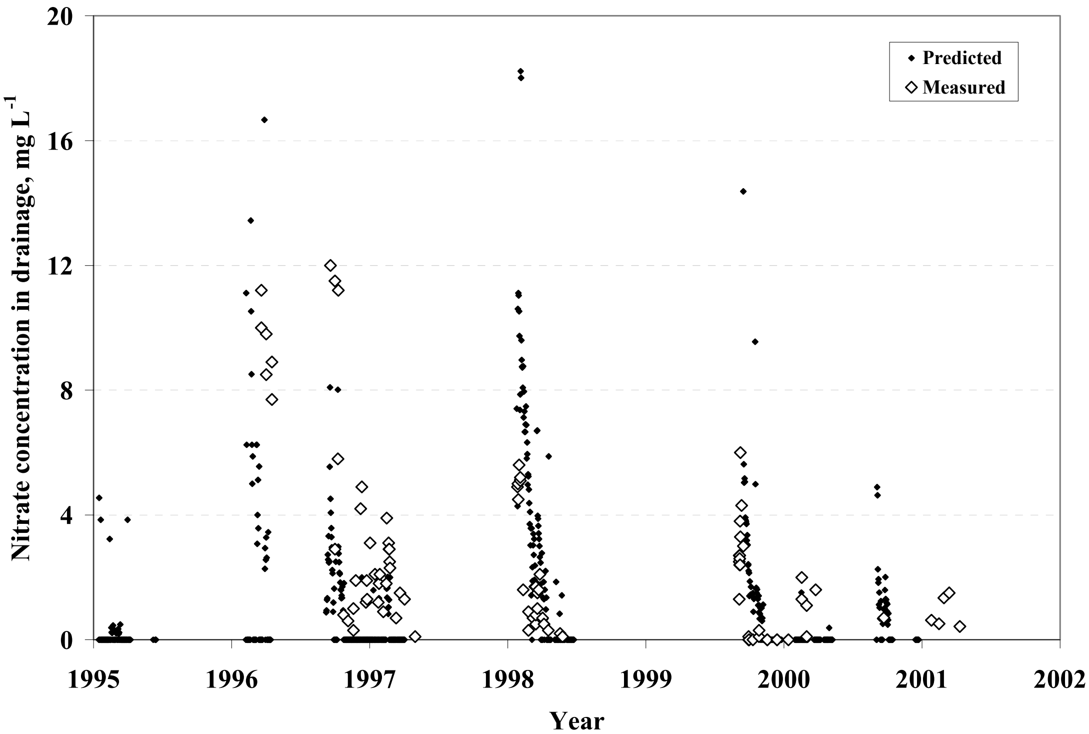

Figure 3.55: Measured and predicted nitrate concentrations for F5 using 1996-1998 calibration.

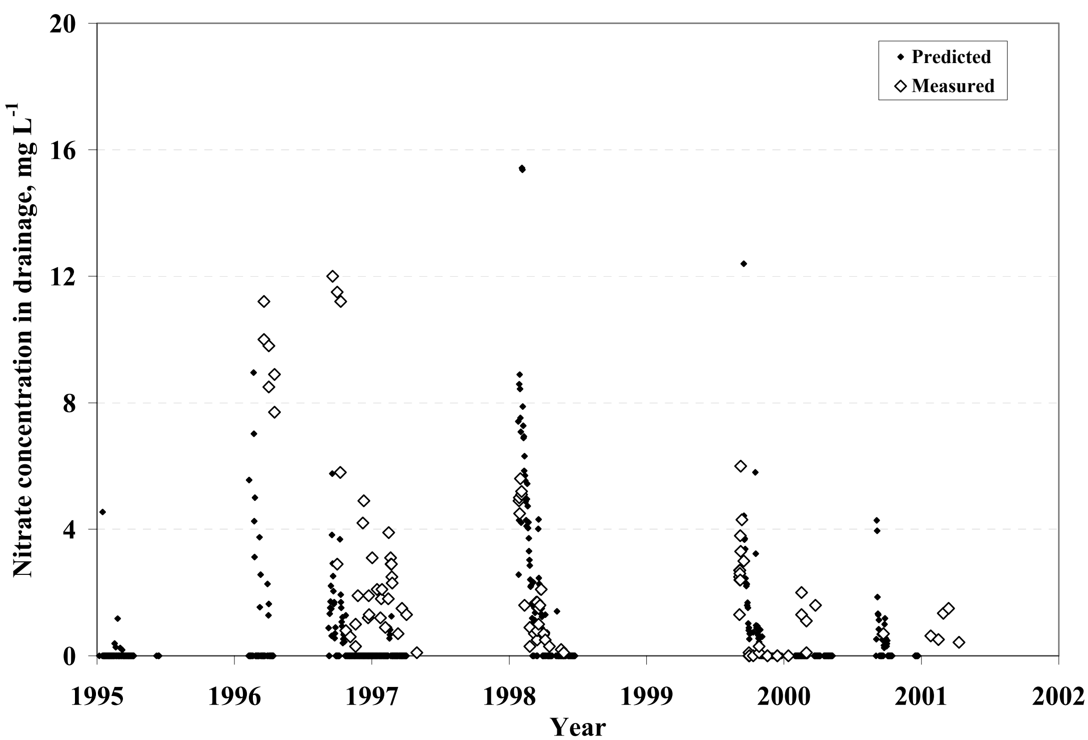

Figure 3.56: Measured and predicted nitrate concentrations for F5 using 1996-2001 calibration.

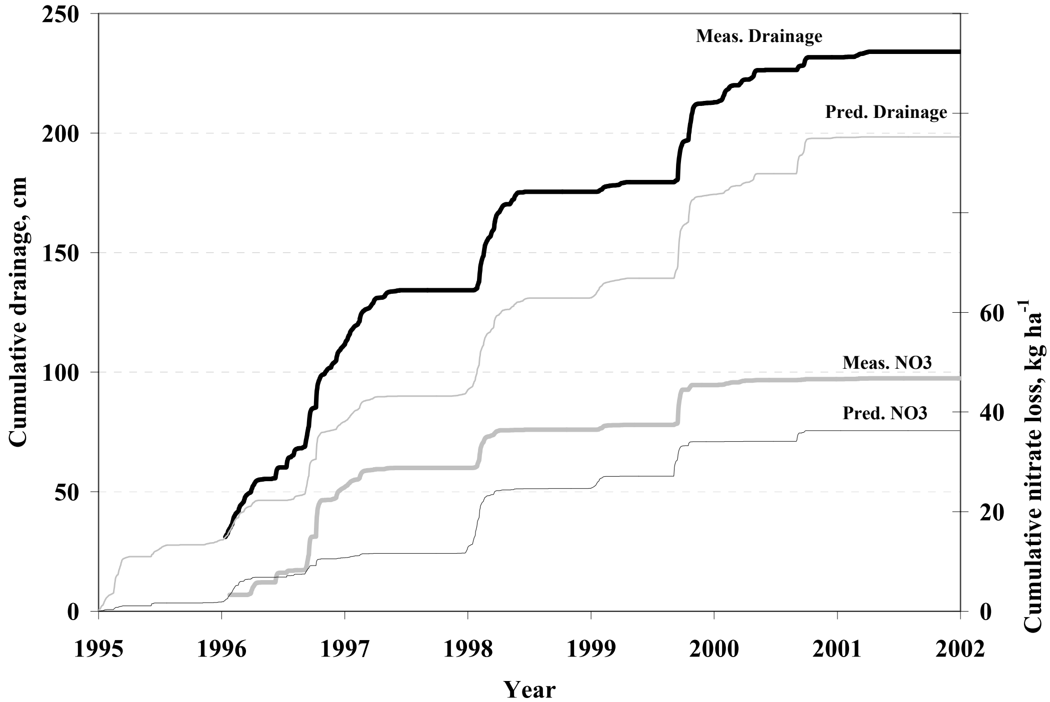

Figure 3.57: Measured and predicted cumulative drainage and nitrate loads for F6 using 1996-2001 calibration.

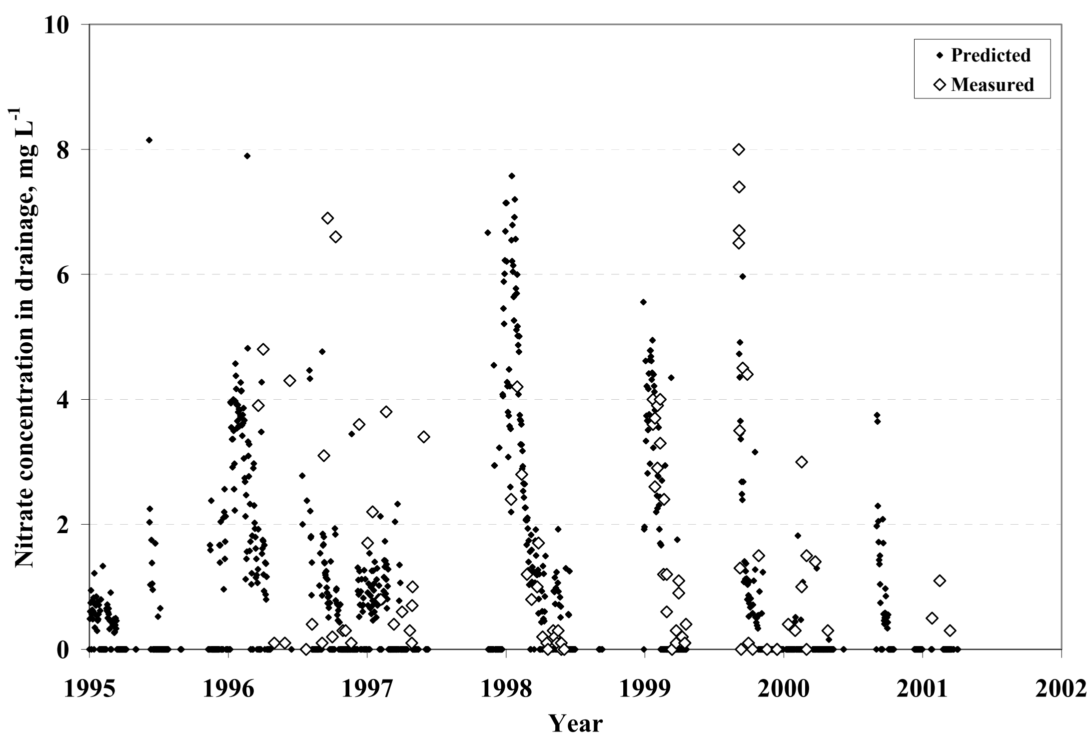

Figure 3.58: Measured and predicted nitrate concentrations for F6 using 1996-2001 calibration.

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APPENDICES

Appendix A: Detailed description of calibration process for *DRAINMOD-N* II.

To calibrate the *DRAINMOD-N* II model, three process rates were adjusted, as necessary: mineralization, denitrification, and nitrification. Process rates were adjusted such that annual process rates would be reasonable when compared to measured values from the literature. Calibrated parameters for each of the process rates are reported in Chapter 2.

The primary parameters affecting mineralization rate in the model are the initial soil organic carbon content and the partitioning of the available organic carbon into active, slow, and passive pools. For this study, the initial soil organic carbon (SOC) was measured from samples from the field, and calibration was not performed for this parameter. The allocation of the total OC between the active, slow, and passive SOM pools was initially set at the same percentages that were used by Youssef (2003) – 0 % for active, 40 % for slow, and 60 % for passive. However, the model overpredicted mineralization when using the 40/60 % allocation. The active pool has the highest decomposition rate, followed by the slow and then the passive. By increasing the allocation of total OC to the passive pool and decreasing the allocation to the slow pool, the mineralization rate was reduced.

Kelly et al. (1997) determined partitions of total OC into active, slow, and passive pools for seven different sites for the CENTURY model. The average, minimum, and maximum allocations of total OC into the three pools from the Kelly et al. (1997) study are shown in Table A.1.

Table A.1: Average, minimum, and maximum allocations of total organic carbon to the active, passive, and slow pools from Kelly et al. (1997).

	Active %	**Passive %**	**Slow %**
Average	3.0	39.8	57.2
Minimum	1.1	17.7	32.1
Maximum	5.2	66.0	77.8

As seen from Table A.1, there is considerable uncertainty in the allocation process. Therefore it was necessary to compare model predictions of annual mineralization with measured values from the literature.

The primary parameters affecting the denitrification and nitrification rates in the model were the Michaelis-Menten parameters: the maximum reaction rate, V_{max}, and the half saturation constant, K_m, which is the substrate concentration at which the reaction rate is half V_{max}. During the calibration process, care was taken so that annual process rates compared well with measured values from the literature.

Increasing V_{max} increases the process rate, and as shown in Figure A.1 for a hypothetical denitrification case, decreasing K_m increases the process rate. In Figure A.1, three curves are plotted of denitrification rate versus nitrate availability. A constant V_{max} value of 25 µg g^{-1} d^{-1} is used for all three curves, and values of 0.5, 2, and 5 mg L^{-1} are used for K_m.

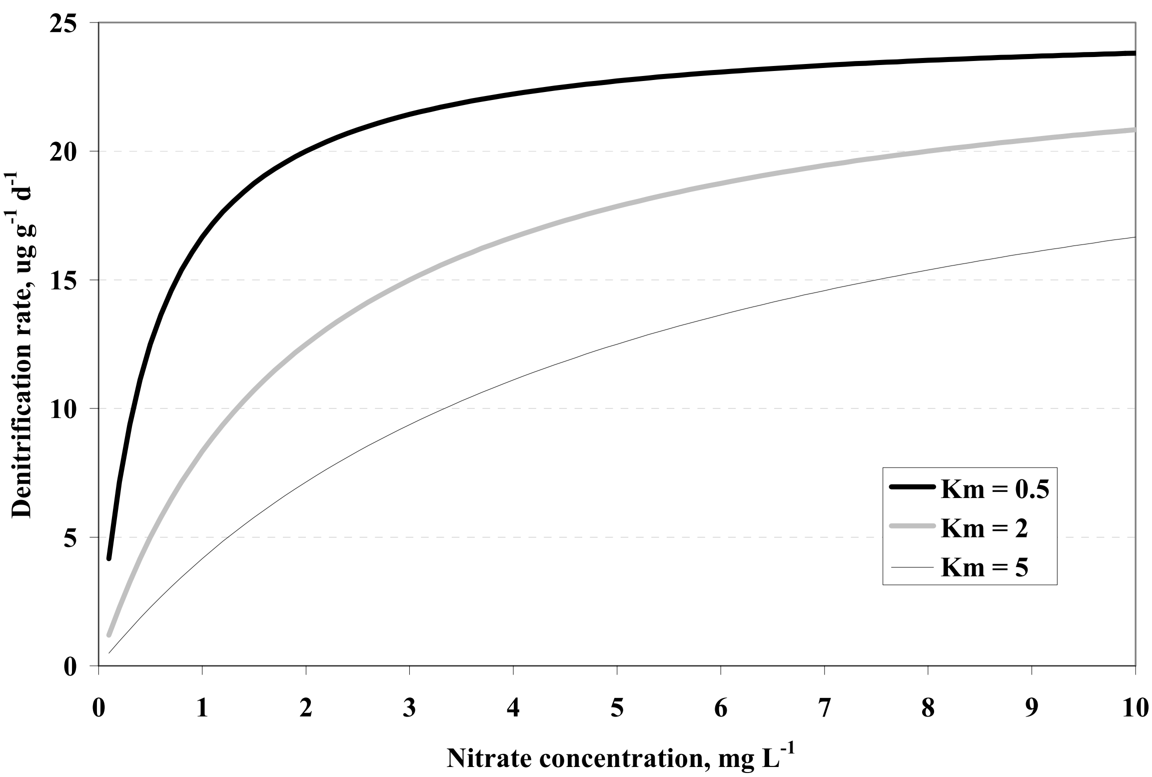

Figure A.1: Hypothetical plot of denitrification rate versus nitrate concentration for three different values of $K_{m,NO3}$ (mg L^{-1}).

The first step in the calibration process was to adjust the mineralization rate. For each field, the model initially overpredicted drainage losses of both NO_3-N and NH_4-N using the 40/60 % allocation of SOC. The mineralization rate was reduced so that the predicted DIN drainage losses were near the observed DIN losses for the calibration period.

The next step was to calibrate the model predictions of DIN into the proper proportions of NO_3-N and NH_4-N by adjusting the nitrification rate. Increasing the nitrification rate increased the NO_3-N lost in drainage while decreasing the NH_4-N lost. Then if there was still too much nitrate lost in drainage, the denitrification rate would be increased.

Youssef (2003) performed an extensive literature review of V_{max} for denitrification and nitrification and found that $V_{max,den}$ varied from 3.3 to 150 μg g^{-1} d^{-1} for denitrification and 4.0 to 38 μg g^{-1} d^{-1} for nitrification. The results from this literature review provided the lower and upper limits for the calibration process for V_{max}. Only the lower limit for denitrification was relevant for this study. The anaerobic denitrification process proceeds more slowly than aerobic nitrification process; therefore, another consideration in the calibration process was that the nitrification rate be greater than the denitrification rate.

The last parameter that was adjusted in the calibration process was the ammonium distribution coefficient, K_d. The K_d values were originally set at the same values that were used in the Youssef (2003) study. K_d was adjusted if the NH_4-N losses were still too large after the previous calibration steps and if the denitrification rate was at the lower limit from the literature review. Increasing K_d has the effect of decreasing ammonium losses because more ammonium is bound to the soil. Smethurst et al. (1999) found that K_d was significantly higher for organic horizons than for mineral horizons. Therefore, it was reasonable to increase K_d for this study on highly organic soils when compared to the more mineral soils of the Youssef (2003) study.

Kelly, R. H., W. J. Parton, G. J. Crocker, P. R. Grace, J. Klír, M.Körschens, P. R. Poulton,and D. D. Richter. 1997. Simulating trends in soil organic carbon in long-term experiments using the CENTURY model. *Geoderma.* 81:75-90.

Smethurst, P.J., G. Matschonat, L. M. Ballard, and J.K. Dingle. 1999. Phase partitioning of ammonium in Australian and European forest soils. *Commun. Soil Sci. Plant Anal.* 30(13&14):2023-2034.

Youssef, M. A. 2003. Modeling nitrogen transport and transformations in high water table soils. PhD dissertation. Raleigh, NC.: North Carolina State University.

Appendix B: Determination of the C:N ratio of the slow and passive organic matter pools.

The C:N ratio of the soil in the top 20 cm was determined from field measurements. Kelly et al. (1997) reported C:N ratios in the passive pools that were consistently less than the C:N ratios in the slow pools. As carbon is broken down in the decomposition process, the C:N ratios decrease. Therefore, it was assumed for this study that the C:N ratio of the passive pool would be 20 % less than the slow pool. The following equation defines the measured C:N ratio in terms of the C:N ratios of the slow and passive pools:

$$CN_{meas} = Frac_{slow} * CN_{slow} + Frac_{passive} * CN_{passive} \quad \text{(B.1)}$$

where CN_{meas} is the measured organic matter C:N ratio, CN_{slow} and $CN_{passive}$ are the C:N ratios of the slow and passive pools, respectively, and $Frac_{slow}$ and $Frac_{passive}$ are the slow and passive fractions of organic matter after partitioning, respectively. Since $CN_{passive}$ was assumed to be 20 % less than CN_{slow}, $CN_{passive}$ was defined as:

$$CN_{passive} = 0.8\ CN_{slow} \quad \text{(B.2)}$$

Equations B.1 and B.2 were then solved for $CN_{passive}$ and CN_{slow} with different partioning fractions, $Frac_{slow}$ and $Frac_{passive}$, and used as inputs in the model.

Kelly, R. H., W. J. Parton, G. J. Crocker, P. R. Grace, J. Klír, M.Körschens, P. R. Poulton,and D. D. Richter. 1997. Simulating trends in soil organic carbon in long-term experiments using the CENTURY model. *Geoderma.* 81:75-90.

Appendix C: *DRAINMOD-N* II .dmn input file for F3 for the 1996-2001 calibration.

```
*General
&=======
&Nrot Ncrop
    1     7
&IsNH4  IsUnif  IsTemp  IsManu
    .T      .T      .T      .T
&OutFlag OutPath
       1

*Grid
&====
&DelZ
  5.0
&G DEPgrid  DZgrid
&1    50.0     5.0
&2   150.0     5.0
&3   215.0     5.0


*Field
&=====
&Soil files
f:\jdiggs\DRAINMODN2\Parker3.mis

f:\jdiggs\DRAINMODN2\Parker3.wdv

&ProfDepth SltClyFrc    YesWTD    YesDDZ
     255.0     0.650     100.0       0.0
&L  DEPsoil HydrCond   WltPnt    Rho_b   SoilpH      K_d
 1     30.0   700.00    0.140     1.24      4.1     2.78
 2     40.0   650.00    0.140     2.00      4.1     2.78
 3     50.0   100.00    0.240     2.00      3.9     2.78
 4     70.0    40.00    0.240     2.00      3.9     2.78
 5    255.0     5.00    0.240     1.66      3.7     1.97

*Crops
&=====
&C  IC IsLeg PlntDay LenGrow PotUptk Lfr Lrt Lup Lmn

C1   1    .F       2     363   110.0   0   1   1   1
C2   2    .F       1     365   106.2   0   2   2   2
C3   3    .F       1     364   103.2   0   3   3   3
C4   4    .F       1     364   117.1   0   4   4   4
C5   5    .F       1     364   112.4   0   5   5   5
C6   6    .F       1     365   101.1   0   6   6   6
C7   7    .F       1     364   100.0   0   7   7   7

*Fertilization
&=============
&F  AppDay FerType  AddFer  AddInh AppMeth  IncDep  IsPost

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```

```
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 1      92        2    36.1    0.00        2    10.0       .F
 1      92        4    72.3    0.00        2    10.0       .F

 3       0        2     5.0    0.00        2    10.0       .F
 3       5        1    19.9    0.00        2    10.0       .F
 3       5        2    19.9    0.00        2    10.0       .F
 3       5        4    39.7    0.00        2    10.0       .F
 3      41        1    16.3    0.00        2    10.0       .F
 3      41        2    16.3    0.00        2    10.0       .F
 3      41        4    32.4    0.00        2    10.0       .F
 3      62        1    13.2    0.00        2    10.0       .F
 3      62        2    13.2    0.00        2    10.0       .F
 3      62        4    26.2    0.00        2    10.0       .F
 3     197        1     4.8    0.00        2    10.0       .T
 3     197        2     4.8    0.00        2    10.0       .T
 3     197        4     9.4    0.00        2    10.0       .T

 4     123        1    20.2    0.00        2    10.0       .F
 4     123        2    20.2    0.00        2    10.0       .F
 4     123        4    40.2    0.00        2    10.0       .F

 5     282        2    25.8    0.00        2    10.0       .T

 6       0        2    78.4    0.00        2    10.0       .F
 6      58        1     9.0    0.00        2    10.0       .F
 6      58        2     9.0    0.00        2    10.0       .F
 6      58        4    17.8    0.00        2    10.0       .F
 6     213        2    31.4    0.00        2    10.0       .T


*Manure Application
&==================
&M  AppDay  AddMan   ManOC  ManLgn  ManCNR AppMeth  IncDep  IsPost
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 1      15   292.2    50.6      20     110       1      20      .F
 1      46   161.0    50.6      20     110       1      20      .F
 1      76    72.9    50.6      20     110       1      20      .F
 1     107    80.8    50.6      20     110       1      20      .F
 1     137    73.5    50.6      20     110       1      20      .F
 1     168    95.4    50.6      20     110       1      20      .F
 1     198    80.8    50.6      20     110       1      20      .F
 1     229   131.8    50.6      20     110       1      20      .F
 1     259   161.0    50.6      20     110       1      20      .F
 1     290   539.9    50.6      20     110       1      20      .F
 1     321   846.0    50.6      20     110       1      20      .F
 1     351   379.6    50.6      20     110       1      20      .F

 2      15   311.7    50.6      20     110       1      20      .F
 2      46   171.8    50.6      20     110       1      20      .F
 2      76    77.8    50.6      20     110       1      20      .F
 2     107    86.2    50.6      20     110       1      20      .F
 2     137    78.5    50.6      20     110       1      20      .F
 2     168   101.8    50.6      20     110       1      20      .F
 2     198    86.2    50.6      20     110       1      20      .F
```

2	229	140.7	50.6	20	110	1	20	.F
2	259	171.8	50.6	20	110	1	20	.F
2	290	576.1	50.6	20	110	1	20	.F
2	321	902.6	50.6	20	110	1	20	.F
2	351	405.0	50.6	20	110	1	20	.F
3	15	350.3	50.6	20	110	1	20	.F
3	46	193.0	50.6	20	110	1	20	.F
3	76	87.4	50.6	20	110	1	20	.F
3	107	96.9	50.6	20	110	1	20	.F
3	137	88.2	50.6	20	110	1	20	.F
3	168	114.4	50.6	20	110	1	20	.F
3	198	96.9	50.6	20	110	1	20	.F
3	229	158.1	50.6	20	110	1	20	.F
3	259	193.0	50.6	20	110	1	20	.F
3	290	647.4	50.6	20	110	1	20	.F
3	321	1014.3	50.6	20	110	1	20	.F
3	351	455.1	50.6	20	110	1	20	.F
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4	46	205.7	50.6	20	110	1	20	.F
4	76	93.1	50.6	20	110	1	20	.F
4	107	103.3	50.6	20	110	1	20	.F
4	137	94.0	50.6	20	110	1	20	.F
4	168	121.9	50.6	20	110	1	20	.F
4	198	103.3	50.6	20	110	1	20	.F
4	229	168.5	50.6	20	110	1	20	.F
4	259	205.7	50.6	20	110	1	20	.F
4	290	690.0	50.6	20	110	1	20	.F
4	321	1081.1	50.6	20	110	1	20	.F
4	351	485.1	50.6	20	110	1	20	.F
5	15	375.9	50.6	20	110	1	20	.F
5	46	207.1	50.6	20	110	1	20	.F
5	76	93.8	50.6	20	110	1	20	.F
5	107	104.0	50.6	20	110	1	20	.F
5	137	94.6	50.6	20	110	1	20	.F
5	168	122.7	50.6	20	110	1	20	.F
5	198	104.0	50.6	20	110	1	20	.F
5	229	169.6	50.6	20	110	1	20	.F
5	259	207.1	50.6	20	110	1	20	.F
5	290	694.6	50.6	20	110	1	20	.F
5	321	1088.4	50.6	20	110	1	20	.F
5	351	488.4	50.6	20	110	1	20	.F
6	15	378.4	50.6	20	110	1	20	.F
6	46	208.5	50.6	20	110	1	20	.F
6	76	94.4	50.6	20	110	1	20	.F
6	107	104.7	50.6	20	110	1	20	.F
6	137	95.2	50.6	20	110	1	20	.F
6	168	123.5	50.6	20	110	1	20	.F
6	198	104.7	50.6	20	110	1	20	.F
6	229	170.7	50.6	20	110	1	20	.F
6	259	208.5	50.6	20	110	1	20	.F
6	290	699.2	50.6	20	110	1	20	.F

```
 6      321  1095.6    50.6       20      110       1      20       .F
 6      351   491.6    50.6       20      110       1      20       .F

 7       15   408.4    50.6       20      110       1      20       .F
 7       46   225.1    50.6       20      110       1      20       .F
 7       76   101.9    50.6       20      110       1      20       .F
 7      107   113.0    50.6       20      110       1      20       .F
 7      137   102.8    50.6       20      110       1      20       .F
 7      168   133.4    50.6       20      110       1      20       .F
 7      198   113.0    50.6       20      110       1      20       .F
 7      229   184.3    50.6       20      110       1      20       .F
 7      259   225.1    50.6       20      110       1      20       .F
 7      290   754.8    50.6       20      110       1      20       .F
 7      321  1182.7    50.6       20      110       1      20       .F
 7      351   530.7    50.6       20      110       1      20       .F

*Uptake
&======
&U  FracGrow   FracUptk
 1     0.000      0.000
 1     0.083      0.022
 1     0.167      0.044
 1     0.250      0.081
 1     0.333      0.160
 1     0.417      0.279
 1     0.500      0.423
 1     0.583      0.592
 1     0.667      0.755
 1     0.750      0.878
 1     0.833      0.952
 1     0.917      0.984
 1     1.000      1.000

 2     0.000      0.000
 2     0.083      0.020
 2     0.167      0.041
 2     0.250      0.072
 2     0.333      0.175
 2     0.417      0.281
 2     0.500      0.429
 2     0.583      0.589
 2     0.667      0.746
 2     0.750      0.870
 2     0.833      0.955
 2     0.917      0.974
 2     1.000      1.000

 3     0.000      0.000
 3     0.083      0.022
 3     0.167      0.055
 3     0.250      0.135
 3     0.333      0.200
 3     0.417      0.289
 3     0.500      0.421
 3     0.583      0.603
```

3	0.667	0.755
3	0.750	0.878
3	0.833	0.956
3	0.917	0.982
3	1.000	1.000
4	0.000	0.000
4	0.083	0.029
4	0.167	0.062
4	0.250	0.108
4	0.333	0.181
4	0.417	0.272
4	0.500	0.419
4	0.583	0.574
4	0.667	0.735
4	0.750	0.861
4	0.833	0.937
4	0.917	0.976
4	1.000	1.000
5	0.000	0.000
5	0.083	0.026
5	0.167	0.051
5	0.250	0.083
5	0.333	0.168
5	0.417	0.256
5	0.500	0.380
5	0.583	0.550
5	0.667	0.713
5	0.750	0.824
5	0.833	0.925
5	0.917	0.984
5	1.000	1.000
6	0.000	0.000
6	0.083	0.022
6	0.167	0.055
6	0.250	0.127
6	0.333	0.199
6	0.417	0.308
6	0.500	0.466
6	0.583	0.617
6	0.667	0.763
6	0.750	0.885
6	0.833	0.962
6	0.917	0.987
6	1.000	1.000
7	0.000	0.000
7	0.083	0.023
7	0.167	0.061
7	0.250	0.116
7	0.333	0.195
7	0.417	0.284
7	0.500	0.434

```
 7     0.583      0.587
 7     0.667      0.749
 7     0.750      0.853
 7     0.833      0.921
 7     0.917      0.972
 7     1.000      1.000

*Rooting Depths
&==============
&R RootDAY     RootDep
 1       1       45.00
 1     365       45.00

 2       1       45.00
 2     366       45.00

 3       1       45.00
 3     365       45.00

 4       1       45.00
 4     365       45.00

 5       1       45.00
 5     365       45.00

 6       1       45.00
 6     366       45.00

 7       1       45.00
 7     365       45.00

*TRANSport/TRANSformations
&=========================

&   Lambda       Tau      Dmol      ErrMax     DTmin
       5.0       0.7      1.34 1.00000E-04     0.001
&   Tavg     Amp    Damp     Phi
&  15.80    9.93    50.0    16.0
&  pHFlg   pHvol   MaxBufCap    Gama
       1     7.5 1.00000E+05    50.0

& Knit_max    Knit_m
       8.0      27.0
&     Topt      Beta
      25.0     0.413
&  WFPSlow  WFPShigh      Fwp     Fsat     Ewc
      0.50      0.60    0.00     0.00     1.0
&Is_pH   pHmin   pHmax   pHlow  pHhigh  FpHmin  FpHmax      EpH
    .T     3.5    10.0     6.7     7.2     0.0     0.0      1.0
& Cinh_max  Cinh_min      Einh   Arrhen1   Arrhen2
&     1.05      0.05       0.5    38.135   12067.3

& Kden_max    Kden_m    Alpha1      Eden
       3.0      45.0      0.05       1.0
&     Topt      Beta
```

```
      36.9     0.186
&  WFPSden       Ewc
      0.82       2.0
&Is_pH   pHmin   pHmax   pHlow  pHhigh  FpHmax      EpH
    .F

&    WCdis      Kdis
      0.20       1.0

& Khyd_max    Khyd_m
     120.0      50.0
&     Topt      Beta
      51.6     0.119
&  WFPSlow  WFPShigh     Fwp    Fsat     Ewc
      0.50      0.70    0.65    0.87     1.0
&Is_pH   pHmin   pHmax   pHlow  pHhigh  FpHmin  FpHmax      EpH
    .T     4.0    10.0     7.0     8.0    0.24     0.5      1.0

*Organic Matter
&==============
&P  PrcntTOC     CNR          Kdec
 1       0.0    15.0   3.75000E-02
 2       0.0   150.0   1.00714E-02
 3       0.0    18.5   1.50000E-02
 4      42.0    18.5   4.07143E-04
 5      58.0    14.8   1.39286E-05

&     Topt      Beta
      36.9     0.186
&  WFPSlow  WFPShigh     Fwp    Fsat     Ewc
      0.50      0.60     0.0    0.60     1.0
&Is_pH   pHmin   pHmax   pHlow  pHhigh  FpHmin  FpHmax      EpH
    .F

&IniInputFlg  SOMFlg
         .T       0
&     TOCmax   Alpha
&4.00000E+04   0.035
&O  DEPsom         TOC
 1     0.0  1.1266E+05
 1     5.0  1.1266E+05
 1    10.0  8.7540E+04
 1    15.0  6.0660E+04
 1    20.0  4.5920E+04
 1    20.1  0.0000E+00
 1   240.0  0.0000E+00

*Initial/Boundary Conditions
&===========================
&TopCNO3 TopCNH4 CNH3air
    0.23    0.39     0.0
&IniInputFlg
         .F
&CNO3ini CNH4ini
     1.0     0.1
```

```
&I     DEP    CNO3    CNH4
&1     0.0    20.0     5.0
&1   240.0     0.0     0.0
```

Appendix D: *DRAINMOD-N* II .dmn input file for F5 for the 1996-2001 calibration.

```
*General
&=======
&Nrot Ncrop
    1     7
&IsNH4  IsUnif  IsTemp  IsManu
    .T     .T     .T     .T
&OutFlag OutPath
       1

*Grid
&====
&DelZ
  5.0
&G DEPgrid  DZgrid
&1    50.0     5.0
&2   150.0     5.0
&3   215.0     5.0


*Field
&=====
&Soil files
f:\jdiggs\drainmodn2\Parker5.mis

f:\jdiggs\drainmodn2\Parker5.wdv

&ProfDepth SltClyFrc    YesWTD    YesDDZ
     250.0     0.650     100.0       0.0
&L  DEPsoil HydrCond   WltPnt    Rho_b   SoilpH      K_d
 1     46.0   550.00    0.290     0.90     3.85     2.30
 2     56.0   400.00    0.270     1.96     3.85     2.30
 3     68.0    10.00    0.290     1.96     3.91     2.30
 4    130.0     5.00    0.340     2.00     3.83     2.20
 5    250.0     5.00    0.130     2.00     3.83     1.97

*Crops
&=====
&C  IC IsLeg PlntDay LenGrow PotUptk Lfr Lrt Lup Lmn

C1   1    .F       2     363   110.0   0   1   1   1
C2   2    .F       1     365   106.2   0   2   2   2
C3   3    .F       1     364   103.2   0   3   3   3
C4   4    .F       1     364   117.1   0   4   4   4
C5   5    .F       1     364   112.4   0   5   5   5
C6   6    .F       1     365   101.1   0   6   6   6
C7   7    .F       1     364   100.0   0   7   7   7

*Fertilization
&=============
&F  AppDay FerType  AddFer  AddInh AppMeth  IncDep  IsPost

 1       0       2    16.8    0.00       2    10.0      .F
 1      92       1    36.1    0.00       2    10.0      .F
```

```
 1      92        2    36.1    0.00        2    10.0       .F
 1      92        4    72.3    0.00        2    10.0       .F

 3       0        2     5.0    0.00        2    10.0       .F
 3       5        1    19.9    0.00        2    10.0       .F
 3       5        2    19.9    0.00        2    10.0       .F
 3       5        4    39.7    0.00        2    10.0       .F
 3      41        1    16.3    0.00        2    10.0       .F
 3      41        2    16.3    0.00        2    10.0       .F
 3      41        4    32.4    0.00        2    10.0       .F
 3      62        1    13.2    0.00        2    10.0       .F
 3      62        2    13.2    0.00        2    10.0       .F
 3      62        4    26.2    0.00        2    10.0       .F
 3     197        1     4.8    0.00        2    10.0       .T
 3     197        2     4.8    0.00        2    10.0       .T
 3     197        4     9.4    0.00        2    10.0       .T

 4     123        1    20.2    0.00        2    10.0       .F
 4     123        2    20.2    0.00        2    10.0       .F
 4     123        4    40.2    0.00        2    10.0       .F

 5     282        2    25.8    0.00        2    10.0       .T

 6       0        2    78.4    0.00        2    10.0       .F
 6      58        1     9.0    0.00        2    10.0       .F
 6      58        2     9.0    0.00        2    10.0       .F
 6      58        4    17.8    0.00        2    10.0       .F
 6     213        2    31.4    0.00        2    10.0       .T


*Manure Application
&==================
&M  AppDay  AddMan   ManOC  ManLgn  ManCNR AppMeth   IncDep  IsPost
 1       2  5500.0    50.6      20     110       1       10      .F
 1      15   277.1    50.6      20     110       1       20      .F
 1      46   152.7    50.6      20     110       1       20      .F
 1      76    69.1    50.6      20     110       1       20      .F
 1     107    76.7    50.6      20     110       1       20      .F
 1     137    69.8    50.6      20     110       1       20      .F
 1     168    90.5    50.6      20     110       1       20      .F
 1     198    76.7    50.6      20     110       1       20      .F
 1     229   125.1    50.6      20     110       1       20      .F
 1     259   152.7    50.6      20     110       1       20      .F
 1     290   512.2    50.6      20     110       1       20      .F
 1     321   802.5    50.6      20     110       1       20      .F
 1     351   360.1    50.6      20     110       1       20      .F

 2      15   300.7    50.6      20     110       1       20      .F
 2      46   165.7    50.6      20     110       1       20      .F
 2      76    75.0    50.6      20     110       1       20      .F
 2     107    83.2    50.6      20     110       1       20      .F
 2     137    75.7    50.6      20     110       1       20      .F
 2     168    98.2    50.6      20     110       1       20      .F
 2     198    83.2    50.6      20     110       1       20      .F
 2     229   135.7    50.6      20     110       1       20      .F
```

2	259	165.7	50.6	20	110	1	20	.F
2	290	555.7	50.6	20	110	1	20	.F
2	321	870.7	50.6	20	110	1	20	.F
2	351	390.7	50.6	20	110	1	20	.F
3	15	300.7	50.6	20	110	1	20	.F
3	46	165.7	50.6	20	110	1	20	.F
3	76	75.0	50.6	20	110	1	20	.F
3	107	83.2	50.6	20	110	1	20	.F
3	137	75.7	50.6	20	110	1	20	.F
3	168	98.2	50.6	20	110	1	20	.F
3	198	83.2	50.6	20	110	1	20	.F
3	229	135.7	50.6	20	110	1	20	.F
3	259	165.7	50.6	20	110	1	20	.F
3	290	555.7	50.6	20	110	1	20	.F
3	321	870.7	50.6	20	110	1	20	.F
3	351	390.7	50.6	20	110	1	20	.F
4	15	335.3	50.6	20	110	1	20	.F
4	46	184.7	50.6	20	110	1	20	.F
4	76	83.6	50.6	20	110	1	20	.F
4	107	92.7	50.6	20	110	1	20	.F
4	137	84.4	50.6	20	110	1	20	.F
4	168	109.5	50.6	20	110	1	20	.F
4	198	92.7	50.6	20	110	1	20	.F
4	229	151.3	50.6	20	110	1	20	.F
4	259	184.7	50.6	20	110	1	20	.F
4	290	619.6	50.6	20	110	1	20	.F
4	321	970.8	50.6	20	110	1	20	.F
4	351	435.6	50.6	20	110	1	20	.F
5	15	358.3	50.6	20	110	1	20	.F
5	46	197.4	50.6	20	110	1	20	.F
5	76	89.4	50.6	20	110	1	20	.F
5	107	99.1	50.6	20	110	1	20	.F
5	137	90.2	50.6	20	110	1	20	.F
5	168	117.0	50.6	20	110	1	20	.F
5	198	99.1	50.6	20	110	1	20	.F
5	229	161.7	50.6	20	110	1	20	.F
5	259	197.4	50.6	20	110	1	20	.F
5	290	662.2	50.6	20	110	1	20	.F
5	321	1037.6	50.6	20	110	1	20	.F
5	351	465.6	50.6	20	110	1	20	.F
6	15	363.3	50.6	20	110	1	20	.F
6	46	200.2	50.6	20	110	1	20	.F
6	76	90.6	50.6	20	110	1	20	.F
6	107	100.5	50.6	20	110	1	20	.F
6	137	91.4	50.6	20	110	1	20	.F
6	168	118.6	50.6	20	110	1	20	.F
6	198	100.5	50.6	20	110	1	20	.F
6	229	163.9	50.6	20	110	1	20	.F
6	259	200.2	50.6	20	110	1	20	.F
6	290	671.4	50.6	20	110	1	20	.F
6	321	1052.1	50.6	20	110	1	20	.F

```
 6      351   472.1     50.6       20      110       1       20       .F

 7       15   367.3     50.6       20      110       1       20       .F
 7       46   202.4     50.6       20      110       1       20       .F
 7       76    91.6     50.6       20      110       1       20       .F
 7      107   101.6     50.6       20      110       1       20       .F
 7      137    92.5     50.6       20      110       1       20       .F
 7      168   119.9     50.6       20      110       1       20       .F
 7      198   101.6     50.6       20      110       1       20       .F
 7      229   165.8     50.6       20      110       1       20       .F
 7      259   202.4     50.6       20      110       1       20       .F
 7      290   678.9     50.6       20      110       1       20       .F
 7      321  1063.7     50.6       20      110       1       20       .F
 7      351   477.3     50.6       20      110       1       20       .F


*Uptake
&======
&U  FracGrow   FracUptk
 1     0.000      0.000
 1     0.083      0.022
 1     0.167      0.044
 1     0.250      0.081
 1     0.333      0.160
 1     0.417      0.279
 1     0.500      0.423
 1     0.583      0.592
 1     0.667      0.755
 1     0.750      0.878
 1     0.833      0.952
 1     0.917      0.984
 1     1.000      1.000

 2     0.000      0.000
 2     0.083      0.020
 2     0.167      0.041
 2     0.250      0.072
 2     0.333      0.175
 2     0.417      0.281
 2     0.500      0.429
 2     0.583      0.589
 2     0.667      0.746
 2     0.750      0.870
 2     0.833      0.955
 2     0.917      0.974
 2     1.000      1.000

 3     0.000      0.000
 3     0.083      0.022
 3     0.167      0.055
 3     0.250      0.135
 3     0.333      0.200
 3     0.417      0.289
 3     0.500      0.421
 3     0.583      0.603
```

3	0.667	0.755
3	0.750	0.878
3	0.833	0.956
3	0.917	0.982
3	1.000	1.000
4	0.000	0.000
4	0.083	0.029
4	0.167	0.062
4	0.250	0.108
4	0.333	0.181
4	0.417	0.272
4	0.500	0.419
4	0.583	0.574
4	0.667	0.735
4	0.750	0.861
4	0.833	0.937
4	0.917	0.976
4	1.000	1.000
5	0.000	0.000
5	0.083	0.026
5	0.167	0.051
5	0.250	0.083
5	0.333	0.168
5	0.417	0.256
5	0.500	0.380
5	0.583	0.550
5	0.667	0.713
5	0.750	0.824
5	0.833	0.925
5	0.917	0.984
5	1.000	1.000
6	0.000	0.000
6	0.083	0.022
6	0.167	0.055
6	0.250	0.127
6	0.333	0.199
6	0.417	0.308
6	0.500	0.466
6	0.583	0.617
6	0.667	0.763
6	0.750	0.885
6	0.833	0.962
6	0.917	0.987
6	1.000	1.000
7	0.000	0.000
7	0.083	0.023
7	0.167	0.061
7	0.250	0.116
7	0.333	0.195
7	0.417	0.284
7	0.500	0.434

```
 7     0.583      0.587
 7     0.667      0.749
 7     0.750      0.853
 7     0.833      0.921
 7     0.917      0.972
 7     1.000      1.000

*Rooting Depths
&==============
&R RootDAY     RootDep
 1       1       45.00
 1     365       45.00

 2       1       45.00
 2     366       45.00

 3       1       45.00
 3     365       45.00

 4       1       45.00
 4     365       45.00

 5       1       45.00
 5     365       45.00

 6       1       45.00
 6     366       45.00

 7       1       45.00
 7     365       45.00

*TRANSport/TRANSformations
&=========================

&   Lambda       Tau      Dmol      ErrMax     DTmin
       5.0       0.7      1.34 1.00000E-04     0.001
&   Tavg     Amp    Damp     Phi
&  15.80    9.93    50.0    16.0
&  pHFlg   pHvol   MaxBufCap    Gama
       1     7.5 1.00000E+05    50.0

& Knit_max    Knit_m
      9.0      45.0
&     Topt      Beta
      25.0     0.413
&  WFPSlow  WFPShigh      Fwp    Fsat     Ewc
      0.50      0.60    0.00    0.00     2.0
&Is_pH   pHmin   pHmax   pHlow  pHhigh  FpHmin  FpHmax      EpH
    .T     3.5    10.0     6.7     7.2     0.0     0.0      1.0
& Cinh_max  Cinh_min      Einh   Arrhen1   Arrhen2
&     1.05      0.05       0.5    38.135   12067.3

& Kden_max    Kden_m    Alpha1      Eden
       4.0      22.0     0.008       1.0
&     Topt      Beta
```

```
      36.9     0.186
&  WFPSden       Ewc
      0.65       1.3
&Is_pH   pHmin   pHmax   pHlow  pHhigh  FpHmax     EpH
    .F

&    WCdis      Kdis
      0.20       1.0

& Khyd_max    Khyd_m
     120.0      50.0
&     Topt      Beta
      51.6     0.119
&  WFPSlow  WFPShigh     Fwp    Fsat     Ewc
      0.50      0.70    0.65    0.87     1.0
&Is_pH   pHmin   pHmax   pHlow  pHhigh  FpHmin  FpHmax     EpH
    .T     4.0    10.0     7.0     8.0    0.24     0.5     1.0

*Organic Matter
&==============
&P  PrcntTOC     CNR          Kdec
 1       0.0    15.0   3.75000E-02
 2       0.0   150.0   1.00714E-02
 3       0.0    38.9   1.50000E-02
 4      20.0    38.9   4.07143E-04
 5      80.0    31.2   1.39286E-05

&     Topt      Beta
      36.9     0.186
&  WFPSlow  WFPShigh     Fwp    Fsat     Ewc
      0.50      0.60     0.0    0.50     2.0
&Is_pH   pHmin   pHmax   pHlow  pHhigh  FpHmin  FpHmax     EpH
    .F

&IniInputFlg  SOMFlg
          .T       0
&     TOCmax   Alpha
&4.00000E+04   0.035
&O  DEPsom         TOC
 1     0.0  2.6488E+05
 1     5.0  2.6488E+05
 1    10.0  3.1923E+05
 1    15.0  3.9473E+05
 1    20.0  3.1337E+05
 1    20.1  0.0000E+00
 1   240.0  0.0000E+00

*Initial/Boundary Conditions
&============================
&TopCNO3 TopCNH4 CNH3air
    0.23    0.39     0.0
&IniInputFlg
          .F
&CNO3ini CNH4ini
     1.0     0.1
```

```
&I     DEP    CNO3    CNH4
&1     0.0    20.0     5.0
&1   240.0     0.0     0.0
```

Appendix E: *DRAINMOD-N* II .dmn input file for F6 for the 1996-2001 calibration.

```
*General
&=======
&Nrot Ncrop
    1     7
&IsNH4  IsUnif  IsTemp  IsManu
    .T      .T      .T      .T
&OutFlag OutPath
       1

*Grid
&====
&DelZ
  5.0
&G DEPgrid  DZgrid
&1    50.0     5.0
&2   150.0     5.0
&3   215.0     5.0


*Field
&=====
&Soil files
f:\jdiggs\drainmodn2\Parker6.mis

f:\jdiggs\drainmodn2\Parker6.wdv

&ProfDepth SltClyFrc    YesWTD    YesDDZ
     250.0     0.650     100.0       0.0
&L  DEPsoil HydrCond   WltPnt    Rho_b   SoilpH      K_d
 1    30.0    700.00    0.320     0.90     4.20     2.80
 2    45.0    350.00    0.320     0.90     4.20     2.80
 3    60.0     10.00    0.320     1.96     4.20     2.50
 4   130.0      5.00    0.180     2.00     4.40     2.37
 5   250.0      5.00    0.130     2.00     4.60     1.97

*Crops
&=====
&C  IC IsLeg PlntDay LenGrow PotUptk Lfr Lrt Lup Lmn

C1   1    .F       2     363    72.9   0   1   1   1
C2   2    .F       1     365    73.0   0   2   2   2
C3   3    .F       1     364    74.8   0   3   3   3
C4   4    .F       1     364    87.8   0   4   4   4
C5   5    .F       1     364    91.4   0   5   5   5
C6   6    .F       1     365    88.5   0   6   6   6
C7   7    .F       1     364    96.2   0   7   7   7

*Fertilization
&=============
&F  AppDay FerType  AddFer  AddInh AppMeth  IncDep  IsPost

 1       0       2    16.8    0.00       2    10.0      .F
 1      92       1    36.1    0.00       2    10.0      .F
```

```
 1      92        2    36.1    0.00        2    10.0       .F
 1      92        4    72.3    0.00        2    10.0       .F

 3       0        2     5.0    0.00        2    10.0       .F
 3       5        1    19.9    0.00        2    10.0       .F
 3       5        2    19.9    0.00        2    10.0       .F
 3       5        4    39.7    0.00        2    10.0       .F
 3      41        1    16.3    0.00        2    10.0       .F
 3      41        2    16.3    0.00        2    10.0       .F
 3      41        4    32.4    0.00        2    10.0       .F
 3      62        1    13.2    0.00        2    10.0       .F
 3      62        2    13.2    0.00        2    10.0       .F
 3      62        4    26.2    0.00        2    10.0       .F
 3     197        1     4.8    0.00        2    10.0       .T
 3     197        2     4.8    0.00        2    10.0       .T
 3     197        4     9.4    0.00        2    10.0       .T

 4     123        1    20.2    0.00        2    10.0       .F
 4     123        2    20.2    0.00        2    10.0       .F
 4     123        4    40.2    0.00        2    10.0       .F

 5     282        2    25.8    0.00        2    10.0       .T

 6       0        2    78.4    0.00        2    10.0       .F
 6      58        1     9.0    0.00        2    10.0       .F
 6      58        2     9.0    0.00        2    10.0       .F
 6      58        4    17.8    0.00        2    10.0       .F
 6     213        2    31.4    0.00        2    10.0       .T


*Manure Application
&==================
&M  AppDay  AddMan   ManOC  ManLgn  ManCNR AppMeth   IncDep  IsPost
 1       2  2200.0    52.0      19     125       1       10      .F
 1      15    82.2    50.6      20     110       1       20      .F
 1      46    45.3    50.6      20     110       1       20      .F
 1      76    20.5    50.6      20     110       1       20      .F
 1     107    22.7    50.6      20     110       1       20      .F
 1     137    20.7    50.6      20     110       1       20      .F
 1     168    26.8    50.6      20     110       1       20      .F
 1     198    22.7    50.6      20     110       1       20      .F
 1     229    37.1    50.6      20     110       1       20      .F
 1     259    45.3    50.6      20     110       1       20      .F
 1     290   151.9    50.6      20     110       1       20      .F
 1     321   238.0    50.6      20     110       1       20      .F
 1     351   106.8    50.6      20     110       1       20      .F

 2      15   103.2    50.6      20     110       1       20      .F
 2      46    56.9    50.6      20     110       1       20      .F
 2      76    25.8    50.6      20     110       1       20      .F
 2     107    28.6    50.6      20     110       1       20      .F
 2     137    26.0    50.6      20     110       1       20      .F
 2     168    33.7    50.6      20     110       1       20      .F
 2     198    28.6    50.6      20     110       1       20      .F
 2     229    46.6    50.6      20     110       1       20      .F
```

2	259	56.9	50.6	20	110	1	20	.F
2	290	190.8	50.6	20	110	1	20	.F
2	321	298.9	50.6	20	110	1	20	.F
2	351	134.1	50.6	20	110	1	20	.F
3	15	120.8	50.6	20	110	1	20	.F
3	46	66.5	50.6	20	110	1	20	.F
3	76	30.1	50.6	20	110	1	20	.F
3	107	33.4	50.6	20	110	1	20	.F
3	137	30.4	50.6	20	110	1	20	.F
3	168	39.4	50.6	20	110	1	20	.F
3	198	33.4	50.6	20	110	1	20	.F
3	229	54.5	50.6	20	110	1	20	.F
3	259	66.5	50.6	20	110	1	20	.F
3	290	223.2	50.6	20	110	1	20	.F
3	321	349.7	50.6	20	110	1	20	.F
3	351	156.9	50.6	20	110	1	20	.F
4	15	135.8	50.6	20	110	1	20	.F
4	46	74.8	50.6	20	110	1	20	.F
4	76	33.9	50.6	20	110	1	20	.F
4	107	37.6	50.6	20	110	1	20	.F
4	137	34.2	50.6	20	110	1	20	.F
4	168	44.3	50.6	20	110	1	20	.F
4	198	37.6	50.6	20	110	1	20	.F
4	229	61.3	50.6	20	110	1	20	.F
4	259	74.8	50.6	20	110	1	20	.F
4	290	251.0	50.6	20	110	1	20	.F
4	321	393.3	50.6	20	110	1	20	.F
4	351	176.5	50.6	20	110	1	20	.F
5	15	149.8	50.6	20	110	1	20	.F
5	46	82.6	50.6	20	110	1	20	.F
5	76	37.4	50.6	20	110	1	20	.F
5	107	41.5	50.6	20	110	1	20	.F
5	137	37.7	50.6	20	110	1	20	.F
5	168	48.9	50.6	20	110	1	20	.F
5	198	41.5	50.6	20	110	1	20	.F
5	229	67.6	50.6	20	110	1	20	.F
5	259	82.6	50.6	20	110	1	20	.F
5	290	276.9	50.6	20	110	1	20	.F
5	321	433.9	50.6	20	110	1	20	.F
5	351	194.7	50.6	20	110	1	20	.F
6	15	167.9	50.6	20	110	1	20	.F
6	46	92.5	50.6	20	110	1	20	.F
6	76	41.9	50.6	20	110	1	20	.F
6	107	46.4	50.6	20	110	1	20	.F
6	137	42.3	50.6	20	110	1	20	.F
6	168	54.8	50.6	20	110	1	20	.F
6	198	46.4	50.6	20	110	1	20	.F
6	229	75.8	50.6	20	110	1	20	.F
6	259	92.5	50.6	20	110	1	20	.F
6	290	310.3	50.6	20	110	1	20	.F
6	321	486.1	50.6	20	110	1	20	.F

```
 6      351   218.1     50.6       20      110       1       20       .F

 7       15   191.9     50.6       20      110       1       20       .F
 7       46   105.8     50.6       20      110       1       20       .F
 7       76    47.9     50.6       20      110       1       20       .F
 7      107    53.1     50.6       20      110       1       20       .F
 7      137    48.3     50.6       20      110       1       20       .F
 7      168    62.7     50.6       20      110       1       20       .F
 7      198    53.1     50.6       20      110       1       20       .F
 7      229    86.6     50.6       20      110       1       20       .F
 7      259   105.8     50.6       20      110       1       20       .F
 7      290   354.7     50.6       20      110       1       20       .F
 7      321   555.8     50.6       20      110       1       20       .F
 7      351   249.4     50.6       20      110       1       20       .F

*Uptake
&======
&U  FracGrow   FracUptk
 1     0.000      0.000
 1     0.083      0.022
 1     0.167      0.044
 1     0.250      0.081
 1     0.333      0.160
 1     0.417      0.279
 1     0.500      0.423
 1     0.583      0.592
 1     0.667      0.755
 1     0.750      0.878
 1     0.833      0.952
 1     0.917      0.984
 1     1.000      1.000

 2     0.000      0.000
 2     0.083      0.020
 2     0.167      0.041
 2     0.250      0.072
 2     0.333      0.175
 2     0.417      0.281
 2     0.500      0.429
 2     0.583      0.589
 2     0.667      0.746
 2     0.750      0.870
 2     0.833      0.955
 2     0.917      0.974
 2     1.000      1.000

 3     0.000      0.000
 3     0.083      0.022
 3     0.167      0.055
 3     0.250      0.135
 3     0.333      0.200
 3     0.417      0.289
 3     0.500      0.421
 3     0.583      0.603
 3     0.667      0.755
```

3	0.750	0.878
3	0.833	0.956
3	0.917	0.982
3	1.000	1.000
4	0.000	0.000
4	0.083	0.029
4	0.167	0.062
4	0.250	0.108
4	0.333	0.181
4	0.417	0.272
4	0.500	0.419
4	0.583	0.574
4	0.667	0.735
4	0.750	0.861
4	0.833	0.937
4	0.917	0.976
4	1.000	1.000
5	0.000	0.000
5	0.083	0.026
5	0.167	0.051
5	0.250	0.083
5	0.333	0.168
5	0.417	0.256
5	0.500	0.380
5	0.583	0.550
5	0.667	0.713
5	0.750	0.824
5	0.833	0.925
5	0.917	0.984
5	1.000	1.000
6	0.000	0.000
6	0.083	0.022
6	0.167	0.055
6	0.250	0.127
6	0.333	0.199
6	0.417	0.308
6	0.500	0.466
6	0.583	0.617
6	0.667	0.763
6	0.750	0.885
6	0.833	0.962
6	0.917	0.987
6	1.000	1.000
7	0.000	0.000
7	0.083	0.023
7	0.167	0.061
7	0.250	0.116
7	0.333	0.195
7	0.417	0.284
7	0.500	0.434
7	0.583	0.587

```
 7     0.667      0.749
 7     0.750      0.853
 7     0.833      0.921
 7     0.917      0.972
 7     1.000      1.000

*Rooting Depths
&==============
&R RootDAY     RootDep
 1       1        6.00
 1     366        6.00

 2       1        6.00
 2     365        6.00

 3       1        9.00
 3     365        9.00

 4       1       15.00
 4     365       15.00

 5       1       23.00
 5     366       23.00

 6       1       31.00
 6     365       31.00

 7       1       43.00
 7     365       43.00

*TRANSport/TRANSformations
&==========================

&   Lambda       Tau      Dmol      ErrMax     DTmin
       5.0       0.7      1.34 1.00000E-04     0.001
&   Tavg      Amp    Damp      Phi
&  15.80    9.93    50.0    16.0
&  pHFlg   pHvol   MaxBufCap    Gama
       1     7.5 1.00000E+05    50.0

& Knit_max    Knit_m
      15.0      30.0
&     Topt      Beta
      25.0     0.413
&  WFPSlow  WFPShigh      Fwp    Fsat     Ewc
      0.50      0.60    0.00    0.00     2.0
&Is_pH   pHmin   pHmax   pHlow  pHhigh  FpHmin  FpHmax      EpH
    .T     3.5    10.0     6.7     7.2     0.0     0.0     1.0
& Cinh_max  Cinh_min      Einh   Arrhen1   Arrhen2
&     1.05      0.05       0.5    38.135   12067.3

& Kden_max    Kden_m    Alpha1      Eden
       3.0      25.0     0.008       1.0
&     Topt      Beta
      36.9     0.186
```

```
&  WFPSden       Ewc
      0.65       1.3
&Is_pH   pHmin   pHmax   pHlow  pHhigh  FpHmax     EpH
    .F

&    WCdis      Kdis
      0.20       1.0

& Khyd_max    Khyd_m
     120.0      50.0
&     Topt      Beta
      51.6     0.119
&  WFPSlow  WFPShigh     Fwp    Fsat     Ewc
      0.50      0.70    0.65    0.87     1.0
&Is_pH   pHmin   pHmax   pHlow  pHhigh  FpHmin  FpHmax     EpH
    .T     4.0    10.0     7.0     8.0    0.24     0.5     1.0


*Organic Matter
&==============
&P  PrcntTOC     CNR          Kdec
 1       0.0    15.0   3.75000E-02
 2       0.0   150.0   1.00714E-02
 3       0.0    27.0   1.50000E-02
 4      14.0    27.0   4.07143E-04
 5      86.0    21.6   1.39286E-05

&     Topt      Beta
      36.9     0.186
&  WFPSlow  WFPShigh     Fwp    Fsat     Ewc
      0.50      0.60     0.0    0.50     2.0
&Is_pH   pHmin   pHmax   pHlow  pHhigh  FpHmin  FpHmax     EpH
    .F

&IniInputFlg  SOMFlg
        .T       0
&     TOCmax   Alpha
&4.00000E+04   0.035
&O  DEPsom         TOC
 1     0.0  3.2330E+05
 1     5.0  3.2330E+05
 1    10.0  3.5420E+05
 1    15.0  3.8483E+05
 1    20.0  3.8883E+05
 1    20.1  0.0000E+00
 1   240.0  0.0000E+00

*Initial/Boundary Conditions
&===========================
&TopCNO3 TopCNH4 CNH3air
    0.23    0.39     0.0
&IniInputFlg
        .F
&CNO3ini CNH4ini
     1.0     0.1
```

```
&I      DEP    CNO3    CNH4
&1      0.0    20.0     5.0
&1    240.0     0.0     0.0
```