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PREDICTING LONG-TERM WETLAND HYDROLOGY FROM HYDRIC SOIL FIELD INDICATORS

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ABSTRACT

Frequency and duration of saturation data are used to evaluate a soil's suitability for on-site waste disposal as well as to determine whether a site is in a jurisdictional wetland. Such data can be acquired from hydrologic models if the models are calibrated for individual sites. The principal objective of this study was to calibrate soil color patterns, specifically percentages of redoximorphic features, to long-term water table fluctuations in two toposequences in the NC Coastal Plain. Water table levels were monitored for up to 3 yrs. in 22 soil plots of the two toposequences. Plots were arranged in transects that extended from well (Typic Paleudults) or moderately well (Aquic Paleudults) to very poorly drained soils (Umbric Paleaquults). Percentages of redoximorphic features were estimated in 15 cm depth increments to a depth of 90 cm in each plot. The hydrologic model, DRAINMOD was calibrated for each soil plot using the record of daily water table levels, in situ saturated hydraulic conductivity, soil water characteristic, depth to impermeable layer, depth of rooting, and rainfall. The calibrated DRAINMOD models were used along with historic rainfall data to estimate the number of times each soil plot experienced saturation events lasting 21 days or longer for a 40-yr. period. Percentages of redoximorphic features (i.e. gray and red colors) were significantly correlated ($r^2 > 0.80$) with average number of saturation events across all soils for individual depths of 45, 60, 75 and 90 cm. Highest correlations (r^2 values > 0.87) were found for relationships between redox depletions and saturation events during the growing season. The hydric soil field indicator the "depleted matrix" occurred in layers that were saturated for 21 to 41 days every year during the 40-yr. period considered.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

LIST OF TABLES (continued)

SUMMARY AND CONCLUSIONS

Current regulations governing wetland identification make it virtually impossible to identify freshwater wetland routinely using current technology. Jurisdictional wetlands include areas that are saturated within 30 cm of the surface for 5% of the growing season in 5 or more years out of 10. Such information on wetland hydrology can be obtained by long-term monitoring studies that span both wet and dry years. These require long periods of time (5 to 10 years) to complete, and are too expensive to do at most sites where the information is needed. An alternative approach is to use hydrologic models to estimate water table data over long periods at a few benchmark sites. These data can be obtained quickly (in less than 6 months). The hydrologic information can be extrapolated to other soils by calibrating soil indicators of saturation for the specific frequencies and durations of saturation estimated by the model. These indicators (basically seen as gray and red colors) occur in most wetland soils that are chemically reduced and can be easily identified during on-site inspections. By using hydrologic models in combination with hydric soil indicators, we should be able to estimate quickly and economically how long the major soils are saturated in the Coastal Plain region of North Carolina. This information should be of great value to those charged with determining wetland boundaries.

Objectives

1. To estimate the time that the soils along a hillslope were saturated each year for a 40-year period using historic rainfall data and a hydrologic model.

2. To compute probabilities that each soil along the hillslope will be saturated at a given depth during a year, both during and outside the growing season.

3. To correlate the hydric soil features observed in each soil to the probability values determined in objective 2.

Methodology

The study was conducted at two locations in the North Carolina Coastal Plain. At both sites transects of soil plots were established along hillslopes with plots in moderately well, somewhat poorly, poorly, and very poorly-drained soils. Four transects of plots were used in Pitt County, NC, and two transects were used in Bertie County, NC. In each soil plot the water table was monitored daily for three years, and redox potential was monitored weekly. Rainfall was monitored hourly at each location.

Pits were dug in each soil plot to a depth of 1.2 m to describe the soil colors and identify hydric soil field indicators. Percentages of gray color (redox depeletions) and red color or mottles (redox concentrations) were estimated by eye. Saturated hydraulic conductivity and pore size distribution were determined for each major horizon in each soil.

DRAINMOD was calibrated to simulate water table fluctuations in each plot using the daily water table data, rainfall, and soil properties. The calibrated models were then used to compute daily water table levels in each soil plot over a 40-year period using daily rainfall levels obtained from the nearest available weather stations.

DRAINMOD output consisted of the number of times per year that the soil was saturated at a single depth for each of the years from 1958 through 1998. Saturation events lasting 21 consecutive days or longer were used. The longest continuous period of saturation will also be estimated for each year. Data were obtained during the growing season, outside the growing season, and the entire year.

Output data were used to compute a "saturation index" value that represented the number of times the soil was saturated for 21 days or longer. The index combined both saturation frequency and duration. A soil with a saturation index of 3 could be saturated for between 21 and 41 days three times per year, or it may be saturated once per year for a period lasting between 63 and 83 days.

Saturation index values were computed for each depth for each of 40 years, and then an average saturation index value was estimated for the 40-year period. The average saturation index values were then correlated with the percentage of redox depletions (gray color) and redox concentrations (red color) observed in each soil for depths of 30, 45, 60, 75, and 90 cm. Data from all soil plots within a site were combined for analysis.

Principal Findings and Significance

DRAINMOD was able to be calibrated to simulate water table levels in all plots of both sites. This is significant because the sites did not contain the network of parallel drains that the model assumes are present. We adjusted the depth and distance of imaginary drains until the model's simulation of water table levels matched the measured values. Depth to impermeable layer, soil porosity, and evapotranspiration were also adjusted by plot to simulate water table levels. Average absolute deviations between simulated and measured values was generally 20 cm or less.

At both sites, the percentages of redox depletions and concentrations were significantly correlated with saturation events, and r2 values were generally between 0.80 and 0.95 for redox depletions and redox concentrations. Higher r2 values were found during the growing season for all soil depths. Each depth had to be treated separately, because a given saturation index produced fewer redox depletions at 90 cm, than at 40 cm.

Correlations were also obtained by combining data for both sites. The r2 values for relations between percentage of redox depletions and saturation index were between 0.80 and 0.95 for saturation periods throughout the year.

These results show that percentages of redoximorphic features can be used to estimate saturation frequency in Coastal Plain soils with a high degree of accuracy. Depths at which redox depletions occur are saturated for at least 21 consecutive days, and the more frequent the saturation, the greater the percentage of depletions. Graphs of the statistical relationships were developed which will allow wetland delineators to determine when wetland hydrology has been met. Such graphs need additional field testing before distribution.

RECOMMENDATIONS

1. Water table fluctuations for long-term periods need to be predicted using DRAINMOD or other hydrologic models in widespread soils found in rapidly developing areas of NC to provide benchmark data that can be used to make land use decisions. DRAINMOD is a versatile model that need not be used only in soils containing drainage ditches.

2. Results of the long-term hydrologic simulations can be extrapolated to other soils in NC by correlating the data to soil color patterns, specifically the percentages of redoximorphic features. Percentages of features can then be measured on individual sites and the data from simulation studies used to estimate the likelihood a soil will become saturated at a specific depth.

3. The soil property described as either the "depth to seasonal high water table" or soil wetness condition, as used in NC regulations governing on-site waste disposal, must be re-defined in order for this property to be verified by water table measurements. By regulation, the depth to the seasonal high water table (or soil wetness condition) must be placed at the shallowest depth where gray (chroma 2 or less) soil colors occur. Results from this study indicate that this depth is where the soil has been saturated long enough for Fe reduction to occur and create the gray colors. Saturation without Fe reduction does not create gray soil colors. For the soils of this study, the average duration of saturation required for Fe reduction was 3 weeks for depths between 15 and 60 cm. Our results showed that soil saturates above the depth at which gray colors occur, but for periods too short for gray soil colors to develop. As a result, this short-duration saturation has generally gone unrecognized. **When identified by the shallowest depth at which gray colors occur in a soil, the seasonal high water table, or soil wetness condition, is in fact the shallowest depth where the soil is saturated long enough for gray soil colors to form.**

Adapting a Drainage Model to Simulate Water Table Levels In Natural Landscapes

INTRODUCTION

Frequency and duration of soil saturation determines a soil's suitability for a variety of uses such as on-site waste disposal, and also determines whether the site is a jurisdictional wetland (Mitsch and Gosselink 1993). Soil scientists predict the shallowest depth that is seasonally saturated by looking for the shallowest depth that contains low chroma or gray colors in a soil profile (Schoeneberger et al. 1998; Vepraskas 1999). Using color to predict where seasonal saturation occurs in a soil is generally reliable in areas where hydrology has not been altered, but it does not tell us how long the water table stays at a given depth, nor do colors tell us if the water table comes to that depth every year or once every 10 years. Land-use regulations are increasingly requiring that saturation frequency and duration be evaluated (Environmental Laboratory 1987).

Long-term daily measurements of water table levels are relatively simple to make and provide reliable data on saturation frequency and duration. Due to the variability of the weather, however, a long period of monitoring is required (> 15 yr.) to make sure that the monitored water table levels represent the response to average weather conditions. Such long-term measurements of water table levels are time-consuming and too expensive to do at all sites where the information is needed. An alternative approach for assessing seasonal saturation is to use hydrologic models to estimate daily water table levels over long (e.g. 40-yr) periods. The water table data can be correlated to soil color patterns, and the colors then used to extrapolate the water data to other non-monitored sites containing similar soils. Such an approach was used by Boersma et al. (1972) and Simonson and Boersma (1972) with limited success.

Hydrologic modeling can be used to predict long-term historic water table fluctuations on a day-to-day basis for a soil (Skaggs 1999). The required input data needed for model calibration can be acquired in a short period (e.g. 6 months) and the long-term simulations using historic rainfall data can be done rapidly on a microcomputer. Once the long-term daily water table data are obtained, probability values for a specific duration of saturation can be computed for any soil depth. The major advantage of using simulation models is that the effects of annual and seasonal variability of weather can be considered in the analysis.

The hydrologic model DRAINMOD has been extensively used in the United States to analyze the long-term effects of drainage on water table fluctuations (Skaggs 1980; Skaggs et al. 1994; Fouss et al. 1987; Konyha et al. 1992). The DRAINMOD model is normally used to simulate the performance of drainage structures and related water table management systems over a long period of climatological record (e.g. 20 to 50 yr). DRAINMOD was originally developed for poorly drained agricultural fields. The model can calculate how often the soil is saturated within a given depth for a specific duration during a certain period in a year. In recent years it has been extended to the watershed scale to describe the hydrology of drained forested land (McCarthy et al. 1992; Amatya et al. 1997). Abdel-Dayem and Skaggs (1990) extended the application of DRAINMOD to arid regions. Additional versions of the model have also been developed to predict the effects of drainage on losses of N (Breve et al. 1997; Zhao et al. 2000) and on soil salinity (Kandil et al. 1993). Reliability of the DRAINMOD model has been verified in extensive field experiments on a wide range of soils, crops, and climatological conditions (Skaggs 1982; Gayle et al. 1985; Fouss et al. 1987).

DRAINMOD was developed specifically for a soil containing a network of parallel drainage ditches or subsurface drains. Many sites for which hydrologic simulations could be used for land-use assessments are not in agricultural fields and do not have parallel drain tubes or ditches. The objective of this portion of the research study was to test whether DRAINMOD could accurately simulate water table fluctuations on soils with a perimeter ditch and a site without ditches. This work was the first step of a broader investigation that related the results of the hydrologic simulations to soil color patterns.

MATERIALS AND METHODS

Experimental sites

Research was conducted at two sites in the North Carolina Coastal Plain which contained toposequences of soils that ranged from well drained to very poorly drained. The Greenville site was located in Pitt County, NC, approximately 5.1 km southwest of Greenville at N 35°34'10", and W 77°26'26". A schematic map showing the experimental area is given in **Fig. 1A**. A ditch occurred along the perimeter of a portion of the site. The ditch ranged from 1 to 2 m wide and was 0.6 to 1.5 m deep. The soil toposequence at the site consisted of soils in the following series: Goldsboro (fine-loamy, siliceous, thermic Aquic Paleudults), Lynchburg (fine-loamy, siliceous, thermic Aeric Paleaquults), Rains (fine-loamy, siliceous, thermic Typic Paleaquults) and Pantego (fine-loamy, siliceous, thermic Umbric Paleaquults).

Experiments were conducted along four transects which contained a total of 13 plots. These transects were established at increasing distances from the ditch. Each transect consisted of three or four plots along the soil toposequence that were placed to include Goldsboro (moderately well drained), Lynchburg (somewhat poorly drained) and to Rains (poorly drained) soils. Each soil contained one plot along each transect. Transect 4 contained an additional plot in the (very poorly drained) Pantego soil. These plots were labeled as: 1G, 1L, 1R, ..., 4G, 4L, 4R and 4P to represent transect and series name. The slope at the site was 2%. Vegetation consisted of loblolly pine (*Pinus taeda* L.), red maple (*Acer rubrum* L.), and white oak (*Quercus alba* L.) etc. Most of the trees were between 10 and 50 years old. Additional data on soil morphology at the site was previously reported by Hayes and Vepraskas (2000).

The second site, the Bertie site, was located in Bertie County, NC at N 76°48'00", and W 36°5'30". A schematic map of the experimental area is shown in **Fig. 1B**. The soil toposequence consisted of soils in the following series: Noboco (fine-loamy, siliceous, thermic Typic Paleudults), Goldsboro (fine-loamy, siliceous, thermic Aquic Paleudults), Lenoir (clayey, mixed, thermic Aeric Paleaquults), and Leaf (clayey, mixed, thermic Typic Albaquults).

The experiment was conducted along two transects, labeled North (N) and South (S), and each transect contained five plots. There was only one plot in the Noboco soil. Plots were labeled as 1, 2N, 3N, 4N, 5N, 2S, 3S, 4S, 5S to represent the soil series (1-Noboco, 2-Goldsboro, 3-Lenoir, 4,5-Leaf) and transect. Vegetation consisted of loblolly pine (*Pinus taeda* L.), red maple (*Acer rubrum* L.), sweet bay (*Magnolia virginiana* L.), white oak (*Quercus alba* L.), red oak (*Quercus borealis* L.), and black cherry (*Padus serotina* L.). No drainage ditches were present at this site.

Water table levels were monitored daily to depths of 2-m at 12:00 AM in each of the 22 plots at the two experimental sites using RDS automatic monitoring wells (Remote Data Systems, Inc. P.O. Box 2522, Wilmington, NC 28402). The water table data were collected from November 1996 until March 1999 at the Greenville site and from December 1996 to October 2000 at the Bertie site.

Wells were installed by augering a 10-cm diameter hole to a depth of 2.25m, inserting the well, and filling in the space between the well screen and soil with sand. A 3-cm thick layer of dry bentonite pellets was then placed on the top of the sand to seal the well from surface water inflow. A conical mound of soil was placed over the bentonite to keep rainfall away from the well.

To ensure that the recording wells were monitoring daily water levels accurately, a manual check well was installed at each plot to a depth of approximately 127 cm below the mineral soil surface. Every two to three weeks, water levels in the check wells were measured to compare with the water table data from RDS wells. Rainfall was also measured daily at each site using recording gauges.

Pits were dug in each plot to a depth of 1 m, and major soil horizons were identified. Undisturbed cores (7.6 cm in diam. by 7.6 cm in height) were collected in each soil horizon except the O horizon (organic layer) by using a Uhland core sampler (Uhland 1950). Soil water characteristics were determined for each undisturbed core using the standard pressure plate method (Klute 1986; Richards and Weaver 1943). Vertical saturated hydraulic conductivity was measured on each undisturbed core using the constant head method (Klute and Dirksen 1986) after the measurements of soil water characteristic were completed for pressure levels >-500 cm. Lateral saturated hydraulic conductivity was measured in the field for each layer at each plot using the Compact Constant Head Permeameter (Amoozegar and Warrick 1986). Soil samples were collected from each plot in 15 cm-depth increments to a depth of 225 cm. The samples were then air-dried, and ground to pass through a 2-mm-mesh sieve. Particle size distribution was determined using the hydrometer method (Gee and Bauder 1986). The position and elevation of each plot in the two experimental sites was determined with a surveyor's transit.

DRAINMOD Description

DRAINMOD is a hydrologic model that simulates water table levels in a soil plot over time from input data consisting of precipitation, evapotranspiration, infiltration, runoff, and subsurface drainage (Skaggs 1999). DRAINMOD was developed specifically for soils with shallow water

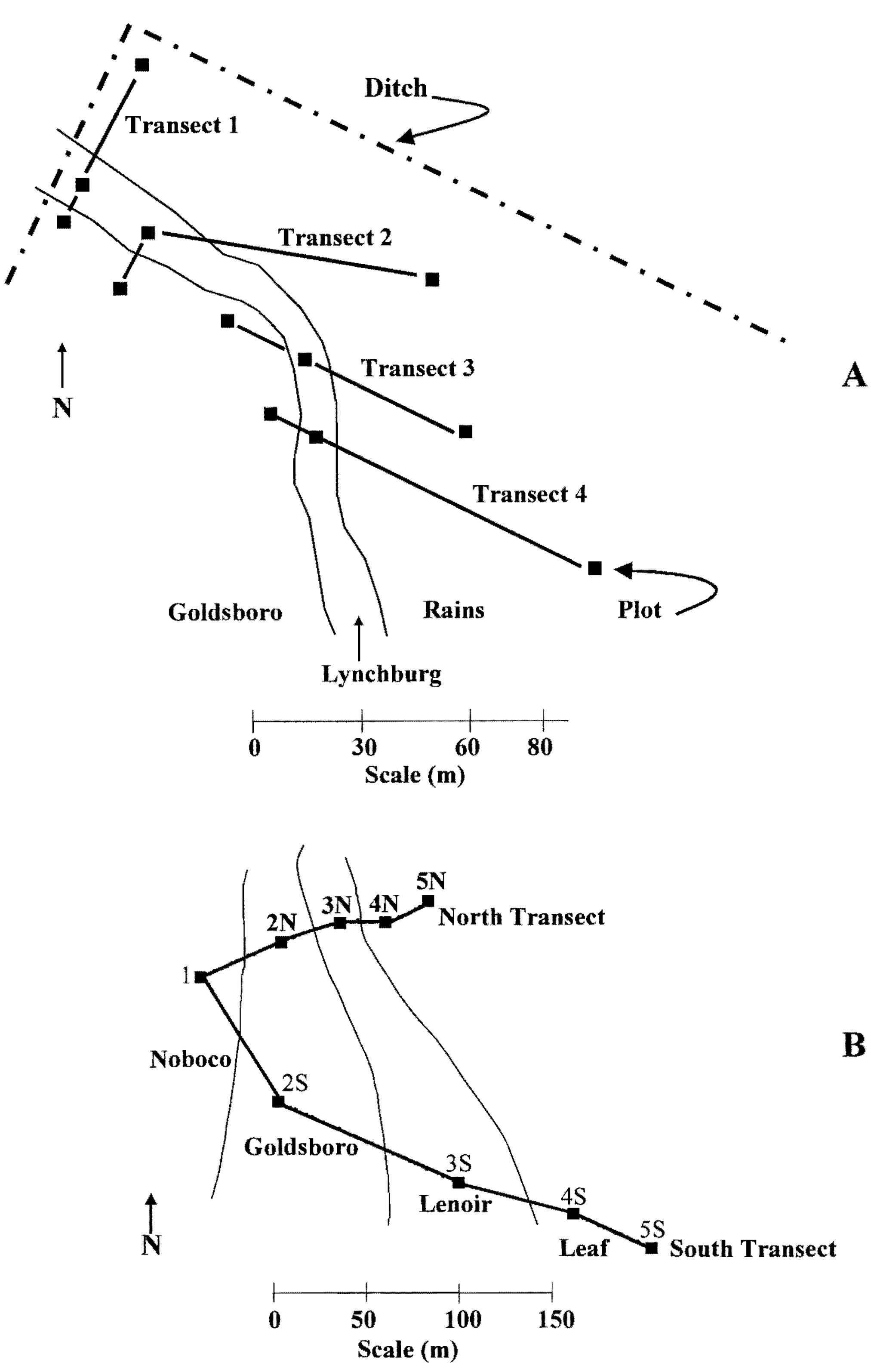

Figure 1. Schematic maps of the Greenville (A) and Bertie sites (B). Soil series boundaries are shown across the transects.

tables and parallel drains that occur on flat landscapes. The model computes a water balance on a soil pedon of unit cross-sectional area. A water balance is determined on a day-by-day, hour-by-hour basis and a water table depth is computed for each time step.

The water balance for a time increment Δt can be written as (Skaggs 1999):

$$\Delta Va = D + ET + DS - I \qquad 1$$

where ΔVa is change of water free pore space or air volume (cm), D is drainage (or subirrigation) from the soil profile (cm), ET is evapotranspiration (cm), DS is deep seepage (cm), and I was infiltration entering the soil profile(cm). A water balance is also computed at the soil surface for each time increment using:

$$P = I + \Delta S + RO \qquad 2$$

where P = precipitation (cm), I = infiltration (cm), ΔS = change in volume of water stored on the surface (cm), RO = surface runoff (cm).

The components for equations 1 and 2 are illustrated in **Fig. 2** for a soil plot like those studied here. The plot has a unit cross-sectional area and extends from the soil surface to the top of a restrictive layer. Precipitation falling on the plot surface collects in shallow depressions and then infiltrates the soil. Once the storage capacity of the depressions is filled, remaining precipitation leaves the plot area by surface runoff. Water that infiltrates moves through an unsaturated zone to the water table. Below the water table the water drains from the plot by lateral movement or vertically downward through a restrictive layer. The depth to the water table is related to the thickness of the unsaturated zone which is expressed as Va in this illustration. Each plot is considered in isolation, and water draining from a plot is assumed to be lost from the landscape and does not directly affect another plot. The components shown in **Fig. 2** apply to any soil plot whether it is drained by ditches or not.

The subsurface drainage rate of water that leaves the pedon below the water table is computed by DRAINMOD in one of two ways depending on whether the surface is ponded with water or not. For the more typical non-ponded conditions, the subsurface drainage rate is computed using the steady-state Hooghoudt equation (Bouwer and van Schlifgaarde 1963). It is assumed that the water table is an elliptically shaped plane between parallel drains and that most drainage occurs below the water table by water moving laterally toward the drains (**Fig. 3**). The soil plot occurs midway between drains where the water table is virtually flat. The Hooghoudt equation may be written as:

$$q = \frac{8Kd_e m + 4Km^2}{L^2} \qquad 3$$

where q is drainage rate (cm/h), d_e is the effective depth of the restrictive layer below the drain (cm), m is the water table height above the drain (cm) in the soil plot which was located at a point midway between ditches, K is effective lateral hydraulic conductivity (cm/h), and L is distance between drains (cm).

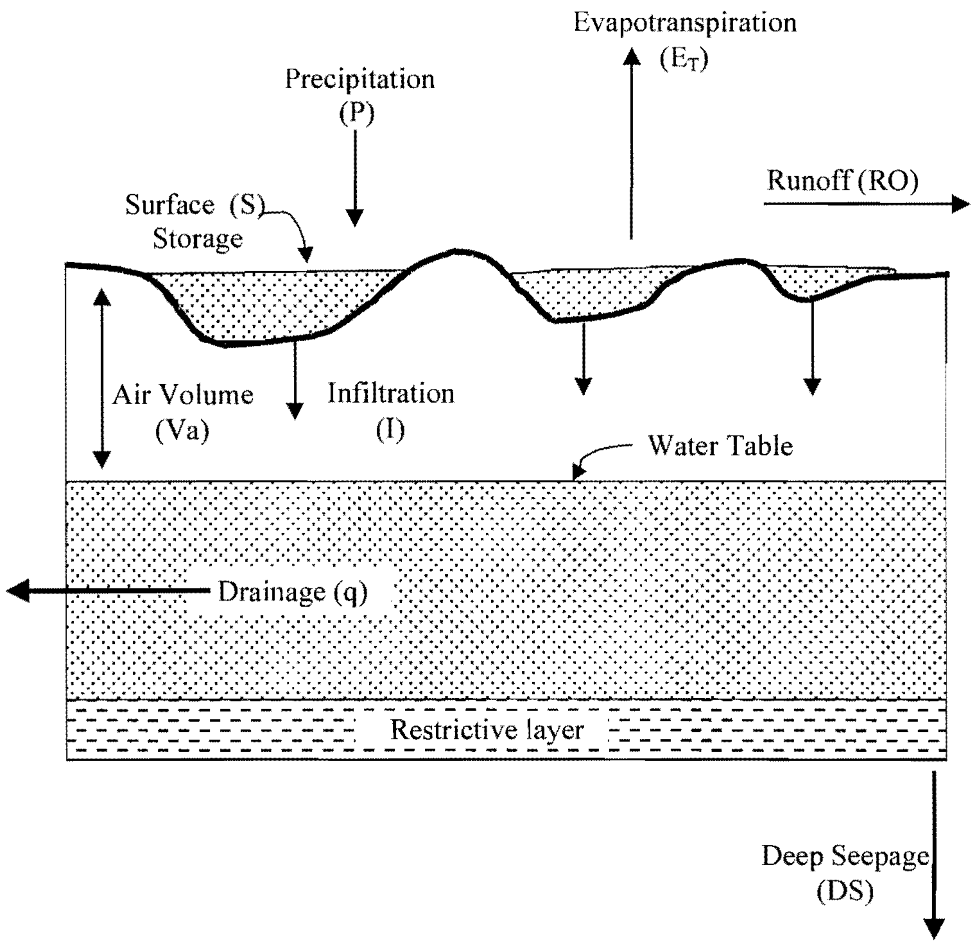

Figure 2. Schematic diagram showing the principal components of input and outputs of water used in the DRAINMOD model.

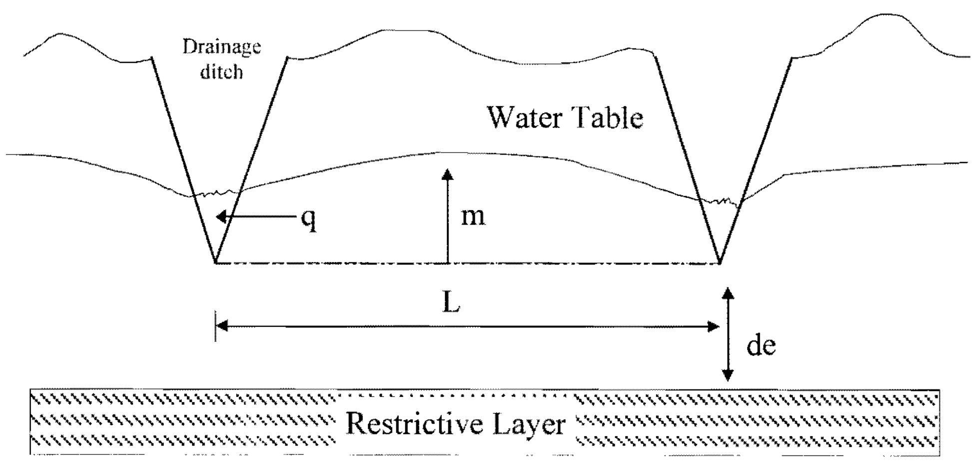

Figure 3. Principal components used for the Houghoudt equation in DRAINMOD which include: de - effective depth of restrictive layer below drain; L - distance between drains; m - height of water table above drain midway between drains; and q - drainage rate.

During large storms or long continuous wet periods the water table may rise to the surface. In such cases the water table does not have the elliptical shape assumed in Hooghoudt equation, and an equation developed by Kirkham (1957) is used in DRAINMOD to quantify drainage. This is a relatively rare case that won't be discussed further.

Climatic inputs for the model include hourly values for precipitation and daily potential evapo-transpiration (PET). Direct PET input data were not available at either of the two study sites. The Thornthwaite (1948) method was used to calculate PET in this study. Daily maximum and minimum temperature data were obtained from the nearest available weather station. The monthly correction factors for PET used in the model were obtained from Workman et al. (1994). Because the vegetation at two experimental sites was forest, rooting depth was the only plant factor considered. Rooting depth was determined from soil pits dug in each plot.

Soil property inputs include soil water characteristic of the A horizon and saturated hydraulic conductivity of soil horizons from the surface to the top of the restrictive layer. Infiltration is calculated by the Green-Ampt equation (Green and Ampt 1911):

$$f = A / F + B \qquad 4$$

where f is infiltration rate (cm/h), F is cumulative infiltration (cm), A and B are parameters that depend on soil properties. The relationship of parameters A and B with water table depth were calculated in this application using the soil preparation program within DRAINMOD.

Surface storage capacity was characterized by the average depth of depression storage which must be satisfied before runoff can begin. Depression storage parameters are generally estimated visually in the field according to the topography. In most cases it is assumed that depression storage is evenly distributed over the field. Depression storage parameters <0.5 cm indicate little ponding of water occurs because the surface is relatively smooth. Areas with some depressions where water ponds after rains have depression storage values between 1 and 1.5 cm, while areas with many depressions causing widespread ponding of water after heavy rains have depression storage values >2 cm.

Model Calibration

The DRAINMOD model was calibrated separately for each experimental plot using a short-term record of observed weather data and water table measurements. Predicted and monitored water table fluctuations were compared and then selected model parameters were adjusted to bring predicted values in line with measured ones. The agreement between monitored and predicted daily water table depths was quantified by both the absolute deviation (α) for the observed period defined as follows:

$$\alpha = \frac{\sum \left| Y_m - Y_p \right|}{n} \qquad 5$$

where n was number of days in observed period, Y_m was monitored water table depth at the end of each day (cm), and Y_p was corresponding predicted water table depth (cm).

ASSUMPTIONS

This research was based on three assumptions that were made for the experimental sites and tested as part of the work:

1. Water table levels can be predicted for individual soil plots in a landscape by treating each plot in isolation. Each plot is calibrated separately from the other plots.

2. Subsurface drainage rates can be approximated in natural landscapes by using the Hooghoudt equation which uses drain spacing and depth as well as depth to a restrictive layer to compute a drainage flux. The drainage system used for calibration in this case is a virtual one.

3. Deep seepage losses are virtually zero, or so small that they can be included with losses by subsurface drainage.

These assumptions may not apply to other landscapes.

RESULTS AND DISCUSSION

Soil Properties

The particle size distribution data for selected plots at both sites are given in **Table 1** to show the range of textures found in the soils. Soils at the Greenville site tended to be sandier than those at the Bertie site. The saturated water content ranged from 0.31 to 0.43 cm^3/cm^3 at the Greenville site, and from 0.32 to 0.46 cm^3/cm^3 at the Bertie site (data not shown). Lateral saturated hydraulic conductivity (K) values are shown in **Table 2** for representative plots at both sites. The K values decreased with depth and were similar among the sites for comparable depths. The data used to initialize the DRAINMOD program for each plot included the K values and soil water characteristic. Crop inputs included the rooting depth that was determined for each plot from observations made in pits.

Calibrating DRAINMOD to account for drainage rate

Water table levels were monitored at the Greenville site from November 1996 to March 1999, and from December 1996 to June 2000 at the Bertie site. At the Bertie site rainfall data prior to December 1999 were incomplete due to malfunctions of the gauge during a hurricane and to a bird nesting in the gauge during another period. The monitored rainfall and well data from January 2000 to June 2000 were selected to calibrate the model. DRAINMOD was calibrated for each plot in order to simulate these measured daily water level values.

Table 1. Particle size distribution data for two plots that contained Goldsboro soils at the Greenville and Bertie sites.

Horizon	Depth	Sand	Silt	Clay	Textural class
	cm		%		
			Plot 1G – Greenville Site		
A	0-12	62	28	11	Sandy loam
E	12-18	61	22	17	"
Bt1	18-48	54	16	29	Sandy clay loam
Bt2	48-66	59	11	30	"
Bt3	66-84	54	11	34	"
Bt4	84+	57	12	31	"
			Plot 2N – Bertie Site		
A	0-15	35	58	7	Silt loam
E	15-29	34	55	11	"
Bt1	29-47	31	56	13	"
Bt2	47-67	22	53	24	"
Bt3	67-90+	23	54	23	"

Table 2. Lateral saturated hydraulic conductivity of two transects at each site.

Soil Series	Plot	Depth	Hydraulic conductivity	Soil Series	Plot	Depth	Hydraulic conductivity
		cm	cm/hr			cm	cm/hr
	Greenville Site				Bertie Site		
Goldsboro				Goldsboro		17	3.38
		25	1.43			36	1.77
	4G	81	0.08		2S	87	0.16
		132	0.01			157	0.04
Lynchburg				Lenoir		18	5.45
		24	6.65			35	1.34
	4L	79	0.23		3S	87	0.21
		115	0.02			150	0.02
Rains				Leaf		19	9.3
		27	2.00			33	2.86
	4R	76	0.11		4S	84	0.06
		220	0.02			154	0.01
Pantego		24	29.38	Leaf		19	0.98
	4P	80	0.11		5S	26	0.03
		120	0.02			154	0.02

Subsurface drainage rate has a major influence on water table levels and the calibration process began by setting this variable for each plot. Drainage rate (q in equation 3) is very sensitive to drain spacing (L) as shown in **Fig. 4**. As drain spacing increases, the drainage rate decreases for a given water table depth. For the plots considered here, the drainage rate varied with a plot's position on the slope. Plots at higher elevations had deeper water tables and drained faster than those at lower elevations which had higher water table levels. Rather than rewriting the drainage algorithm in DRAINMOD, we used the Hooghoudt equation with drain spacing and depth as calibration parameters. The drain spacing was adjusted by trial and error for each plot to minimize the average absolute deviations between measured and predicted water table levels. For these adjustments a drain depth of 65 cm was assumed because this was the average depth of the perimeter ditch at the site.

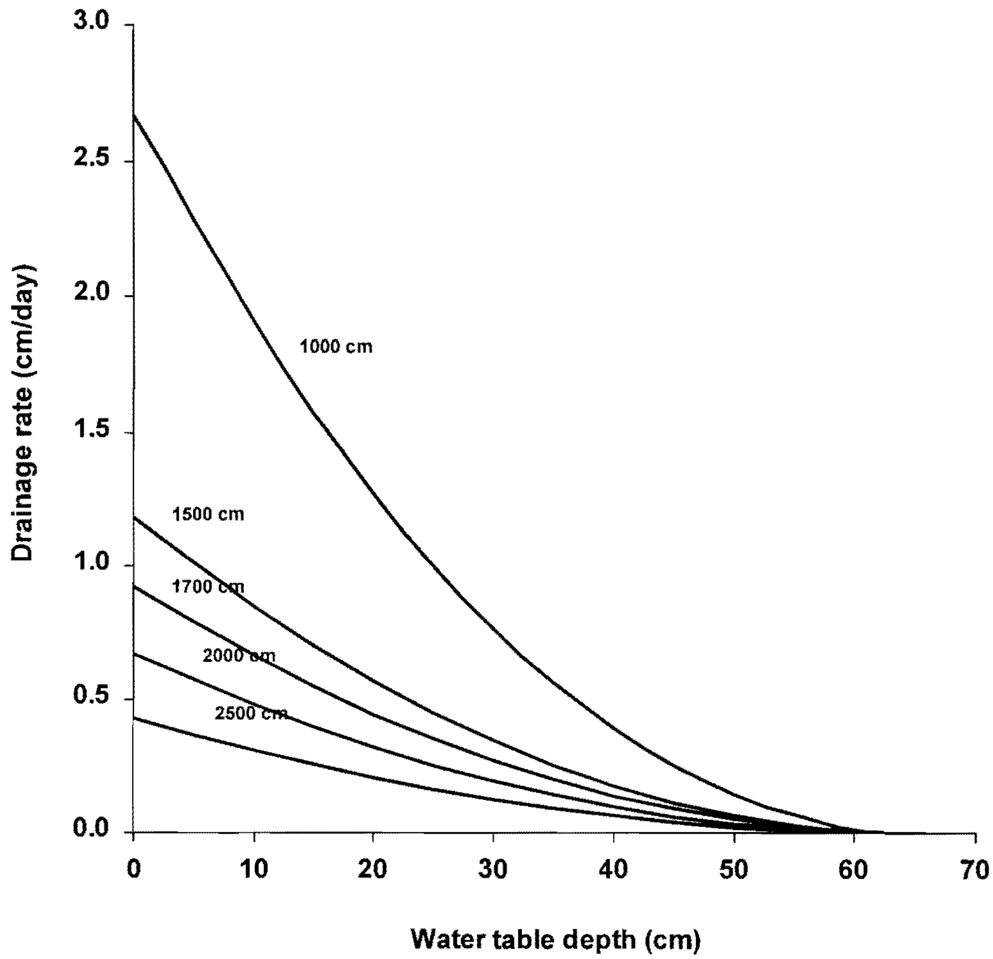

Figure 4. Schematic relationship of drainage rate vs. water table depth as affected by different drain spacing for a drain depth of 65 cm.

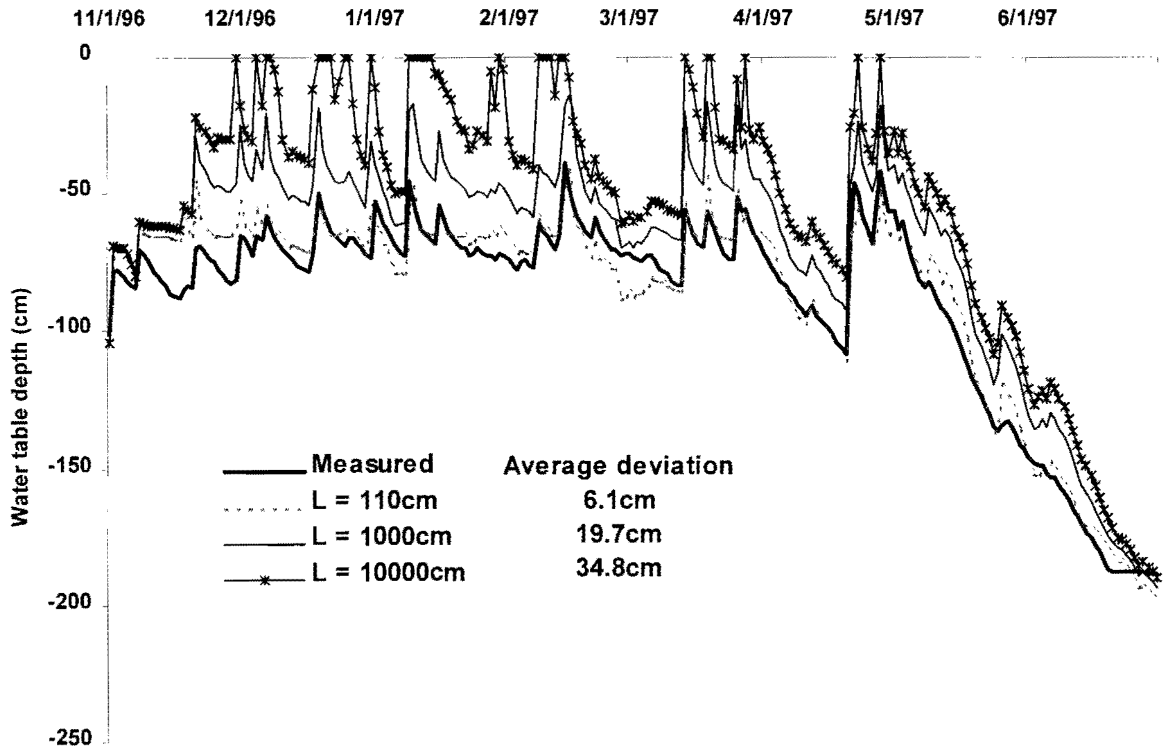

Figure 5. Effect of different drain spacings (L) on water table fluctuations at plot 2G.

Figure 5 shows the effect that changes to drain spacing (L) had on bringing simulated water table levels into agreement with measured values for the period November 1996 to July 1997 for plot 2G at the Greenville site. The optimum value for L in this plot was found to be 110 cm. As L increased the drainage rate decreased and the predicted water table level rose closer to the surface. Plots in Lynchburg and Rains soils were at lower elevations than the Goldsboro plots, and needed smaller drainage rates. Larger values of L were used for plots in these soils, and optimum values were found to be about 1700 cm for Lynchburg plots and about 4000 cm for Rains plots. The final drain spacing parameters for all plots are given in **Table 3**. There were differences in drain spacing for some plots found in the same soil series because small elevation differences and location on the landscape among plots affected drainage rates (**Fig. 6**). The effect of elevation differences on spacing parameter values can be seen by comparing elevation and L values of plot 2R to those of plot 1R at the Greenville site. Plot 2R required a larger drain spacing than plot 1R because its lower elevation caused its natural drainage rate to be lower. While the ditches used in this calibration process were virtual ones, they had the same effect on the water table fluctuations as are found for hydraulic gradient in Darcy's law. Deep, closely spaced ditches simulate a large hydraulic gradient that increases the drainage of water from the plot as would be found in a moderately well-drained soil. Conversely, widely spaced ditches simulated small hydraulic gradients which then slowed the rate of drainage of water from the plot as would be found in a poorly drained soil.

Table 3. Calibrated drainage input parameters for the Greenville and Bertie sites. These parameters were obtained by calibration to represent the relationship between net drainage flux and water table depth for each plot.

Soil series	Plot	Drain depth parameter	Drain spacing parameter	Equivalent depth to restrictive layer	Depressional surface storage
		------------------------cm------------------------			
			Greenville Site		
Goldsboro	1G	65	100	160	0.1
"	2G	65	110	170	0.1
"	3G	65	100	180	0.1
"	4G	65	100	180	0.1
Lynchburg	1L	65	800	180	1.0
"	2L	65	1700	220	1.0
"	3L	65	1700	165	1.0
"	4L	65	1700	180	1.0
Rains	1R	65	3100	180	1.5
"	2R	65	4000	170	2.0
"	3R	65	4300	180	2.0
"	4R	65	3200	220	1.5
Pantego	4P	65	6000	120	5.0
			Bertie Site		
Goldsboro	2N	100	800	250	0.5
"	2S	100	600	250	0.5
Lenoir	3N	50	1800	150	1.0
"	3S	50	1300	150	1.0
Leaf	4N	50	900	250	1.5
"	4S	50	3000	150	1.5
"	5N	50	1400	150	2.0
"	5S	50	2000	150	2.0

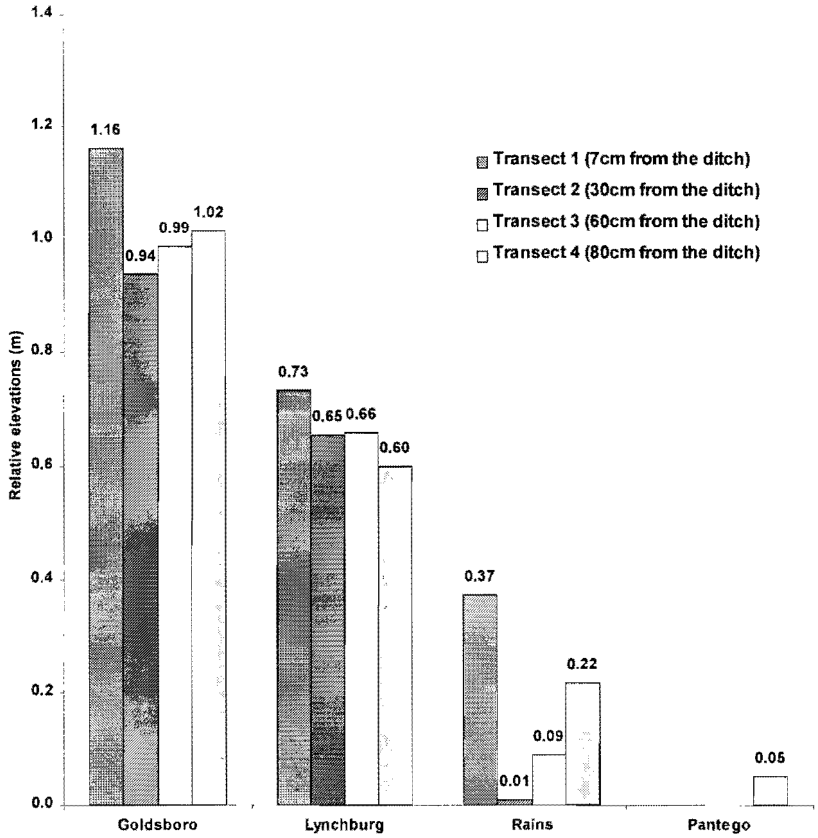

Figure 6. Relative elevations of different soils with different distances from the ditch in the Greenville site.

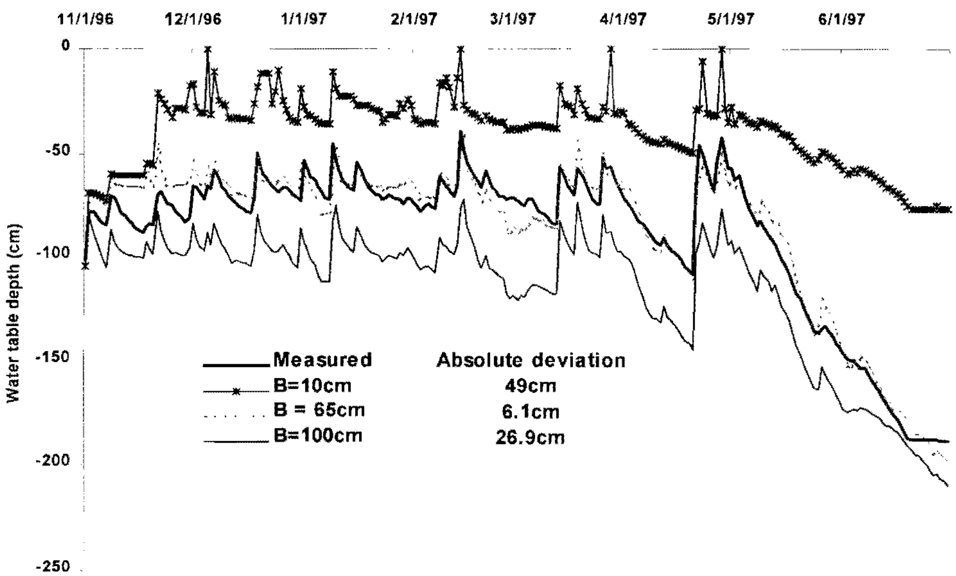

Figure 7. Effect of different ditch depths on water table fluctuations in plot 2G at the Greenville site.

Once optimum spacing parameter values were determined, drain depth was the next parameter adjusted for each plot. The effect of different values for the drain depth parameter on the predicted water table levels is shown in **Fig. 7**. The predicted water table is raised with decreased drain depth. The average absolute deviations for drain depths of 10 cm, 65 cm, and 100 cm were 49 cm, 6.1 cm and 26.9 cm, respectively. A drain depth of 65 cm was found to be optimum for all plots at the Greenville site. As shown in **Table 3**, drain depths ranged from 50 to 100 cm at the Bertie site.

The parameter representing the equivalent depth to the restrictive layer in the Hooghoudt equation also needed to be adjusted to compute drainage rate. This parameter mainly affected the predicted water table level during the dry season (**Fig. 8**). The shallower the restrictive layer, the higher the predicted water table will be during the dry season. The K measurements suggested the restrictive layer would occur between 1 to 2 m for most plots but no clear depth could be identified in any plot where the K_{sat} values abruptly decreased. However, equation 3 requires that a specific depth be used in the model where a restrictive layer "effectively begins." The actual values of this parameter for all the plots were determined by trial and error and ranged between 120 and 250 cm for both sites (**Table 3**). The restrictive layer occurred in layers whose measured saturated K values were between 0.01 and 0.02 cm/hr.

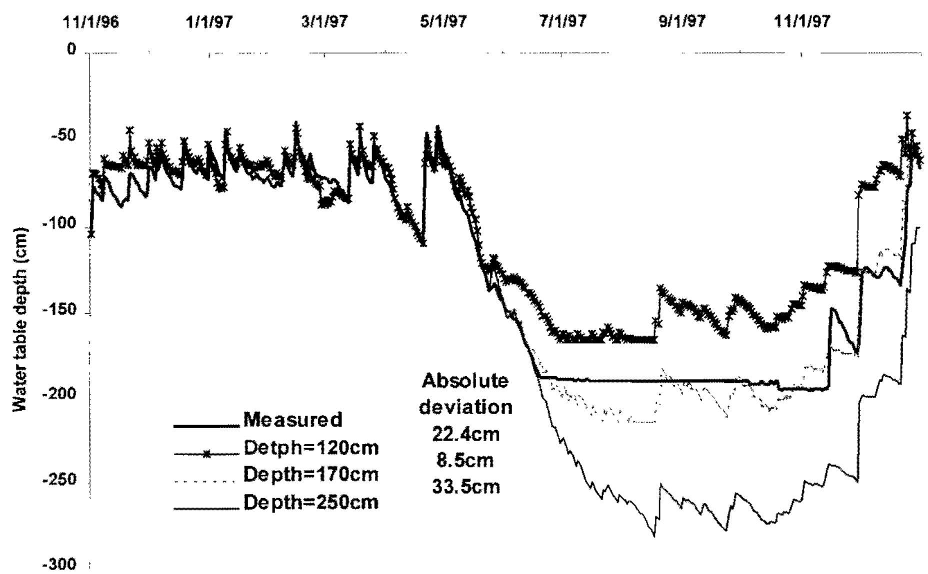

Figure 8. Effect of different depths to impermeable layer on water table fluctuations in plot 2G at the Greenville site.

Calibrating DRAINMOD for depressional storage, drainable porosity, and ET

Depressional storage is another DRAINMOD input parameter that affects water table depths following longer rainfall events. This parameter is important for sites where the water table frequently rises to the soil surface. It has a minor effect for sites having deeper water tables. Depressional storage values represent the average depths of pocket-like depressions on the surface that hold water. Runoff occurs after depressional storage sites are filled. Values of the surface depressional storage were selected to optimize agreement between predicted and measured water table depths. As shown in **Table 3**, depressional storage values were lowest in the upland areas and increased as soils became more poorly drained. The highest depressional storage value of 5 cm was found for the Pantego plot (4P) at the Greenville site. The plot was in a depression that had a hummocky surface. The hummocks may have been created as tree-throw mounds which developed after a tree was overturned and its trunk and upturned root mass decomposed.

During high water table seasons (from November to March), simulated and measured water tables in some plots of Goldsboro and Lynchburg soils at the Greenville site showed good agreement between measured and simulated water table levels (data not shown). However, other wetter plots showed much greater fluctuations in the predicted water table levels than in the measured values, particularly where the water table was within 20 cm of the surface as illustrated in **Fig. 9A** for plot 2R of the Greenville site. The cause of this great variability was improper selection of drainable porosity values for the O horizons.

The relationship between drained volume, or water-free pore space (cm), and water table depth is a DRAINMOD input. This relationship was calculated from the soil water characteristics for all the soil horizons except the O horizons. Drainable porosity is defined as the volume of water drained from the soil plot for each unit change of the water table depth. The drainable porosity of the upper 20 cm at plot 2R as calculated from the soil water characteristics ranged from 0.001 to 0.01 cm/cm. However, the O horizon (organic soil material) in the plot was 20 cm thick and consisted of partially decomposed leaves, twigs, and roots that made the horizon very porous. It had a much higher drainable porosity than the mineral soil beneath it. Thus, when the relationship between drainage volume and water table depth was based solely on soil water characteristics of the mineral soil (ignoring the O horizon), the predicted water table fluctuated rapidly with the addition (by precipitation) or removal (by drainage and ET) of water either to or from the soil plot. In the drier plots, e.g. 1L of the Greenville site, the water table rarely came within the O horizon and consequently the high drainable porosity of the organic layer did not affect predicted water table fluctuations. The drainable porosity of the horizon at a depth of 0 to 20 cm was adjusted to be 0.2 cm/cm in DRAINMOD. The effect of this change on water table fluctuation is illustrated in **Fig. 9B**.

The last parameter adjusted was the ET factor. Large differences between predicted and measured water tables were also found in a few months such as March and April (**Fig. 9B**). The correction factor for ET was adjusted to improve the simulation in these months (**Fig. 10**). The ET correction factors for selected plots are shown for all months in **Table 4** to illustrate the range in values found.

Evaluation of the adjusted DRAINMOD models

A summary of the average deviations for individual plots at the two experimental sites is presented separately in **Table 5**. The water table fluctuations within 100 cm of the surface were of

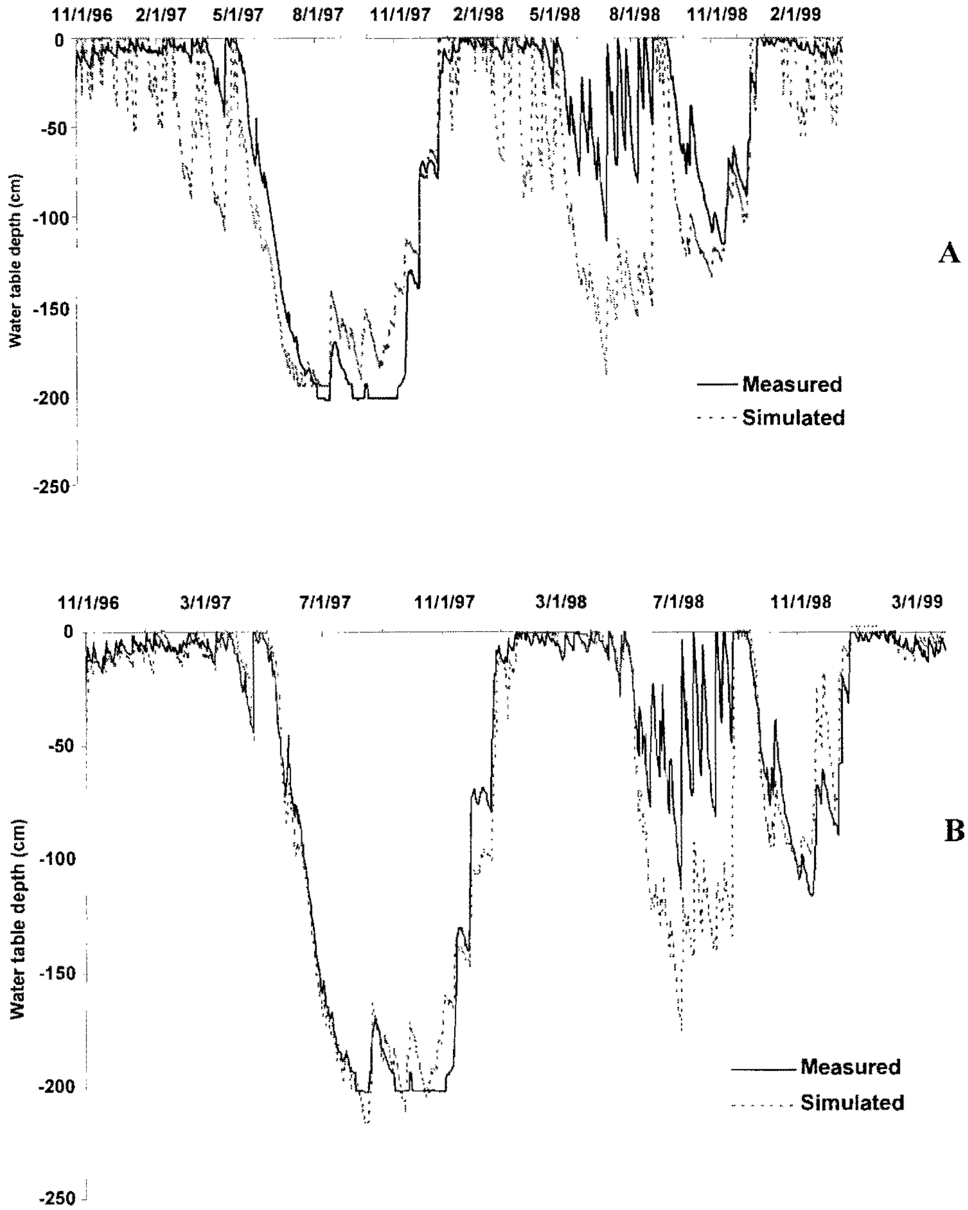

Figure 9. Comparison of the simulated and measured water table fluctuations at plot 2R of the Greenville site illustrating the effects of drainable porosity on degree of fluctuations.
A: Simulated water levels show a high degree of fluctuation during the period of November 1996 to May 1997 because drainable porosity within 20 cm of the surface was assumed to be low.
B: Fluctuation has been reduced as drainable porosity was increased to account for a porous O horizon.

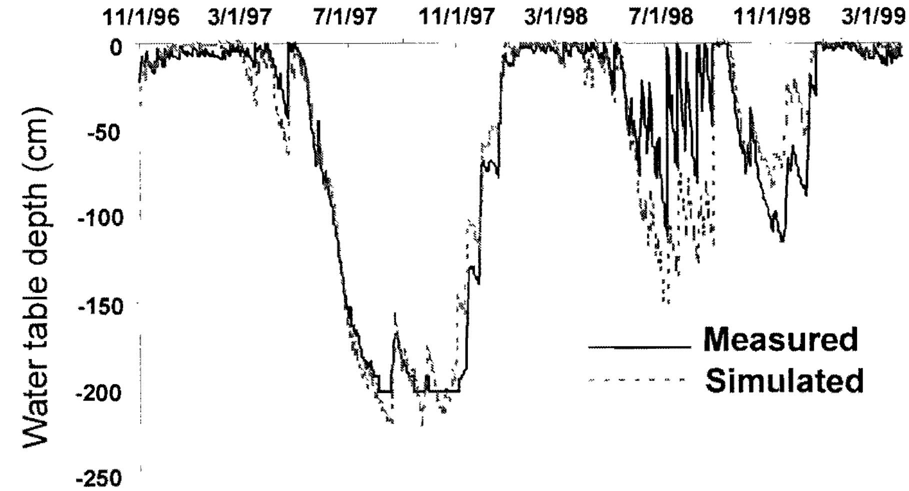

Figure 10. Water table fluctuations with adjusted ET at plot 2R.

Table 4. A summary of monthly correction factor for ET calculation in DRAINMOD for selected plots at both sites.

Plot	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
						cm						
						Greenville site						
1G	2.01	2.32	0.6	1.3	1.23	1	0.86	0.82	0.92	1.05	1.22	1.44
1L	2.01	2.32	0.7	1.4	1.23	1	0.86	0.82	0.92	1.05	1.22	1.44
1R	2.01	2.32	0.3	1.1	1.23	1	0.86	0.82	0.92	1.05	1.22	1.44
						Bertie site						
4N	2.01	2.32	2.1	1.72	1.23	1	0.86	0.82	0.92	1.05	1.22	1.44
4S	2.01	2.32	2.1	1.72	1.23	1.6	0.86	0.82	0.92	1.05	1.22	1.44
5N	2.01	2.32	2.1	1.72	1.23	1.25	0.86	0.82	0.92	1.05	1.22	1.44
5S	2.01	2.32	2.1	1.72	1.23	1.2	0.86	0.82	0.92	1.05	1.22	1.44

Table 5. A summary of average absolute deviations (α) used for comparison of observed water table fluctuations with predictions by DRAINMOD for the Greenville site and Bertie sites.

Plot	November 1996 to March 1999	November 1996 to April 1997	November 1997 to April 1998	November 1998 to March 1999
---cm---				
		Greenville site		
1G	13.9	8.5	12.5	16.5
1L	12.5	6.5	6.3	15.7
1R	15.1	5.6	15.9	9.2
2G	14.2	6.6	8.5	15.8
2L	13.7	4.7	11.1	18.5
2R	15.1	3.7	9.5	9.1
3G	15.4	9.0	7.2	24.6
3L	14.1	6.0	8.3	18.4
3R	15.1	3.5	10.5	10.6
4G	15.6	7.6	9.6	23.4
4L	13.5	5.6	8.5	no data
4R	16.9	4.3	8.2	11.9
		Bertie site		
	January to June 1999	January to June 2000		
2N	22.5	8.4		
3N	21.9	7.2		
4N	15.9	11.9		
5N	13.1	7.9		
2S	no data	7.6		
3S	16.8	7.3		
4S	16.2	8.0		
5S	no data	10.9		

greatest interest in this study. During the wet season from November to April, the predicted and observed water table depths for most plots at the Greenville site were in good agreement with the average deviations ranging from approximately 3 cm to 25 cm. The agreement between predicted and observed values at all plots was particularly good during the period of November 1996 to April 1997 and the period of November 1997 to April 1998. The average deviations for most plots were less than 10 cm from November 1996 to April 1997. During the next wet season (1997-1998), the average deviations were less than 15 cm for most plots. Although agreement between predicted and observed results was not as close as at the other plots, it is still satisfactory considering the complexity of drainage processes and the variability of field conditions. Because the wells did not measure water tables below a depth of 2 m during the dry season, the average deviations for this period were not considered in the evaluation of simulation results.

At the Bertie site, rainfall data were not measured for as long as at the Greenville site and were also not as complete as at the Greenville site. Fortunately, we did have reliable data during the wet season from January to June of 2000. Average deviations varied from 7.2 cm to 11.9 cm. The simulated water table agreed very well with monitored values. The prediction models calibrated with the 2000 data were also compared to the measured data from Jan. to Jun of 1999, which were not available at 2S and 5S. Agreement between observed and predicted results were considered satisfactory for this period.

CONCLUSIONS

DRAINMOD was tested for its ability to simulate water table levels at two experimental sites in the NC Coastal Plain. The model was developed for fields that contain a network of parallel drains, but neither site in this study satisfied the requirement for the application of DRAINMOD. Model simulations were accurate among the 21 plots evaluated at two sites. The successful application of DRAINMOD to these sites showed that our three assumptions were justified. DRAINMOD has to be calibrated to accurately simulate water table fluctuations in a landscape consisting of isolated soil plots. Subsurface drainage rates were approximated using the Hooghoudt equation which uses drain spacing and depth as well as depth to a restrictive layer to compute a drainage flux. Deep seepage losses were either zero or included with losses by subsurface drainage. Estimates of hydraulic head gradients used in Darcy's Law were not necessary for water table simulation in these relatively flat Coastal Plain toposequences. Drain spacing and depth could be used as substitutes for hydraulic head gradients. However, we do not know whether DRAINMOD can be applied successfully to more steeply sloping landscapes.

Porous organic layers were found to have large effects on water table fluctuations in the plots where water tables came to the surface. The large drainable porosity of such layers must be accounted for to minimize water table fluctuations near the surface. Because most agricultural fields do not have such layers, their effect has been overlooked in earlier applications of this model.

Parameter adjustments must be used to improve model predictions and are justified because measured inputs always include some errors. Workman and Skaggs (1989) stated that errors caused by the limitations of the accuracy of the required inputs in DRAINMOD appear to be more important than errors due to the approximations in the model. Calibrating the model exposes the problems in the measured data inputs and so improves the accuracy of the final prediction. Once a calibrated model is available, long-term water table levels can be computed using historic rainfall data in order to determine the probability that a site will be saturated at selected depths.

A Method to Predict Soil Saturation Frequency and Duration from Soil Color

INTRODUCTION

Soil color patterns that include low chroma or gray colors are commonly used to predict where seasonal saturation occurs in soils (Daniels et al. 1971; Bouma 1983; Pickering and Veneman 1984; Buol and Rebertus 1988; Veneman et al. 1998). This works because the low chroma colors increase in abundance the longer a soil is saturated and chemically reduced (Vepraskas 1999). Daniels et al. (1971) used a statistical model to compute water table levels in a toposequence of Paleudults and Paleaquults that summarized water levels during an average year. Data were collected for a 2-year period. They noted that as soils became saturated for longer periods the chroma of the Bt horizons decreased. Horizons containing colors with chromas of 2 or less and values of 4 or more were saturated from 10 to 50% of the year. Simonson and Boersma (1972) related faint and distinct mottling with average durations of saturation that were estimated for a 29-year period. The studies of Daniels et al. (1971) and Simonson and Boersma (1972) were original, but they did not define a simple relationship between saturation frequency and redoximorphic feature abundance. As a result, it has been difficult to extrapolate their saturation data to other sites in order to make specific interpretations regarding saturation frequency or duration.

Some land-use regulations require that frequency and duration of saturated conditions be determined in order to assess a soil's suitability for a given use. For example, jurisdictional wetlands must meet the requirements for wetland hydrology which requires that an area be saturated to the surface for at least 5% of the growing season with a frequency of at least 5 years out of 10 (Environmental Laboratory 1987). On-site wetland inspections to determine whether a site meets the wetland hydrology requirement must be completed in about 1 hr. There is currently no technology known to the authors that would enable a field scientist to determine whether a site actually meets the saturation frequency and duration requirements for wetland hydrology requirement during a single site visit.

We hypothesized that rapid assessment of a soil's frequency of saturation for specific durations might be accomplished if the soil color patterns (redoximorphic features) were calibrated to these hydrologic parameters. This requires that a hydrologic model first be calibrated on-site to simulate water table levels using rainfall as the major input variable. Once the model is calibrated for a specific soil, long-term (i.e. 40 yr.) rainfall data could then be read into the model to compute saturation durations and frequencies for each depth in the soil. By correlating the historic data on saturation with the percentages of redoxmorphic features in the soil, it should be possible to calibrate the percentages of redoximorphic features to specific saturation durations and frequencies. If the statistical analyses are successful, then we might be able to predict for example that a soil having 40% redox depletions at a depth of 60 cm is saturated for at least 21 consecutive days in 8 out of 10 years. Once the redoximorphic features of one soil have been calibrated in this way, they then can be used to predict saturation frequency and duration in similar soils where water table levels have not been measured. Vepraskas (2000) reported on a pilot study where this approach was successfully applied to three soil plots.

This study was conducted to determine the relationship between the percentage of redoximorphic features and a frequency and duration of saturation for a toposequence of soils. The specific objectives were: 1) to use a hydrologic model to compute a 40-yr record of water table fluctuations for a toposequence of soils; 2) to develop a technique that indexes the water level data to summarize saturation freuqency for each soil in the toposequence; and 3) to correlate percentages of redox depletions and concentrations with the saturation index values for a certain duration of saturation.

MATERIALS AND METHODS

Soil profile descriptions

Soil profiles were described from pits (1.5 m x 1.5 m x 1.0 m) placed in each plot at the Greenville site **(Fig. 1)**. Each pit was approximately 10 m from the water monitoring instruments to avoid interference with a plot's hydrology. The soils were described to approximately 100 cm below the soil surface. Some data were reported earlier by Hayes and Vepraskas (2000). Soil morphological features were estimated using standard field methods (Schoeneberger et al. 1998). The abundance and size of redoximorphic features were estimated visually by comparing the features with proportion charts by two people separately. These visual estimations were made by the same two individuals in all pits to minimize variability. The results from both describers were averaged for each depth in each profile.

Redox potentials and soil pH

Five platinum electrodes were inserted at depths of 15, 30, and 60 cm in each plot to measure oxidation-reduction (redox) potential. Detailed construction of these electrodes was given by Hayes (1998). Field voltage was measured weekly at each depth in each plot using an Accumet 1002 pH/mV meter from the Fisher Scientific Co. (Pittsburgh, PA) and a Ag/AgCl, saturated KCl reference electrode from Jensen Instruments (Tacoma, WA). Salt bridges were used to connect the reference electrode to the soil. All the field readings were converted to Eh values (true redox potentials) by adding a temperature-dependent conversion factor to the voltages measured in the field. In the summer of every year when the redox potentials were very high all the electrodes were pulled from the field. The platinum tips were cleaned with steel wool, and the electrodes were checked for accuracy with a redox buffer and water, and working electrodes were reinstalled. The Eh measurements were made weekly for approximately 2.5 years.

Soil pH values at depths of 15 cm, 30 cm and 60 cm were also measured on soil slurries (1:1 soil to water ratio) in each plot several times from 1998 to 1999. Soil pH was read using an Accumet 1002 pH/mV meter and a glass pH electrode.

Soil temperature

Soil temperature was measured weekly with thermocouples at depths of 15, 30, and 60 cm of each plot. A separate thermocouple was used for each depth. One end of the thermocouple was placed at the desired depth and the other end was extended above the soil surface for the convenience of reading temperature. The thermocouples were made using ANSI Type TX Extension Grade Copper/Constantan 20 grade thermocouple wire with polyvinyl insulation (Omega Engineering, Inc., P.O. Box 2284, Stamford, CT 06906). Detailed construction, installation procedures of thermocouples were previously given by Hayes (1998). The soil temperatures were read by an Omega Microcomputer Thermometer Model HH-71 T (Omega Engineering, Inc, Stamford, CT).

Historic rainfall and temperature data

Historic water table levels were predicted using the calibrated DRAINMOD models for each plot (described earlier) and long-term rainfall data. Forty years of historic daily rainfall data were available for the period from January 1, 1959, through December 31, 1998, from a weather station that was within 9.2 km of the site. The daily rainfall were then disaggregated into hourly data and converted to a format compatible with DRAINMOD using a computer program developed by Robbins (1988). Daily maximum and minimum temperature data and geographic location were required for the PET (potential evapotranspiration) calculation in DRAINMOD. These data were also obtained from the weather station that supplied rainfall data.

Water table simulation and statistical analysis

Daily water table levels were computed for each of the 13 plots for the past 40 yr. period using the calibrated DRAINMOD models. Required inputs for the hydrology analysis included the starting day and ending day of the simulation, continuous days of saturation, and maximum depth to saturation. Hydrology within the growing season and out of the growing season were of interest. The growing season (frost-free period) started on March 16, and ended on November 13 in Pitt County for an air temperature of 28°F and a probability of 5 years in 10 (Karnowski et al. 1974). To determine whether soil temperature influenced relationships between saturation frequency and soil color, water table levels for four periods of each year were simulated (January 1 to March 15, March 16 to July 15, July 16 to November 13, and November 14 to December 31), two in the growing season and two out of the growing season. Saturation frequency was determined for durations of $\geq$21 days, for soil depths of 15cm to 90 cm in increments of 15cm.

Percentages of redox depletions (with chromas of 2 or less and values of 4 or more) and concentrations (or red mottles) were determined for each depth range using an interpolation method based on the soil profile description data. Statistical analyses were conducted to correlate the percentages of redox depletions and concentrations, and saturation index using SAS statistical software (Version 7.0 SAS 1998). Saturation events within the growing season, out of the growing season and during a year were used in the correlation.

RESULTS AND DISCUSSION

Matrix color and redoximorphic features

Soil profile descriptions, including matix color, percentages of redoximorphic features, and organic concentrations for each horizon were reported previously by Hayes and Vepraskas (2000). The percentages of redox depletions and redox concentrations were summarized for each depth range in **Table 6** to illustrate the range in values encountered. The E and B horizons of some soils had dark organic stains or organic materials had Munsell values ≤ 4 and chromas ≤ 1. These features were included with the percentage of redox depletions for this study. Such organic features were found only in poorly drained Rains soils and very poorly drained Pantego soils.

The abundance of redox depletions increased in a consistent manner in the sequence from moderately well drained Goldsboro soils to very poorly drained Pantego soils. Percentage of redox concentrations increased from moderately well drained Goldsboro soils to poorly drained Rains soils and then decreased in very poorly drained Pantego soils.

Iron reduction and redox potentials

Iron reduction must occur for low chroma colors or redox depletions to develop in a soil (Vepraskas 1999). Below a temperature of 5°C microbial activity within soils is assumed to be insignificant (Soil Survey Staff 1975). Soil temperatures for different soil series were averaged across the transects for depths of 60 cm and are shown in **Fig. 11**, and show that the average daily soil temperatures were above 5 °C indicating that Fe reduction could occur throughout the year.

The beginning of Fe reduction was determined by redox potentials (Eh) data. The threshold Eh value for the beginning of Fe reduction was estimated from an Eh-pH diagram developed for the mineral $Fe(OH)_3$ that can be computed from (Vepraskas 2000):

$$Eh(Fe^{2+}) = 1235 - 177pH \qquad \text{(for pH's < 7.5)} \qquad 6$$

The pH values determined for each plot were used for the estimation of $Eh(Fe^{2+})$. Average soil pH values measured in the field at depths of 15, 30 and 60 cm ranged from 3.8 to 4.9 across all soil plots.

Means and ranges of redox potentials at plot 2R from 1997 to 1998 at depths of 15, 30 and 60 cm were examined to determine the amount of time required for Fe reduction to occur after an aerated soil became saturated. An example of the redox data is shown in **Fig. 12** for soil at 30 cm in plot 2R. The line showing when Fe reduction occurred was computed using equation 6.

For one wetting period in 1997-1998, the lag between the onset of saturation (which began on Dec. 25, 1997) and the beginning of Fe reduction (which occurred on Jan. 15, 1998) was 22 days. At 15 and 60 cm the lag time between saturation and iron reduction was 6 and 35 days, respectively. This indicated that a longer duration of saturation was required for iron reduction to occur

Table 6. Means (with minimum and maximum values) of redoximorphic features found in the four soils of the Greenville site. Data were obtained from profile descriptions and estimated for the pre-selected depths. Data for the Pantego soil were obtained from one pit.

	Soil			
Depth	Goldsboro	Lynchburg	Rains	Pantego
cm	% Redox Depletions			
0 to 15	0	0	1 (0 to 3)	0
15to 30	0	0	20 (0 to 38)	23
30 to 45	0	1 (0 to 4)	87 (85 to 88)	98
45 to 60	0	19 (2 to 32)	74 (62 to 85)	92
60 to 75	<1 (0 to 1)	24 (5 to 40)	74 (62 to 85)	78
75 to 90	6 (3 to 10)	26 (8 to 40)	71 (58 to 86	70
	% Redox Concentratons			
0 to 15	0	0	0	0
15to 30	0	3 (0 to 8)	1 (0 to 3)	0
30 to 45	0	9 (3 to 15)	14 (12 to 15)	2
45 to 60	11 (8 to 14)	13 (11 to 15)	26 (15 to 38)	8
60 to 75	28 (21 to 31)	19 (3 to 43)	27 (15 to 38)	22
75 to 90	26 (13 to 40)	26 (3 to 45)	29 (14 to 42)	30

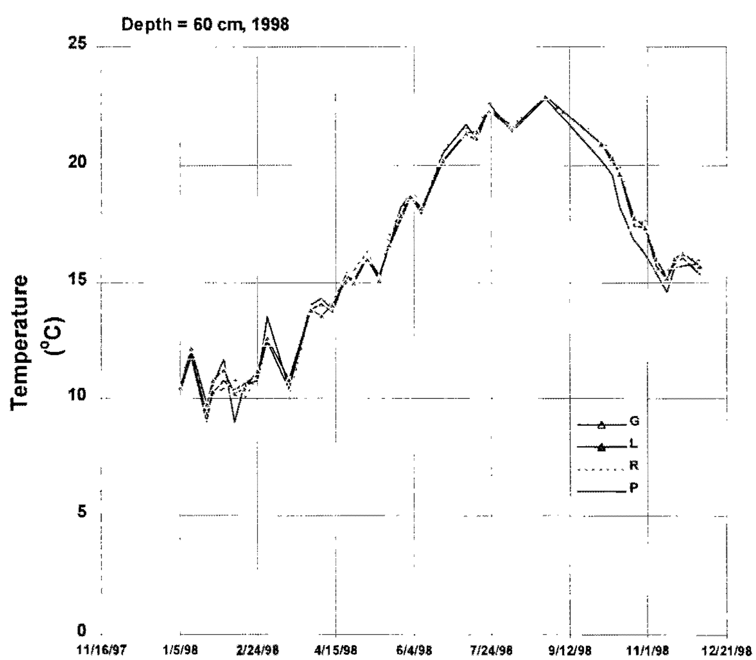

Figure 11. Average daily soil temperatures in the Goldsboro (G), Lynchburg (L), Rains (R), and Pantego (P) plots.

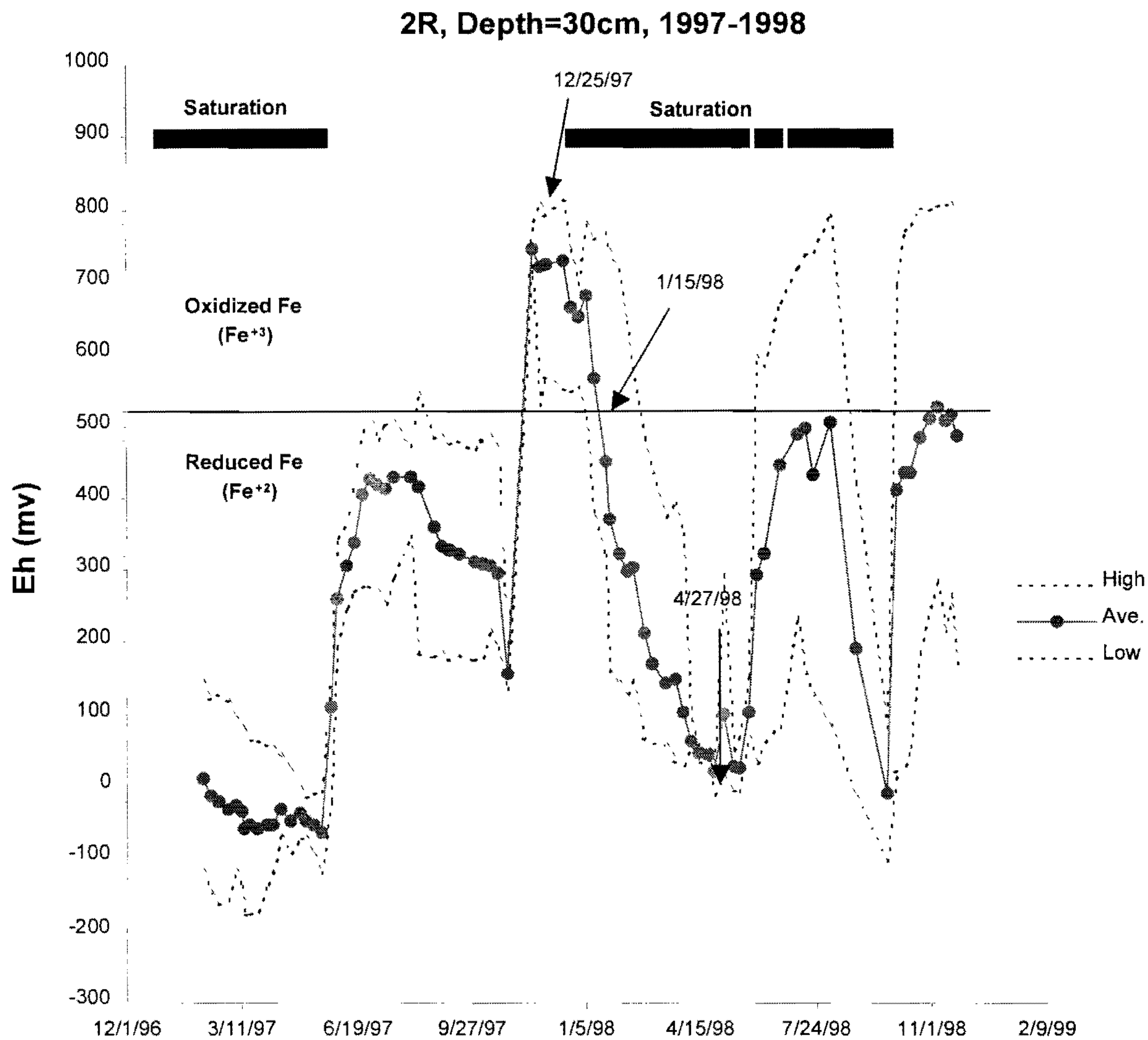

Figure 12. Variation in redox potential (Eh) over time for plot 2R at a depth of 30 cm. Mean and range in Eh are shown as determined from five electrodes at this depth. The data were used to determine the time required for the mean Eh value to fall to where Fe reduction would occur following a saturation event. In this example, the soil had a high mean Eh prior to December 25, and it required 21 days of saturation before the mean Eh value fell into the level where Fe reduction was expected.

in deeper horizons, probably due to the low organic matter content and high pH value found there (Hayes and Vepraskas 2000). The average lag period between onset of saturation and onset of reduction for the 15, 30, and 60 cm depths was found to be 21 days. This 21-day value was the average amount of time that a horizon had to be saturated before the chemical reactions that produce redoximorphic features will occur. In other words, periods of saturation that lasted less than 21 days would be too short for redoximorphic features to develop. This value pertains to this landscape and does not necessarily represent conditions found in other areas.

Saturation events

DRAINMOD computed the number of times the soil in a plot was saturated for 21 consecutive days or longer each year above specific depths. The model also computed the longest continuous period of saturation found during a specific period of the year. An example of the output from DRAINMOD is shown in **Table 7** for plot 2R at a depth of 75 cm. The period of simulation extended from day 1 (January 1) through day 74 (March 15) of each year. It can be seen from the table that plot 2R was predicted to have a water table within 75 cm of the surface one time during the period (January to March) with the water table remaining above 75 cm for between 52 and 74 days over the 40-year period.

We initially used the value for "number of periods the water table was within 75 cm" for correlation with percentages of redoximorphic features. This was found to be unsuitable because two soil plots could both have been saturated once during the period while their durations of saturation ranged widely. Some plots were saturated for 25 days while others were saturated for 74 days. We expected that the soil plots that were saturated for the longer period would have more redoximorphic features. Another measure of saturation, termed *saturation event*, was computed that incorporated both the saturation frequency and longest period of duration as computed by DRAINMOD. This variable gave more weight to longer saturation events than to shorter ones. Saturation events were computed for each year by combining both the number of times the water table rose above a specific depth with the longest duration of saturation predicted for the year and period evaluated. Saturation events were computed by year from the DRAINMOD output as follows:

No. of saturation events

= Integer of (Longest Consecutive Period of Saturation/21 days)

+ (Number of Periods of Saturation of 21 days or longer – 1) 7

The ***number of saturation events*** was computed for each depth simulated in a plot.

Examples of the computations are shown in **Table 7** for plots in the Rains and Goldsboro soils. The Rains plot 2R was saturated above a depth of 75 cm once every year for 40 years. Each saturation event was long, lasting between 52 and 74 days. Most years contained three saturation events as computed by equation 7. On average, 2.9 *saturation events* occurred per year over the

Table 7. Calculation of saturation events occurring above a depth of 75cm for periods lasting a minimum of 21 consecutive days in plots 2R and 2G during the first simulated period from Jan.1 to Mar. 15. Total and average values were computed for the full record of data which lasted from 1959 to1998, while only a partial record is reproduced below.

Year	Number of periods of saturation	Duration of longest period of saturation	Number of saturation events*
		days	
		Plot 2R (Rains series)	
1959	1	74	3
1960	1	74	3
1961	1	74	3
1995	1	55	2
1996	1	74	3
1997	1	74	3
1998	1	74	3
Total	40	--	117
Average (per year)	1	--	2.9
		Plot 2G (Goldsboro series)	
1959	1	25	1
1960	1	56	2
1961	2	48	3
1995	1	35	1
1996	1	44	2
1997	1	44	2
1998	1	50	2
Total	49	--	86
Average (per year)	1.2	--	2.2

*Saturation events were calculated from equation 2.2.

period from 1958 through 1998. In contrast to the Rains plot 2R, data for the Goldsboro plot 2G (**Table 7**) showed the water table rose above a depth of 75 cm from one to three times per year. Each time the water table remained above 75 cm for 25 to 74 days. While the water table rose more frequently in this plot, the longest periods of saturation were shorter than those of the Rains plot 2R. The computed *saturation events* ranged from 1 to 3 for the 40-yr. simulation period, and the average number of saturation events per year was 2.2.

The computation of number of saturation events allowed us to compute a measure of saturation frequency for durations of 21 consecutive days. **Table 8** shows the average number of saturation events that were computed for each plot. We interpret the average number of saturation events to represent the probability that the water table will rise above a specific depth in a year and remain above that depth for 21 days. In other words, if a given plot had an average number of saturation events of 4.0 at a depth of 60 cm, then the water table would rise above that depth four times per year, and each time fall below 60 cm after 41 days. However, in actuality the water table might rise only once in some years but remain above a depth of 60 cm for 84 to 104 days. The average number of saturation events can be met with different frequencies and durations of saturation.

Correlation of soil redoximorphic features with saturation events

Once the average number of saturation events was determined for the depth ranges of interest, these values were then correlated with the percentage of redox concentrations, percentage of redox depletions, and a combination of both. Periods of interest included within growing season, out of growing season, and for an entire year. The average number of saturation events for an entire year was computed by simply adding the saturation event index values in the four simulated periods in a year. Average number of saturation events within growing season and out of growing season was calculated in same way by adding the average values in the two simulated periods within or out of the growing season. Because there were few redoximorphic features in the top 30 cm layer of most soils, the correlations were completed for the depths below 30 cm of the surface. All correlations between percentage of redoximorphic features and saturation events within the growing season, out of growing season and throughout a year were determined using the simple regression model:

$$\text{Saturation Events} = \text{Slope} \times (\%\ \text{Redoximorphic features}) \qquad 8$$

As shown in **Fig. 13** the relationships between redoximorphic feature percentage and saturation events varied with depth, so regression analyses were computed for the depths shown in **Table 9**. The r^2 values in **Table 9** were relatively high, indicating that our assumption of a linear relationship between redoximorphic feature percentage and average number of saturation events was justified. Correlations between percentage of redox depletions and saturation events in deeper horizons (i.e. 75 and 90 cm) were not as good as in shallower horizons. One reason for this is that only saturation events lasting 21 consecutive days or longer were considered. As discussed earlier, the 21-day value was selected because it was the average length of time needed for Fe reduction to occur in saturated horizons. Longer durations of saturation are probably needed for

Table 8. Saturation events computed for the time the water table was within the indicated depth consecutively for at least 21 days during the given period on the 13 plots at the Greenville site.

Period	Plot	Distance from ditch (m)	Depth (cm) 15	30	45	60	75	90
Jan 1 - Mar 15	1G	7	0.0	0.0	0.0	0.0	2.1	2.7
	2G	30	0.0	0.0	0.0	0.0	2.2	2.7
	3G	60	0.0	0.0	0.0	0.0	2.3	2.8
	4G	80	0.0	0.0	0.0	0.0	2.3	2.8
	1L	7	0.0	0.0	0.2	2.3	2.7	2.9
	2L	30	0.0	0.0	0.6	2.3	2.7	2.8
	3L	60	0.0	0.0	0.9	2.5	2.8	2.9
	4L	80	0.0	0.1	1.5	2.5	2.8	2.9
	1R	7	0.3	1.3	2.5	2.8	2.9	2.9
	2R	30	2.2	2.7	2.8	2.9	2.9	2.9
	3R	60	2.3	2.6	2.8	2.8	2.9	2.9
	4R	80	2.1	2.4	2.7	2.8	2.9	2.9
	4P	80	2.7	2.9	2.9	3.0	3.0	3.0
Mar 16 - Jul 15	1G	7	0.0	0.0	0.0	0.0	0.5	1.2
	2G	30	0.0	0.0	0.0	0.0	0.6	1.3
	3G	60	0.0	0.0	0.0	0.0	0.6	1.4
	4G	80	0.0	0.0	0.0	0.0	0.4	1.0
	1L	7	0.0	0.0	0.0	0.7	1.6	2.2
	2L	30	0.0	0.0	0.1	1.0	1.8	2.5
	3L	60	0.0	0.0	0.2	1.0	1.7	2.1
	4L	80	0.0	0.0	0.5	1.2	1.9	2.4
	1R	7	0.1	0.5	1.3	2.0	2.8	3.5
	2R	30	1.2	1.6	1.8	2.1	2.5	3.1
	3R	60	1.3	1.6	1.8	2.1	2.5	3.1
	4R	80	1.0	1.5	1.6	1.9	2.4	3.0
	4P	80	1.4	1.9	2.5	2.8	3.3	3.6
Jul 16 - Nov 13	1G	7	0.0	0.0	0.0	0.0	0.1	0.3
	2G	30	0.0	0.0	0.0	0.0	0.1	0.3
	3G	60	0.0	0.0	0.0	0.0	0.1	0.6
	4G	80	0.0	0.0	0.0	0.0	0.1	0.6
	1L	7	0.0	0.0	0.0	0.1	0.6	1.0
	2L	30	0.0	0.0	0.0	0.3	0.8	1.2
	3L	60	0.0	0.0	0.0	0.4	0.7	1.1
	4L	80	0.0	0.0	0.1	0.4	0.8	1.0
	1R	7	0.0	0.2	0.3	0.9	1.2	1.8
	2R	30	0.3	0.5	0.7	0.8	1.1	1.6
	3R	60	0.3	0.6	0.7	0.9	1.2	1.7
	4R	80	0.2	0.4	0.5	0.8	1.0	1.4
	4P	80	0.7	1.0	1.5	1.9	2.3	2.7
Nov 14 - Dec 31	1G	7	0.0	0.0	0.0	0.0	0.6	0.8
	2G	30	0.0	0.0	0.0	0.0	0.6	0.8
	3G	60	0.0	0.0	0.0	0.0	0.6	0.9
	4G	80	0.0	0.0	0.0	0.0	0.6	0.9
	1L	7	0.0	0.0	0.0	0.6	0.9	1.0
	2L	30	0.0	0.0	0.1	0.6	0.9	1.1
	3L	60	0.0	0.0	0.1	0.6	0.9	1.0
	4L	80	0.0	0.0	0.3	0.7	0.9	1.0
	1R	7	0.0	0.1	0.5	0.8	1.1	1.2
	2R	30	0.4	0.6	0.7	0.8	1.0	1.3
	3R	60	0.5	0.7	0.7	0.9	1.1	1.3
	4R	80	0.3	0.5	0.7	0.8	1.1	1.4
	4P	80	0.7	1.1	1.4	1.4	1.5	1.8
Total (Jan - Dec)	1G	7	0.0	0.0	0.0	0.0	3.2	5.1
	2G	30	0.0	0.0	0.0	0.0	3.3	5.1
	3G	60	0.0	0.0	0.0	0.0	3.6	5.6
	4G	80	0.0	0.0	0.0	0.0	3.4	5.3
	1L	7	0.0	0.0	0.2	3.8	5.8	7.1
	2L	30	0.0	0.0	0.7	4.1	6.1	7.5
	3L	60	0.0	0.0	1.1	4.4	6.1	7.1
	4L	80	0.0	0.1	2.3	4.7	6.3	7.3
	1R	7	0.4	2.0	4.5	6.5	7.9	9.4
	2R	30	4.0	5.3	5.9	6.6	7.5	8.9
	3R	60	4.3	5.5	6.0	6.6	7.6	8.9
	4R	80	3.5	4.9	5.5	6.3	7.4	8.7
	4P	80	5.6	6.8	8.3	9.1	10.1	11.0

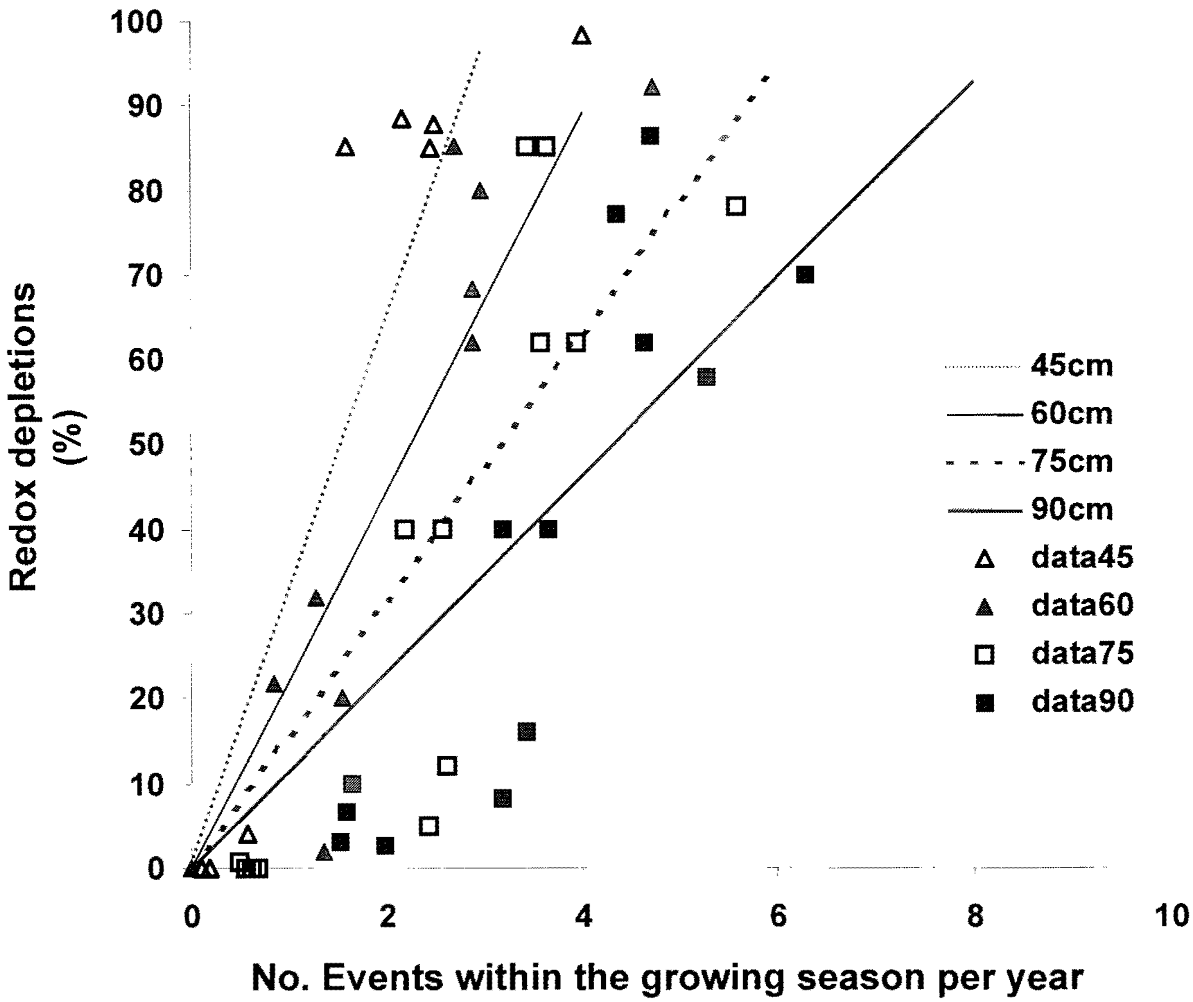

Figure 13. Regression lines and data points for the relationship between saturation events and the percentage of redox depletions for all plots at the Greenville site. Saturation events during the growing season are shown in this example. The data show that linear relationships are justified for all depths.

Fe reduction to occur in horizons below 75 cm in these soils. Nevertheless, the results show that once saturation duration exceeds 21 days, then the more frequently a soil is saturated, or the longer it is saturated, the more redox depletions a horizon will have. This is probably due to there being more organic C near the surface which promotes a greater amount of Fe reduction, and hence a greater production of redox depletions (Hayes and Vepraskas 2000).

Best correlations were found within the growing season with r^2 values higher than 0.9 at 45 cm and 60 cm, and higher than 0.85 at 75 and 90 cm. Water tables stayed within 75 cm almost the entire period outside of the growing season in most soils. This limited the range of saturation events and contributed to lower r^2 values. Regressions with saturation events throughout a year, including both growing season and out of the growing season, improved the r^2 values over what

Table 9. Summary of parameters for relating average number of saturation events to percentage of redox depletions and redox concentrations in single variable linear regression models.

	Saturation event vs. Redox Depletions		Saturation events vs. Redox Concentrations
Depth cm	Slope	r^2	r^2
	Within Growing Season		
45	0.029	0.93	0.68
60	0.042	0.94	0.81
75	0.055	0.87	0.60
90	0.074	0.86	0.70
	Outside of Growing Season		
45	0.040	0.94	0.79
60	0.052	0.82	0.78
75	0.059	0.66	0.78
90	0.069	0.67	0.77
	Throughout the Year		
45	0.069	0.95	0.75
60	0.095	0.89	0.81
75	0.114	0.78	0.73
90	0.143	0.78	0.76

was obtained for the period outside the growing season. As shown in **Table 9**, correlations between redox concentration percentage and saturation events were not as strong as with redox depletions and saturation events, and regression line slopes are not reported.

Saturation events were related to both the percentage of redox depletions and percentage of redox concentrations using the following regression model:

$$\text{Saturation Events} = A \times \%\ \text{Redox depletions} + B \times \%\ \text{Redox concentrations} \qquad 9$$

Model parameters A and B for percentage of redox depletions and percentage of redox concentrations are tabulated in **Table 10**. Most R^2 values were above 0.9 for relationships at each depth and during each period of interest. Regression results for depths of 75 and 90 cm were improved over those found when only percentage of redox depletions was put in the model. Parameters A and B both increased with the increasing depth showing that longer saturation were required to form redoximorphic features in deeper horizons.

APPLICATIONS

Currently, the occurrence of soil saturation is assessed by looking for the depth that redox depletions occur. If redox depletions are found at a depth of 45 cm in a soil, then it is assumed that the ***seasonal high water table*** occurs at a depth of 45 cm. While it is never known whether the "seasonal high water table" rises annually to the shallowest depth where redox depletions are found, soil scientists have generally believed that the water table rises to that level, and no higher, in most years. The duration of saturation for the depth at which gray colors occur has never been known. **Tables 9** and **10** show that percentages of redoximorphic features can be calibrated to data from hydrologic models in order to estimate saturation frequency for fixed

Table 10. Summary of regression parameters for the relationship between percentages of two kinds of redoximorphic features and saturation index. Linear regression models were determined for three periods, within growing season, out of growing season, and throughout a year, using data for the Greenville site.

Depth cm	% Redox depletions Parameter A	% Redox concentrations Parameter B	R^2
	Within growing season		
45	0.03	0.02	0.93
60	0.04	0.01	0.94
75	0.04	0.03	0.94
90	0.05	0.05	0.97
	Out of growing season		
45	0.03	0.04	0.95
60	0.04	0.06	0.88
75	0.03	0.08	0.92
90	0.04	0.08	0.90
	Throughout a year		
45	0.07	0.03	0.95
60	0.08	0.07	0.92
75	0.08	0.12	0.94
90	0.09	0.13	0.95

durations. The correlation results for redox depletions and saturation events were graphed in **Fig. 14** to illustrate how such data can be used. The data used for the correlations and in **Fig. 14** came from all 13 plots studied, and so the results can be applied to the Goldsboro, Lynchburg, Rains, and Pantego soils at this site.

Figure 14 shows that rather than estimate a vague concept such as "seasonal high water table," the depth and percentage of redox depletions can be used to estimate both a frequency and duration of saturation. For example, if a soil were found to have 15% redox depletions at a depth of 45 cm, then the soil would have a saturation event number of 1. This means that the soil at a depth of 45 cm saturates for 21 to 41 days on average about once per year. If time of year is important for an interpretation, then graphs such as in **Fig. 14** can also be developed to show the likelihood of saturation occurring inside or outside of the growing season. Graphs such as those shown in **Fig. 14** will allow county sanitarians and consultants to evaluate seasonal wetness in soils with greater precision than every before. With additional work, we may even be able to estimate wetland hydrology from soil color patterns.

Models using only the percentage of redox depletions in the regressions are easily shown in a graph. Such graphs are simple to use and provide a more convenient way to apply in the field because the saturation event values can be read directly. Considering both the percentages of redox depletions and redox concentrations provides better estimates of saturation conditions, but such combinations are not easily graphed.

The methods used here can be applied to virtually any soil or toposequence. The results of this study should be considered site-specific at this point. Different results might be expected for soils containing more organic matter, those found in cooler temperatures, or on different landscape positions. At this time the results reported here should not be used for interpretations of saturation on soils other than the series evaluated.

These results are based on a minimum saturation duration of 21 consecutive days. This value was selected because it was the average duration a soil needed to be saturated before Fe reduction occurred. Iron reduction is the process that begins the formation of redox depletions or gray soil colors. As discussed earlier, the 21-day value is site-specific and was intended to be applied to all depths between 0 and 90 cm. Should hydrologic information be needed solely for shallow depths, then a shorter duration of saturation might be appropriate.

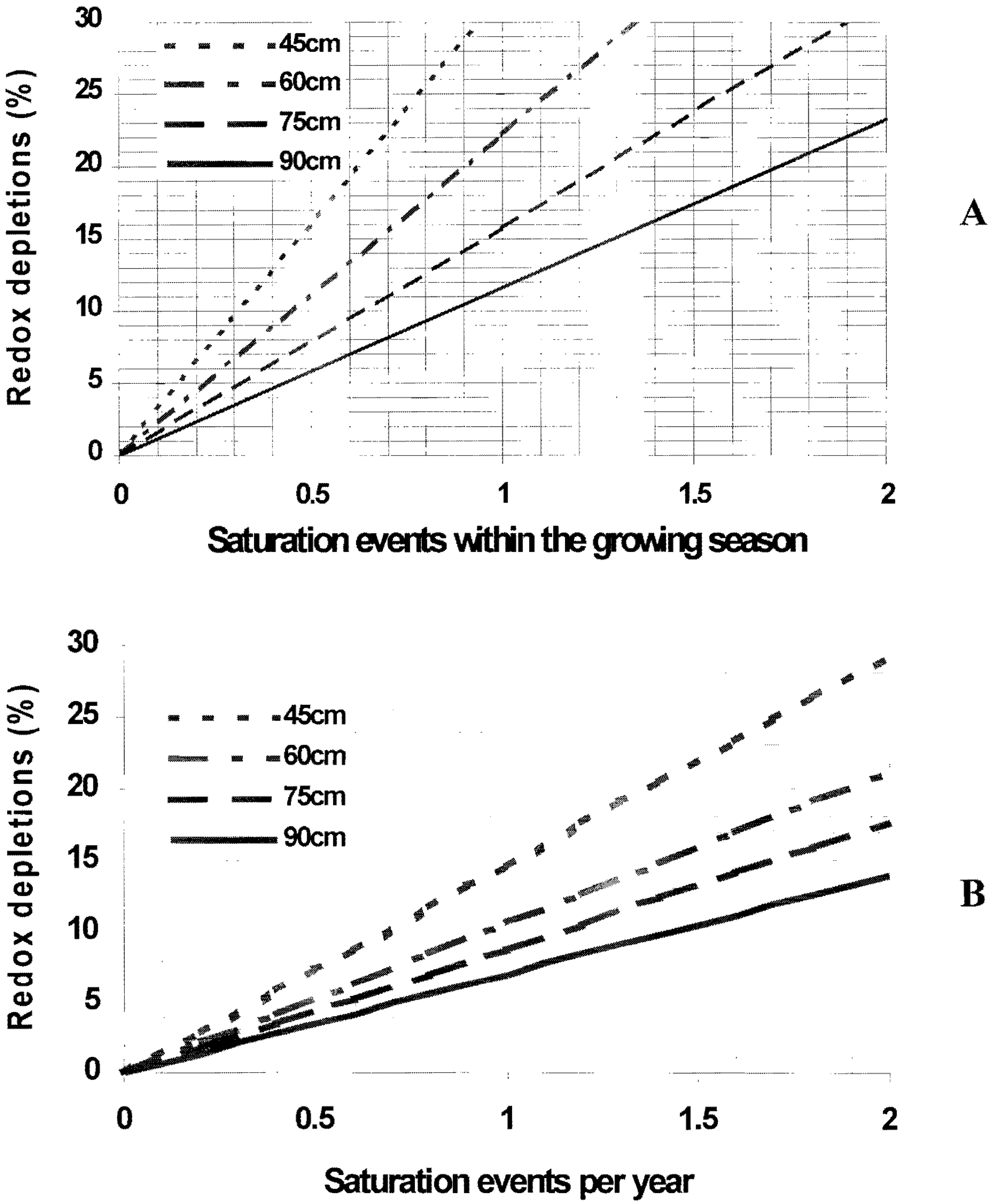

Figure 14. Relationships between saturation events and percentage of redox depletions for the periods (A) during the growing season and (B) during the entire year. Data were obtained from all plots at the Greenville site. Depths are shown.

Predicting Soil Saturation Frequency and Duration Using Soil Color in Two Toposequences

INTRODUCTION

In previous sections it was shown that the results of simulation modeling that predicted long-term saturation frequency and duration could be correlated with percentages of redoximorphic features for a single toposequence of soils in the fine-loamy particle size class. The purpose of this investigation was to test the methods of the previous study to determine whether similar results could be obtained in soils of a fine particle size class. The objectives of this chapter were: 1) To correlate the soil color patterns with the saturation events in a toposequence containing clayey soils, and 2) To compare this relationship to the one obtained in a separate watershed containing fine-loamy soils.

MATERIALS AND METHODS

The site was located in Bertie County, NC, at N 76^0 48' 00", W 36^0 5' 30". The toposequence included the well drained Noboco series (fine-loamy, siliceous, thermic Typic Paleudults), moderately well drained Goldsboro series (fine-loamy, siliceous, thermic Aquic Paleudults), somewhat poorly drained Lenoir series (clayey, mixed, thermic Aeric Paleaquults) and poorly drained Leaf series (clayey, mixed, thermic Typic Albaquults). The vegetation was forest consisting of loblolly pine (*Pinus taeda* L.), red maple (*Acer rubrum* L), sweet bay (*Magnolia virginiana* L.), white oak (*Quercus alba* L.), red oak (*Quercus borealis* L.), and black cherry (*Padus serotina* L.). Two transects were established with each having four plots, one Goldsboro plot, one Lenoir plot and two Leaf plots from the upper to lower landscape position (**Fig. 1B).** One Noboco plot was shared by both of two transects. Plots were instrumented as described in "A Method to Predict Soil Saturation Frequency and Duration from Soil Color."

RESULTS AND DISCUSSION

Soil properties

Particle size data for selected plots of the toposequence are summarized in **Table 11**. In the drainage sequence from Goldsboro to Leaf soils, silt content decreased and clay content increased. The content of sand and silt decreased with depth. In Lenoir and Leaf soils, clay content consistently increased with depth. Soils in the south transect had a much lower clay content than soils in the north transect. Clay content was especially high in plot 3N (Lenoir soil in the north transect), being even higher than the Leaf soils. Percentages of redox depletions and redox concentrations both increased from moderately well drained soils to poorly drained soils. In Leaf soils the percentages of redox concentrations increased with depth and redox depletions decreased with depth. In Goldsboro soils both redox depletions and redox concentrations increased with depth. Redox concentrations were most abundant from 45 to 60 cm in Lenoir soils.

Table 11. Particle size distributions for plots at the Bertie site.

Horizon	Depth	Sand	Silt	Clay	Textural class
	cm	----------------------	%	----------------	
		2N - Goldsboro			
A	0-15	35	58	7	Silt loam
E	15-29	34	55	11	"
Bt1	29-47	31	56	13	"
Bt2	47-67	22	53	24	"
Bt3	67-90+	23	54	23	"
		3N - Lenoir			
A	0-5	35	57	8	"
E	5-11	29	59	12	"
Bt1	11-19	29	52	19	"
Btg1	19-52	13	42	45	Silty clay
Btg2	52-80+	10	40	50	Clay
		4N - Leaf			
A	0-8	45	50	5	Silt loam
Eg	8-21	43	45	12	Loam
Btg1	21-48	26	41	34	Clay loam
Btg2	48-87+	21	39	40	Clay
		5N - Leaf			
A	0-11	37	54	9	Silt loam
Eg	11-20	37	51	11	"
Btg1	20-33	29	48	23	Loam
Btg2	33-61	19	40	41	Clay
Btg3	61-90+	16	39	45	"
		2S - Goldsboro			
A	0-9	32	62	5	Silt loam
E	9-14	30	66	5	"
Bs/w	14-25	27	58	15	"
E'	25-43	26	61	13	"
Bt1	43-60	20	53	27	Silty clay loam
Bt2	60-80+	16	47	37	"
		3S – Lenoir			
A	0-8	37	57	6	Silt loam
E	8-20	36	53	11	"
Bt1	20-35	31	49	20	"
Bt1	35-59	30	48	22	Loam
Bt2	59-95+	29	46	25	"
		4S - Leaf			
A	0-11	33	61	6	Silt loam
E	11-16	30	60	10	"
Bt	16-37	24	53	24	"
Btg1	37-50	22	51	27	"
Btg2	50-65	20	53	27	"
Btg3	65-90+	20	50	30	Silty clay loam
		5S – Leaf			
A	0-6	40	52	8	Silt loam
E	6-18	32	49	19	Loam
Btg1	18-43	35	43	22	"
Btg2	43-80+	21	34	45	Clay

Soil profile descriptions showing the types and percentages of redoximorphic features are given in **Table 12**. Percentages of redoximorphic features found at the site are graphed in **Table 13** for individual soil series to show major trends. The percentages of redox depletions and percentages of redox concentrations in these soils consistently increased in the sequence from the moderately well drained Goldsboro soils to poorly drained Leaf soils. Redox depletions having a value of 4 or more and chroma of 2 or less first occurred as mottles and gradually became the matrix color with increasingly poorer drainage. The percentages of redox concentrations and depletions were almost constant for depths deeper than 45 cm below the surface in most soils. High percentages of redox concentrations even occurred at 5 cm below the surface.

Correlation of redoximorphic features with saturation events

Saturation event indices were calculated for the depths from 15 to 90 cm below the soil surface in each tested period (**Table 14**). The percentages of redox depletions were correlated with saturation index using the regression models for three time periods: within growing season (April 3 to October 30), out of growing season (October 31 to April 2) and throughout a year (January 1 to December 31) using the basic regression models:

$$\text{Saturation Events} = \text{Slope} \times \%\ \text{redox depletions} \qquad (10)$$

$$\text{Saturation Events} = \text{Slope} \times \%\ \text{redox concentrations} \qquad (11)$$

$$\text{Saturation Events} = A \times \%\ \text{redox depletions} + B \times \%\ \text{redox concentrations} \qquad (12)$$

Slope parameters of the regression lines for equations 10 and 11 were summarized in **Table 15** along with the r^2 values. The r^2 values were high for both redox depletions and redox concentrations for depths $\geq$ 30 cm and all three time periods.

The results of the regression analyses were graphed in **Fig. 15** to show the general trends for both types of redoximorphic features. The relationship between saturation events and redox depletions varied with soil depth as was found for the Greenville site discussed in Chapter 2. Slopes of the regression lines became progressively smaller with increasing depth for depths $\geq$30 cm. This was probably due to the decrease with organic matter with increasing depth, such that it required a longer duration of saturation at 90 cm to initiate the iron-reducing reactions that create the redox depletions than would be found at 30 cm where organic material was more plentiful.

Soil at a depth of 15 cm, however, had a regression line slope in between that of soil at depths of 45 and 60 cm that is not accounted for by the explanation just given for the deeper soil layers (**Table 15**). This showed that a given saturation event produced a smaller percentage of redox depletions at 15 cm than was found at 30 cm. The reason for this is that organic stains effectively masked the color of redox depletions. Organic stains were described primarily at 15 cm (**Table 11**). As a result, the amounts of redox depletions described were less than what would be found if organic coatings could be removed.

Table 12. Soil profile descriptions of plots at the Bertie site.

Plot	Horizon	Depth cm	Matrix	Redox depletions	Redox concentrations	Organic stains
				Goldsboro		
	Oi	3-0				
	A	0-15	10YR 3/1			
2N	E	15-29	2.5Y 6/4			
	Bt1	29-47	2.5Y 5/6			
	Bt2	47-67	2.5Y 5/6	2.5Y 7/1, 7%	10YR 5/6, 10%	
	Bt3	67-90	2.5Y 5/4	2.5Y 7/1, 10%	10YR 5/6, 20%	
	Oi	1-0				
	A	0-9	10YR 4/1			10YR 3/2, 30%
2S	E	9-14	10YR 6/2			
	Bs	14-15	10YR 4/3			
	Bw	15-25	10YR 4/4		10YR + 2.5Y 5/6, 6%	
	E'	25-43	2.5Y 6/4		10YR 5/6, 1%	
	Bt	43-100+	2.5Y 5/4	2.5Y 6/1, 10%	5Y 5/6, 15%	
				Lenoir		
	Oi	4-0				
	A	0-5	10YR 4/1			
	BE	5-11	2.5Y 6/3		10YR 5/6, 15%, 7.5YR 5/6, 2%	2.5Y 4/1, 30%
3N	Bt	11-19	2.5Y 6/4		10YR 5/8, 1%, 2.5Y 5/6, 15%	2.5Y 4/1, 5%
	Btg1	19-52	2.5Y 5/2		10YR 5/6 + 5/8, 15%	
	Btg2	52-80	2.5Y 6/1		10YR 5/6 + 2.5YR 4/8, 15%	
	Btg3	80-100+	10YR 5/1		2.5YR 4/6, 10%, 2.5Y 5/4, 5%	
	Oe	5-0				
	A	0-8	2.5Y 2.5/1			10YR 4/4, 30%
3S	E	8-20	2.5Y 5/4		2.5Y 6/6, 7%	
	Bt1	20-35	2.5Y 6/6	2.5Y 6/2, 1%	10YR 5/6, 7%	
	Bt2	35-59	2.5Y 6/6	2.5Y 6/2, 12%	10YR 5/6, 20%	
	Bt3	59-95+	10YR 5/6	2.5Y 6/1, 20%	10YR 5/8, 15%	
				Leaf		
	Oi	3-0				
	A	0-8	10YR 2/1			
4N	Eg	8-21	5Y 6/2		2.5Y 6/6, 4%	10YR 4/1, 5%
	Btg1	21-48	2.5Y 6/2		10YR 5/6, 35%	10YR 4/1, 2%
	Btg2	48-87+	2.5Y 6/1		10YR 5/6, 25%, 2.5YR 4/8, 10%	
	Oi	3-0				
	A	0-11	2.5Y 2.5/1			2.5Y 4/1, 10%
5N	Eg	11-20	5Y 6/1		2.5Y 6/6, 15%, 7.5YR 5/8 1%	10YR 4/4, 10%
	Btg1	20-33	5Y 6/1		10YR 5/6, 20%	
	Btg2	33-61	2.5Y 6/1		10YR 5/6, 35%, 2.5YR 4/8, 2%	
	Btg3	61-90+	2.5Y 6/1		10YR 5/6, 40%, 2.5YR 4/8, 10%	
	Oe	10-0				
	A	0-11	10YR 2/1			2.5Y 3/1, 40%
4S	E	11-16	2.5Y 6/2		2.5Y 7/4, 20%, 7.5YR 5/8 2%	10YR 4/2, 10%
	Bt	16-37	2.5Y 6/4	2.5Y 6/2, 20%	10YR 5/6, 20%, 7.5YR 5/8 2%	
	Btg1	37-50	2.5Y 6/2		10YR 5/6 + 5YR 5/8, 25%	
	Btg2	50-65	2.5Y 6/2		10YR 5/6, 30%, 5YR 5/8, 5%	
	Btg3	65-90+	2.5Y 6/2		10YR 5/6, 30%, 2.5YR 4/8, 7%	
	Oi	4-0				
	A	0-6	2.5Y 2.5/1	2.5Y 5/1, 2%		
5S	E	6-18	2.5Y 7/2		10YR 5/6 + 2.5Y 5/6, 15%	2.5Y 4/1, 1%
	Btg1	18-43	10YR 5/1		10YR 5/6, 25%	
	Btg2	43-80+	10YR 6/1		10YR 5/6, 15%, 2.5YR 4/8, 15%	

Table 13. Means (with minimum and maximum values) of redoximorphic features found in the three soils of the Bertie site. Data were obtained from profile descriptions and estimated for the pre-selected depths.

		Soil	
Depth cm	Goldsboro	Lenoir	Leaf
		% Redox Depletions	
0 to 15	0	0	35 (21 to 45)
15to 30	0	31 (0 to 62)	78 (77 to 81)
30 to 45	<1 (0 to 1)	47 (8 to 85)	71 (65 to 76)
45 to 60	8 (6 to 10)	49 (13 to 85)	67 (63 to 70)
60 to 75	9 (9 to 10)	53 (20 to 85)	62 (51 to 70)
75 to 90	10 (10)	53 (20 to 85)	62 (50 to 70)
		% Redox Concentratons	
0 to 15	0	4 (3 to 4)	5 (2 to 9)
15to 30	0	11 (7 to 15)	22 (19 to 23)
30 to 45	1` (0 to 2)	15 (15 to 16)	29 (24 to 35)
45 to 60	12 (9 to 15)	17 (15 to 20)	33 (30 to 37)
60 to 75	15 (15)	15 (15)	38 (30 to 49)
75 to 90	18 (15 to 20)	15 (15)	38 (30 to 50)

Table 14. Saturation event indices for soils at the Bertie site showing the frequency that the water table was within the indicated depth for at least 21 consecutive days during the periods shown.

Period	Plot	Soil	Depth (cm)					
			15	30	45	60	75	90
Jan 1 – Apr 2	2N	Goldsboro	0.1	0.4	0.7	1.7	2.8	3.1
	2S	Goldsboro	0.0	0.0	0.0	0.1	0.5	1.5
	3N	Lenoir	2.7	3.0	3.1	3.3	3.4	3.6
	3S	Lenoir	1.8	3.1	3.4	3.6	3.7	3.8
	4N	Leaf	3.1	3.3	3.4	3.5	3.6	3.7
	4S	Leaf	3.1	3.5	3.5	3.7	3.7	3.8
	5N	Leaf	3.2	3.4	3.6	3.6	3.7	3.8
	5S	Leaf	3.2	3.5	3.5	3.6	3.7	3.7
Apr 3 – Jul 17	2N	Goldsboro	0.0	0.0	0.1	0.1	0.4	0.7
	2S	Goldsboro	0.0	0.0	0.0	0.0	0.0	0.1
	3N	Lenoir	0.5	0.7	0.9	1.1	1.4	1.7
	3S	Lenoir	0.1	0.5	0.8	1.0	1.5	1.7
	4N	Leaf	0.5	0.8	0.8	1.0	1.1	1.4
	4S	Leaf	0.4	0.7	0.9	1.2	1.4	1.7
	5N	Leaf	0.7	0.9	1.2	1.4	1.6	2.0
	5S	Leaf	0.6	0.9	1.0	1.1	1.3	1.5
Jul 18 – Oct 30	2N	Goldsboro	0.0	0.0	0.0	0.1	0.2	0.4
	2S	Goldsboro	0.0	0.0	0.0	0.0	0.0	0.0
	3N	Lenoir	0.2	0.3	0.4	0.5	0.7	0.8
	3S	Lenoir	0.1	0.2	0.6	0.9	1.2	1.3
	4N	Leaf	0.4	0.6	0.8	1.0	1.0	1.1
	4S	Leaf	0.2	0.5	0.7	0.8	0.9	1.0
	5N	Leaf	0.5	0.7	0.9	1.1	1.3	1.5
	5S	Leaf	0.5	0.8	0.9	1.1	1.2	1.4
Oct 31 – Dec 31	2N	Goldsboro	0.0	0.0	0.0	0.2	0.3	0.5
	2S	Goldsboro	0.0	0.0	0.0	0.0	0.0	0.3
	3N	Lenoir	0.4	0.5	0.6	0.6	0.7	0.8
	3S	Lenoir	0.2	0.5	0.8	1.0	1.0	1.0
	4N	Leaf	0.6	0.7	0.7	0.8	0.8	0.8
	4S	Leaf	0.5	0.6	0.7	0.7	0.8	0.8
	5N	Leaf	0.6	0.8	0.8	0.9	1.0	1.0
	5S	Leaf	0.6	0.7	0.8	0.8	0.8	0.9
Total (Jan – Dec)	2N	Goldsboro	0.1	0.4	0.8	2.1	3.6	4.7
	2S	Goldsboro	0.0	0.0	0.0	0.1	0.5	1.8
	3N	Lenoir	3.7	4.4	4.9	5.5	6.2	6.8
	3S	Lenoir	2.1	4.4	5.6	6.4	7.3	7.7
	4N	Leaf	4.5	5.3	5.6	6.2	6.5	7.0
	4S	Leaf	4.1	5.3	5.8	6.3	6.7	7.3
	5N	Leaf	5.0	5.8	6.5	7.0	7.5	8.3
	5S	Leaf	4.8	5.8	6.2	6.6	7.0	7.5

Table 15. Summary of regression line slopes for in single variable linear regression models that relate percentages of redoximorphic features to saturation event indices for three time periods: within the growing season, out of the growing season, and throughout a year.

Depth	Redox depletions		Redox concentrations	
	Slope	r^2	Slope	r^2
cm				
		Within growing season		
15	0.023	0.765	0.143	0.801
30	0.018	0.981	0.067	0.971
45	0.022	0.938	0.060	0.960
60	0.028	0.935	0.062	0.927
75	0.033	0.923	0.062	0.902
90	0.040	0.905	0.074	0.916
		Out of growing season		
15	0.092	0.748	0.582	0.830
30	0.052	0.997	0.191	0.987
45	0.055	0.971	0.145	0.941
60	0.060	0.950	0.131	0.910
75	0.064	0.904	0.121	0.899
90	0.067	0.885	0.126	0.914
		Throughout a year		
15	0.116	0.756	0.726	0.829
30	0.070	0.997	0.259	0.987
45	0.077	0.965	0.205	0.950
60	0.088	0.952	0.194	0.922
75	0.098	0.921	0.184	0.911
90	0.108	0.906	0.200	0.929

The regression line slopes for relationships between percentage of redox concentrations and saturation event indices is shown in **Table 15**. High r^2 values with most above 0.9 suggested a good simple linear relationship between abundance of redox concentrations and saturation index. Regression line slopes for percentage of redox concentrations are quite constant below 15 cm of the surface. Relationships for the time period outside of the growing season have higher parameters than within the growing season because soils were saturated for longer periods outside of the growing season. Redox concentrations form by oxidation of the reduced Fe. Such oxidation can occur over a broad depth range because the reduced Fe moves through the soil following reduction but before it is oxidized. Soil at 15 cm again showed a different relationship than found for the lower depths. This is probably not due to masking effects, but rather to the accumulation of Fe oxides in zones of higher clay contents. Clays have a much higher surface area than sands, and the Fe oxides are found preferentially on the surfaces of soil particles following the oxidation of the Fe. The highest clay percentages in the soils were generally found below a depth of 20 cm.

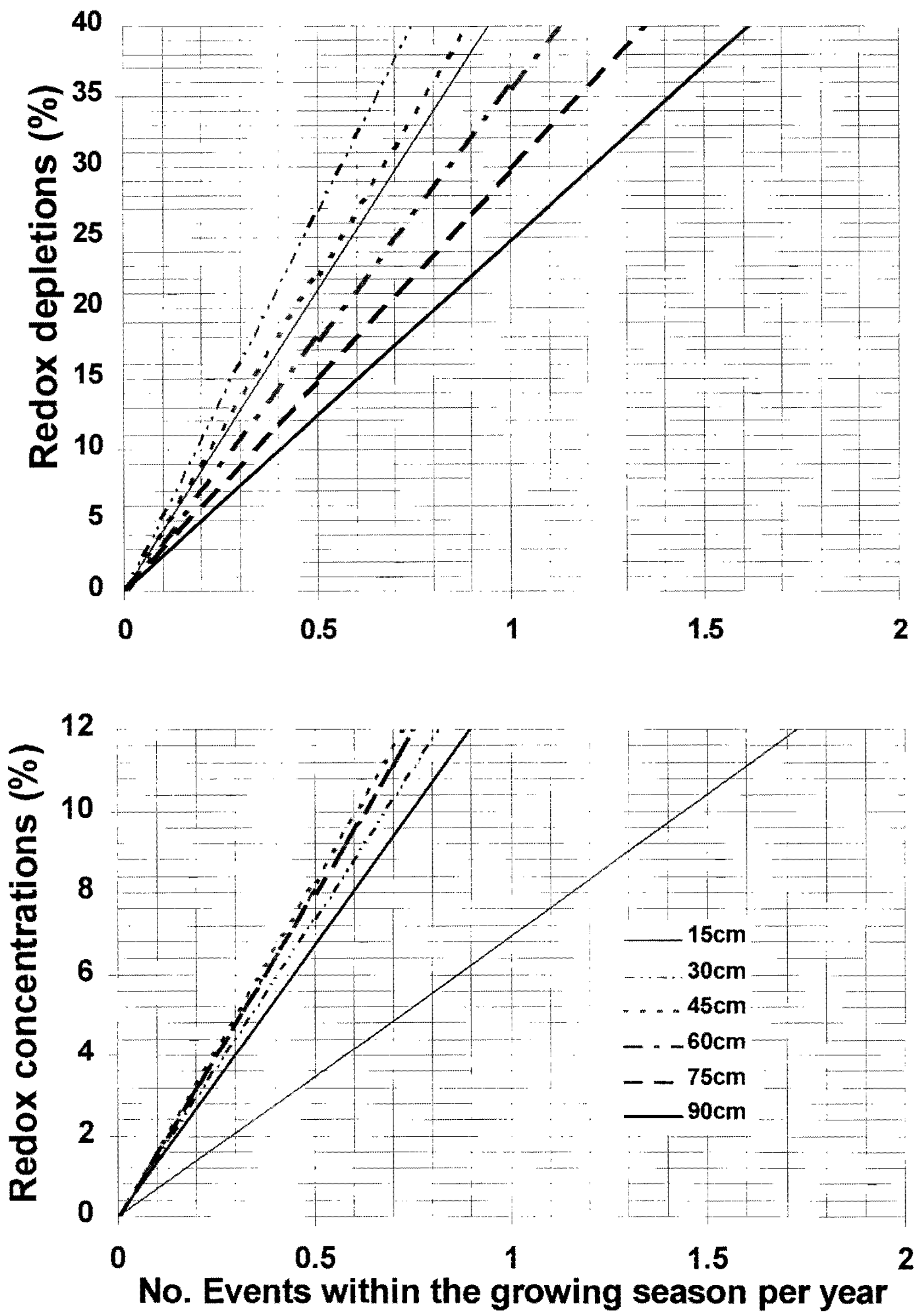

Figure 15. Relationships between saturation events and percentage of redox depletions and redox concentrations during the growing season. Data from all plots at the Bertie site were used for analysis.

Very high R^2 values were obtained when both redox depletions and concentrations were used in regression equations to relate to saturation events (**Table 16**). The R^2 values were slightly lower for a depth of 15 cm, but were virtually the same for all lower depths. There was no obvious impact of time of year on the R^2 values but parameter values did change.

Comparison of the relationships between saturation index and soil color patterns obtained in the Bertie site and in the Greenville site

The Bertie site has a thin organic layer upon a thin dark surface horizon which has Munsell values less than 4 and chromas of 1. Redoximorphic features occurred within 15 cm of the surface. Good relationships between redoximorphic features and saturation index were obtained for each depth increment from 15 to 90 cm. In the Greenville site, however, the dark surface horizon is much thicker and few redoximorphic features occurred within 30 cm of the surface. Significant correlations between the saturation index and redoximorphic features were only obtained for depths below 30cm.

In both sites the percentage of redox depletions was highly correlated with saturation event index. In the Bertie site, correlations between redox depletions and saturation index for each depth were high ($r^2 > 0.80$) both within and out of the growing season. In the Greenville site percentage of redox depletions was highly correlated with saturation index at depths of 45 and 60 cm. Below 60 cm of the surface, good correlations ($r^2 > 0.80$) were only found within the growing season. Most soils at the Greenville site were saturated for long periods below 60 cm outside of the growing season, and differences among soils in saturation durations could only be found during the growing season between the months of March and October.

Amounts of redox concentrations increased from better to poorer drained soils in the Bertie site. Good relationships were obtained between saturation events and percentage of redox concentrations with most r^2 values above 0.9 for all depths of interest. In the Greenville site, however, the percentage of redox concentrations was not correlated as well to the saturation events (r^2's between 0.60 and 0.81) in simple linear regressions.

Hayes and Vepraskas (2000) showed that the percentages of redox concentrations increased toward the perimeter ditch in the Goldsboro, Lynchburg, and Rains soils at the Greenville site. The concentrations were accumulating at the discharge points in the landscape, possibly because groundwater was bringing dissolved Fe to these points which then oxidized when the water table fell and oxygen entered the soil.

Important differences occurred between the two sites in the relationship between percentage of redox depletions and saturation event index during the growing season. For example, a single saturation event was related to 22% redox depletions at a depth of 60 cm in the Greenville site, but in the Bertie site it corresponded to 36% redox depletions. A longer saturation period or a higher saturation index were required to form the same amount of redox depletions in the Greenville site than the Bertie site. The higher sandy content in the Greenville site and higher silt and clay content found in the Bertie site may explain this. The finer textures of the Bertie soils

Table 16. Summary of parameters for the relationship between the percentage of redoximorphic features and saturation event indices in double-variable, linear regression models for three time periods: within the growing season, out of the growing season, and throughout a year.

Depth cm	Redox depletions (Parameter A)	Redox concentrations (Parameter B)	R^2
	Within growing season		
15	0.011	0.087	0.862
30	0.018	0.001	0.981
45	0.009	0.036	0.982
60	0.015	0.030	0.969
75	0.019	0.030	0.975
90	0.020	0.041	0.978
	Out of growing season		
15	0.038	0.393	0.873
30	0.051	0.001	0.997
45	0.034	0.058	0.991
60	0.039	0.050	0.971
75	0.035	0.063	0.963
90	0.032	0.074	0.967
	Throughout a year		
15	0.050	0.480	0.876
30	0.070	0.003	0.997
45	0.044	0.094	0.991
60	0.054	0.081	0.977
75	0.054	0.094	0.978
90	0.053	0.116	0.985

causes the soils to maintain higher moisture contents when unsaturated than would be expected in sandy soils. As water contents increase there is less pore space available for oxygen storage. When the water table rises, we expect that the Bertie soils will become Fe reduced faster than would the sandy soils of the Greenville site. Faster development of Fe reduction means that for a given saturation event more gray color (redox depletions) would be produced.

Differences between the redox depletion-saturation event relationships between the two sites were most apparent during the growing season. Data from both sites were combined to correlate the redox depletion percentage and saturation event index throughout a year with good results. As shown in **Fig. 16**, good correlations were obtained for depths $\geq$ 45 cm with r^2 values above 0.9 at 45 and 60 cm, and above 0.8 at 75 and 90 cm. Without considering the soil texture, these relationships are more convenient to use than those obtained separately at either the Greenville site or the Bertie site. However, we recommend that if saturation events during the growing season are of interest, then it would be best to use relationships developed for each soil. The relationships between redox depletion percentage and saturation events may vary with soil temperature, because redox depletions are produced by reducing chemical reactions which dissolve Fe oxides. These reactions are catalyzed by bacteria which oxidize organic residues in the soil. Greater bacterial activity is expected during the warmer growing season period than during the winter months. As a result, a given saturation event should produce more redox depletions if it occurs during the growing season rather than outside it.

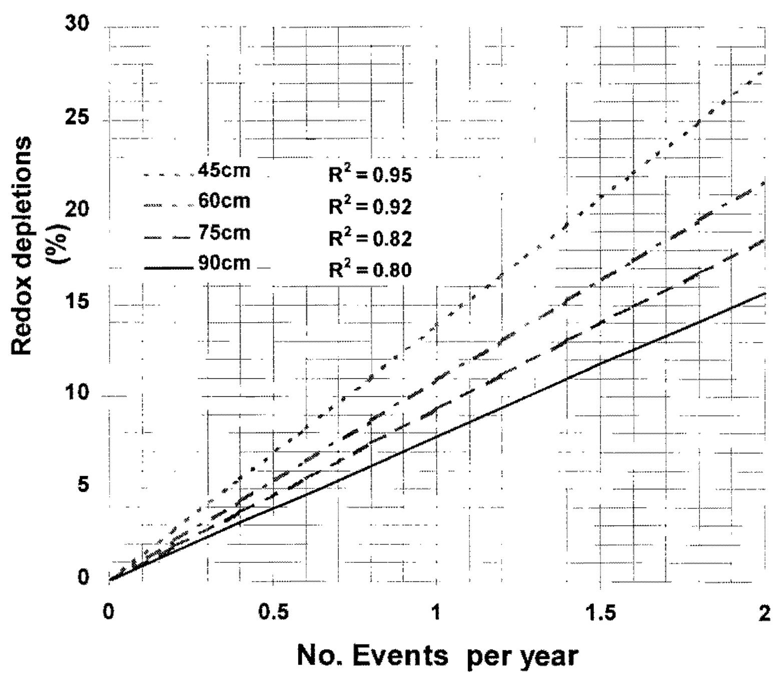

Figure 16. Relationship between percentage of redox depletions and saturation events during the year for both the Greenville and Bertie sites.

CONCLUSIONS

Similar tendencies in the change of redox depletions and redox concentrations along the drainage sequence were found in the toposequences at the two sites on North Carolina Coastal Plain. The abundance of redox depletions and redox concentrations both consistently increased from moderately well drained soils to poorly drained soils. Percentages of redox depletions were correlated with saturation-event index by simple linear regression in both sites. A good simple linear relationship between percentage of redox concentrations was established in the Bertie site, but not in the Greenville site for saturation events lasting at least 21 consecutive days. Combining both the percentage of redox depletions and percentage of redox concentrations in the correlation between saturation events and redoximorphic features gave high R^2 values above 0.9 in each of the two sites.

Differences between the relationships obtained in the two study sites were primarily caused by the differences in soil texture. Soils were sandy in the Greenville site but more silty and clayey in the Bertie site. To produce a certain amount of redox depletions (or gray colors) and redox concentrations (or red mottles), longer saturation periods or more saturation events were required in the Greenville site than in the Bertie site during the growing season. These relationships may be useful to estimate the hydrology in the soils in other areas on NC Coastal Plains, but more testing must be done to verify this.

Implications of the Research Results

Seasonal high water table determinations

In NC over 40,000 septic systems are installed each year in areas not served by municipal sewers (A. Amoozegar, personal communication). At each of these sites, soils are evaluated for their ability to allow an on-site waste disposal system to function properly. One of the assessments that must be made is to determine the *depth to seasonal high water table (DSHWT)*. The DSHWT is a concept that has not been well-defined. It is evaluated as if it were a soil property that remained virtually unchanged over time, much like sand percentage or depth to bedrock. The term implies that DSHWT is the highest level, or shallowest depth, that the water table reaches in a year. The problem with this concept is that the water table does not reach the same depth each year due to differences in rainfall amounts and distribution. Furthermore, there is no generally accepted procedure that describes how to determine the DSHWT using water table measurements. The seasonal high water table is normally determined not on the basis of water table measurements, but simply on the basis of soil color.

In practice the DSHWT is assumed to be equal to the shallowest depth at which low-chroma or gray colors occur in the soil. In most cases this is the shallowest depth that redox depletions occur in the soil. This depth is important because it is assumed that each year the soil will be saturated for some period below this depth.

Using soil color to determine the DSHWT is relatively simple and justified for soils where the hydrology has not been changed by land drainage practices such as ditching or tile drainage. However, if the water tables have been lowered by drainage practices then the depth to the low chroma colors may relate better to the water table levels that existed prior to drainage. Identifying DSHWT in these modified areas will have to be done using on-site measurements of the water table, or by use of hydrologic models in conjunction with some on-site calibration. As noted earlier, there is as yet no accepted procedure for doing this.

The results of this study can be used to show what is actually being done when field scientists identify seasonal high water table using soil color. The results can also be used to show how water table data need to be interpreted to ensure that equivalent depths are found when evaluating the seasonal high water table at a site using either on-site measurements of water table levels or soil color. As explained earlier, low chroma colors or redox depletions form when Fe oxides are reduced, dissolved and removed from the surfaces of soil particles. Reduction does not begin as soon as the soil saturates. In the Greenville site, Fe reduction occurred on average 21 days after saturation began. This means that there was a lag period of 21 days when the soil was saturated but the chemical reactions needed to form redox depletions were not occurring. If the soils were saturated for less than 21 days, then in general no redox depletions would be expected, particularly at depths of 60 cm and deeper.

When field soil scientists identify gray redox depletions they are finding the depth at which Fe reduction has occurred. This process happens when: 1) soils are saturated, 2) organic C is present, 3) bacteria are respiring and decomposing organic tissues, and 4) as part of the respiration process the electron acceptors of O_2, and $Fe(OH)_3$ are reduced along with other electron acceptors (Vepraskas 2000). While soil saturation is needed to exclude atmospheric oxygen, saturation by itself is not sufficient to ensure that Fe reduction is occurring. In summary, redox depletions are found in the soil at the points where Fe reduction has occurred. The depth at which the redox depletions are found normally does not mark the highest point that a water table has risen unless the water table remained at that point long enough to allow Fe reducing reactions to occur.

This research can be used to propose a procedure to identify a comparable DSHWT using either on-site measurements of water tables or soil color. To use water table measurements we suggest that daily measurements be made for a period of approximately six months during the time the water table is nearest the surface. For NC this would normally be in the late fall, winter, and early spring. Water table data would have to be collected during a period of normal rainfall, which is monthly rainfall occurring between the the 30^{th} and 70^{th} percentiles of the long-term averages. Once the water table data are available for a normal rainfall period, the depth at which the soil has been saturated for at least 21 consecutive days is determined, and that depth is used as the DSHWT. Comparable results should be obtained using the depth to the presence of redox depletions or low chroma soil colors.

Wetland hydrology determinations

Section 404 of the Clean Water Act requires that dredge or fill material cannot be discharged into wetlands. Accordingly, any activity that potentially could fill a wetland has to be permitted by the U.S. Army Corps of Engineers. The boundaries of jurisdictional wetlands must be delineated as part of the permitting process. Wetlands are identified on the basis of three parameters: 1) hydrophytic plants, 2) wetland hydrology, and 3) hydric soils (Environmental Laboratory 1987). Hydrophytic plants are adapted for life in saturated, anaerobic soil. Wetland hydrology requires, in essence, that an area be inundated or saturated to the surface for at least 5% of the growing season with a frequency of at least 5 years in 10. Hydric soils are those that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part (USDA-NRCS 1998).

Jurisdictional wetland boundaries are placed around areas that meet the three parameters. It is required that evidence of each parameter be present in order for an area to be considered a jurisdictional wetland. Lists of hydrophytic plants have been prepared for use in wetland identification. Hydric soils are commonly identified by looking for field indicators, and a comprehensive list of such indicators has been prepared (USDA-NRCS 1998). Wetland hydrology can be identified using field indicators where flooding or ponding have occurred (Environmental Laboratory 1987). However, the only indicator available for wetlands produced by seasonally high water tables is direct observation of the water table. This is considered impractical in most cases unless one happens to be at the site at the time water tables are high. Two or more secondary indicators of hydrology may be used but their connection to the precise definition of wetland hydrology has not been established in our opinion.

Our research suggests that the hydric soil field indicators defined by the USDA-NRCS (1998) may be used to identify wetland hydrology. The most common field indicator of hydric soils found in the U.S. is called the depleted matrix. It is defined as a layer of soil that is at least 15 cm thick, whose upper boundary begins within 20 cm of the surface, and whose matrix has a color with chroma 2 or less, and value 4 or more in at least 60% of the layer. Redox concentrations are required in an abundance of 2% or more if the matrix value is generally 4 and sometimes 5. The depleted matrix is basically a layer containing 60% or more redox depletions.

Table 14 can be used to estimate the saturation event index for a soil layer whose upper boundary is at 15 cm and whose matrix contains 60% redox depletions with 2% redox concentrations. Using the parameters shown for a depth of 15 cm during the growing season a saturation event index of approximately 0.8 event/year is computed. This means that on average, the soil would saturate for 21 to 41 consecutive days every 8 years in 10 during the growing season. This exceeds the minimum requirement of 14 days (for NC) in 5 years out of 10. In other words, soils like those at the Bertie site that meet the requirements of the depleted matrix field indicator will also meet the requirements for wetland hydrology.

By calibrating the hydric soil field indicators in this way, wetland delineators will be able to identify areas with hydric soils and wetland hydrology at the same time. More work is needed on a greater variety of soils in order to identify the needed statistical relationships between saturation events and redoximorphic features that will be required to reach this goal. The research reported here indicates such relationships can be obtained.

REFERENCES

Abdel-Dayem, S. and R. W. Skaggs. 1990. Extension of DRAINMOD for simulating water management in arid regions. Vol. II. Proceedings of Symposium on Land Drainage for Salinity Control in Arid and Semi-Arid Regions. Drain. Res. Institute, WRC, Cairo, Egypt: 201-212.

Amatya, D. M., R. W. Skaggs, and J. D. Gregory. 1997. Evaluation of a watershed scale forest hydrologic model. Agric. Water Manag. 32: 239-258.

Amoozegar, A. and A.W. Warrick. 1986. Hydraulic conductivity of saturated soils: field methods. p. 735-770. *In* A. Klute (ed.) Methods of soil analysis. Part 1, 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Boersma, L., G.H. Simonson, and D.G. Watts. 1972. Soil morphology and water table relations: I. Annual water table fluctuations. Soil Sci. Soc. Am. Proc. 36:644-648.

Buol, S. W., F. D. Hole, and R. J. McCracken. 1989. Soil genesis and classification, 3rd ed. Iowa State University Press, Ames, Iowa.

Buol, S. W. and R. A. Rebertus. 1988. Soil formation under hydromorphic conditions. p. 253-262. *In* D. D. Hook et al. (ed.) The ecology and management of wetlands. Vol. 1: Ecology of wetlands. Timber Press, Portland, OR.

Bouma, J. 1983. Hydrology and soil genesis of soils with aquic moisture regimes. p. 253-281. *In* L. P. Wilding et al. (eds.) Pedogenesis and soil taxonomy. I. Concepts and interactions. Elsevier, Amsterdam, the Netherlands.

Bouwer, H. and J. van Schlifgaarde. 1963. Simplified method of predicting fall of water table in drained land. Trans. ASAE. 6(4): 288-291.

Breve, M.A., R. W. Skaggs, J. E. Parsons, and J. W. Gilliam. 1997. DRAINMOD-N, A Nitrogen Model for Artificially Drained Soils. Trans. ASAE. 40(4): 1077-1085.

Daniels, R.B., E. E. Gamble, and L. A. Nelson. 1971. Relations between soil morphology and water-table levels on a dissected North Carolina Coastal Plain surface. Soil Sci. Soc. Am. Proc. 35:781-784.

Environmental Laboratory, 1987. Corps of Engineers Wetland Delineation Manual. Technical Report Y-87-1. US Army Engineers Waterways Experiment Station, Vicksburg, MS.

Environmental Laboratory. 1987. Corps of Engineers Wetlands Delineation Manual. U.S. Army Corps of Eng. Tech. Rep. Y-87-1. U.S. Gov. Print. Office, Washington, DC.

Fouss, J. L., R. W. Skaggs and J. S. Rogers. 1987. Two-stage weir control for subsurface drainage in humid areas. Trans. ASAE, 30(6): 1713-1719.

Gayle, G. A., R. W. Skaggs and C. E. Carter. 1985. Evaluation of a water management model for a Louisiana sugar cane field. J. Am. Soc. Sugar Cane Tech. 4: 18-28.

Gee, G.W. and J.W. Bauder. 1986. Particle-size analysis. P. 383-411. In A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. ASA and SSSA, Madison, WI.

Green, W. H. and G. Ampt. 1911. Studies of soil physics, part I. – the flow of air and water through soil. J. Agric. Sci. 4: 1-24.

Hayes, W. A., Jr. 1998. Effect of ditching on soil morphology, saturation, and reduction in a catena of Coastal Plain soil. M.S. thesis, North Carolina State University, Raleigh, NC.

Hayes, W. A., Jr. and M.J. Vepraskas. 2000. Morphological changes in soils produced when hydrology is altered by ditching. Soil Sci. Soc. Am. J. 64:1893-1904.

He, X., M.J. Vepaskas, R.W. Skaggs, and D.L. Lindbo. 2001. Adapting a drainage model to simulate water table levels in natural landscapes. Soil Sci. Soc. Am. J. (in review).

Kandil, H. M., R. W. Skaggs, S. Abdel-Dayem, and Y. Aiad. 1993. DRAINMOD-S: Water management model for irrigated lands, crop yield and application. *In*: E. Lorre (ed) Subsurface Drainage Simulation Models, Transactions of Workshop, 15th Congress ICID, The Hague: 257-275.

Karnowski, E. H., J.B. Newman, J. Dunn, and J. A. Meadows. 1974. p.71. Soil Conservation Service. U.S. Government Printing Office. Washington, D.C.

Kirkham, D. 1957. Theory of land drainage. *In* J.N. Luthin (ed.) Drainage of agricultural lands. Agron. Mon. No. 7, Amer. Soc. Agron., Madison, WI.

Klute, A. 1986. Water retention: Laboratory methods. *In* Methods of Soil Analysis, Part 1. Second edition. Am. Soc. Agron., Madison, WI. pp. 635-662.

Klute, A. and C. Dirksen. 1986. Hydraulic conductivity and diffusivity; Laboratory methods. *In* Methods of Soil Analysis, Part 1. Second edition. Am. Soc. Agron., Madison, WI. pp. 687-734.

Konyha, K. D., R. W. Skaggs and J. W. Gilliam. 1992. Effects of drainage and water management practices on hydrology. J. Irrig. Drain. 118(5): 807-819.

McCarthy, E. J., J. W. Flewelling and R. W. Skaggs. 1992. A hydrologic model for a drained forested watershed. J. Irrig. Drain. Eng. 118(2): 242-255.

Mitsch, W. J. and J. G. Gosselink. 1993. Wetlands. 2nd ed. Van Norstand Reinhold Co., New York, NY.

Pickering E. W., and P. L. M. Veneman. 1984. Moisture regimes and morphological characteristics in a hydrosequence in central Massachusetts. Soil Sci. Soc. Am. Proc. 48:113-118.

Ponnamperuma, F. N. 1972. The chemistry of submerged soils. Adv. Agron. 24: 29-96.

Richards, L. A. and L. R. Weaver. 1943. Fifteen atmosphere percentage as related to the permanent wilting percentage. Soil Sci. 56:331-340.

Robbins, K. D. 1988. Simulated climate inputs for DRAINMOD. Ph.D. dissertation. North Carolina State University. Raleigh, NC.

SAS Institute, Inc. 1998. SAS user's guide. Version seven. SAS, Inc., Cary, NC.

Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and W.D. Broderson. 1998. Field book for describing and sampling soils. Version 1.1. Natural Resources Conservation Center, USDA, National Soil Survey Center, Lincoln, NE.

Simonson, G.H. and L. Boersma. 1972. Soil morphology and water table relationships. II. Correlation between annual water table fluctuations and profile features. Soil Sci. Soc. Am. Proc. 36:649-653.

Skaggs, R. W. 1978. A water management model for shallow water table soils. Technical Report 134. Water Res. Inst., Raleigh, NC.

Skaggs, R. W. 1980. Combination surface-subsurface drainage systems for humid regions. J. Irrig. Drain. Div., ASCE. 106 (IR4) 265-283.

Skaggs, R. W. 1982. Field evaluation of a water management model. Trans. ASAE 25(3): 666-674.

Skaggs, R.W. 1999. Drainage simulation models., p. 461-492. *In* R.W. Skaggs and J. van Schilfgaarde (eds.) Agricultural Drainage. Agron. Monogr. 38, ASA, CSSA, and SSSA, Madison, WI.

Skaggs, R.W., D. Amatya, R.O. Evans, and J.E. Parsons. 1994. Characterization and evaluation of proposed hydrologic criteria for wetlands. J. Soil Water Conserv. 49(5):501-510.
Soil Survey Staff. 1975. Soil Survey Manual. US Department of Agriculture Handbook No. 18, 2nd ed. U.S. Gov. Print. Off., Washington, D.C.
Tant, P. L., R. H. Ranson, J. A. Gagnon, E. W. Mellette, I. M. Allen, and W. A. Hayes, Jr. 1990. Soil Survey of Bertie County, NC. p. 83. United States Department of Agriculture, Soil Conservation Service.
Thornthwaite, C. W. 1948. An approach toward a rational classification of climate. Geog. Rev. 38: 55-94.
Uhland, R. E. 1950. Physical properties of soils modified by crops and management. Soil Sci. Soc. Am. Proc. 14:361-366.
United States Dep. of Agriculture, Natural Resources Conservation Service. 1998. Field indicators of hydric soils in the United States. Version 4.0. G.W. Hurt, P.M. Whited, and R.F. Pringle (eds.) USDA, NRCS, Ft. Worth, TX.
Veneman, P.L.M., L.A. Spokas, and D.L. Lindbo. 1998. Soil moisture and redoximorphic features: A historical perspective. P. 1-23. *In* M.C. Rabenhorst, J.C. Bell, and P.C. McDaniel (eds.) Quantifying soil hydromorphology. SSSA Special Publ. No. 54, Soil Sci. Soc. Am., Madison, WI.
Vepraskas, M. J. 1996. Redoximorphic features for identifying aquic conditions. Tech. Bull. 301. NC Agric. Exp. Sta., Raleigh, NC.
Vepraskas, M.J. 1999. Redoximorphic features for identifying aquic conditions. NC Agric. Res. Serv. Tech. Bull. 301, Raleigh, NC.
Vepraskas, M. J. 2000. Morphological features of seasonally reduced soils. p. 163-182. In J. L. Richardson and M. J. Vepraskas. (ed.) Wetland Soils-Genesis, Hydrology, Landscapes, and Classification. CRC Press LLC. Boca Raton, Florida.
Vepraskas, M.J. 2000. Morphological features of seasonally reduced soils. Chpt. 7. In J.L. Richardson and M.J. Vepraskas (eds.) Wetland soils: genesis, hydrology, landscapes, and classification. Lewis Publ., Boca Raton, FL.
Workman, S. R., J. E. Parsons, G. M. Chescheir, R. W. Skaggs, and J. F. Rice. 1994. DRAINMOD User's guide. NRSC. United States of Department of Agriculture.
Zhao, S.L., S.C. Gupta, D.R. Huggins, and J.F. Moncrief. 2000. Predicting subsurface drainage, corn yield and nitrate nitrogen losses with DRAINMOD-N. J. Environ. Qual. 29:817-825.