EFFECT OF MINOR DRAINAGE ON HYDROLOGY OF FORESTED WETLANDS

advances in forest hydrology

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ABSTRACT. *Results of a simulation study to determine the impacts of minor drainage for silviculture on wetland hydrology are presented in this article. Long-term DRAINMOD simulations were conducted to determine the threshold drainage intensity (ditch depth and spacing) that removes wetland hydrology from forested wetlands. Analyses were conducted for 13 soil series and profile combinations at ten locations from Norfolk, Virginia, to Baton Rouge, Louisiana, in the Atlantic and Gulf coastal states. Threshold ditch spacings (L_T) were obtained for five ditch depths for all combinations of soil profiles and locations. Analysis of the results showed that L_T can be approximated as $L_T = C\sqrt{T}$, where T is the horizontal hydraulic transmissivity of the soil profile, and C is a coefficient dependent on ditch depth and geographic location. The C values for all combinations of ditch depth and location are given in this article. The threshold spacings can be used as benchmarks to directly evaluate the impact of drainage alternatives on wetland hydrology. They were also used herein to determine T_{25} inputs for previously developed methods to predict the lateral impact of a single ditch on wetland hydrology. Lateral impacts were determined and presented for a 0.9 m (3 ft) deep drainage ditch for all soils and locations considered. The T_{25} values presented can be used to determine lateral impacts for other ditch depths and soils. The analyses in this study were conducted for a surface depressional storage of 5 cm. More work is needed to define T_{25} values for smaller surface storages, including those smaller values needed for application to agricultural cropland.*

Keywords. *Drainage, Minor drainage, Silviculture, Wetland forests, Wetland hydrology.*

Drainage for silviculture is a common practice in poorly drained soils of the south and southeast. In many cases, the lands affected by the practice are jurisdictional wetlands. In such cases, drainage is allowed as part of ongoing silvicultural activities, which are exempted under Section 404 of the federal Clean Water Act (1972); however, the drainage prescription should be "minor" and not convert the site to a non-wetland condition. The silvicultural drainage system should be sufficient to provide access to the lands for forest operations without damaging the soil and water resources, and to facilitate regeneration of the site. A drainage system for facilitating silvicultural activities typically incorporates a network of relatively shallow (0.6 to 1.2 m, 2 to 4 ft deep) field ditches, which empty into collector ditches and main canals (Terry and Campbell, 1981). Since it is assumed that silvicultural drainage systems do not significantly alter the wetland hydrology, they are typically termed "minor drainage." The purpose of this study is to evaluate the effects of minor drainage on wetland hydrology and to provide a basis for guidelines to reduce impacts on jurisdictional wetlands.

Before proceeding, it is necessary to define the hydrologic criterion for wetlands. The criterion may be expressed as follows: wetland hydrology exists on a site if, during the growing season, the water table is normally within 30 cm of the surface for a continuous critical duration. The 1987 U.S. Army Corps of Engineers Wetland Delineation Manual (USACE, 1987) specifies the critical duration as 5% to 12.5% of the length of the growing season. Recognizing the uncertainty in the data supporting a critical duration, the National Research Council Committee on Characterization of Wetlands (NRC, 1995) recommended that a duration of 14 days be used until more definitive limits could be determined. This duration has been accepted by the USACE as a basis for analyzing observed water table data to determine wetland hydrologic status (USACE, 2005). Accordingly, the critical duration was set to 14 days for this study. For many years, the growing season has been defined as the period between the average last date of -2°C (28°F) in the spring to the average first date of -2°C (28°F) in the fall, as given in the published county soil survey. A recent U.S. Army Corps of Engineers guidance document (USACE, 2008) for the coastal plains of the south and southeast defines the growing season in terms of soil temperature at depth 30 cm (1 ft). It specifies that, for purposes of monitoring water tables to determine wetland hydrologic status, the growing season includes any day when the minimum soil temperature at the 30 cm depth is above 5°C. The document states that when on-site data for soil temperatures at the 30 cm depth are unavailable, the growing season may be approximated by the median dates of -2°C (28°F) air temperature, as specified above. This approach was taken in this study, as soil temperatures at 30 cm depth were not

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available. Finally, the word "normally" in the criterion is defined as meaning that water table conditions satisfying the criterion occur at least once in two years on average (e.g., 25 out of 50 years).

The effects of drainage on hydrology, and therefore on wetland hydrology, are dependent on soil properties, topography (including surface depressions), crop or vegetative cover, climate (rainfall and evapotranspiration), growing season (therefore location), and drainage system design and intensity. The objective was to provide guidance in identifying limits to minor drainage for silvicultural purposes so that the effects do not compromise the jurisdictional wetland hydrology. Our approach was to conduct a simulation study, using the drainage water management model DRAINMOD (Skaggs, 1982, 1999), to analyze effects of minor drainage on wetland hydrology.

APPROACH

Simulations were conducted to determine threshold ditch spacings for benchmark soils that are commonly drained for silvicultural purposes in the Atlantic and Gulf coastal plains. A schematic of a forest soil drained with a system of parallel drainage ditches is shown in figure 1. Drainage may also be provided by single ditches constructed to remove excess water from depressions or other wet areas. However, the most prevalent need for drainage in the southeast is in the broad, nearly flat areas between streams in the lower coastal plains, where most of the land requires drainage for agricultural or forestry production. Drainage necessary for forestry in these areas is most efficiently and commonly done by the use of parallel open ditches. Silviculture drainage is most critical during the harvesting and regeneration (planting) stages, which occur during a 2 to 5 year period over the typical 25 to 35 year rotation of a southern pine forest. Drainage requirements are thus much less intensive than for other land uses, such as agricultural production, for example. In most cases, ditches for silviculture are not as deep and are spaced at distances much greater than would be used for agriculture or other land uses. However, even a shallow ditch may remove wetland hydrology from a strip of land directly adjacent to the ditch. The threshold ditch spacing is defined for this analysis as the spacing that would just barely remove wetland hydrology from the land midway between the drainage ditches. It is therefore an indicator of the effect of drainage on wetland hydrology for a given soil at a given location. Ditches spaced farther apart than the threshold spacing will remove wetland hydrology from a strip close to the ditch, but wetland hydrology will continue to be present in a portion of the transect between the ditches. Once the threshold spacing has been defined, recently developed methods (Skaggs et al., 2005; Phillips et al., 2010) can be used to calculate the width of the strip adjacent to the ditch from which wetland hydrology has been removed.

The DRAINMOD model conducts a water balance in the soil profile between parallel drains and predicts, on an hour-by-hour, day-by-day basis, water table depth, drainage, evapotranspiration (ET), and surface runoff for given weather, soil properties, vegetative cover, and site conditions. Simulations are typically conducted for long periods of time to reflect the natural variability of rainfall and evapotranspiration. Daily water table depths are predicted, allowing the results to be analyzed to determine whether the hydrologic criterion for wetlands is satisfied for a given site. Reliability of the model predictions has been verified in extensive field experiments (Skaggs, 1982; Chang et al., 1983; Rogers, 1985; Susanto et al., 1987; Fouss et al., 1987; Youssef et al., 2006; Thorp et al., 2009; Ale et al., 2009; Salazar et al., 2009, and others). The model has also been tested and applied to characterize wetland hydrology on numerous sites (Skaggs et al., 1980, 1994; Chescheir et al., 1992; Broadhead et al., 1989; Hunt et al., 1995, He et al., 2002, 2003; Vepraskas et al., 2004; Vepraskas and Caldwell, 2008; Caldwell et al., 2007).

DRAINMOD was programmed for application to wetlands by adding a counter that accumulates the number of days that the water table remains continuously above (closer to the surface than) a specific depth. Elements defining the criterion are read into DRAINMOD as inputs and used together with daily predicted water table depths to determine if the wetland hydrologic criterion is satisfied on an annual basis. Results for the 50-year period are then analyzed to determine if the hydrologic criterion is satisfied for more than 50% of the years, and wetland hydrologic status is defined accordingly.

EXAMPLE

The following example demonstrates how DRAINMOD was used to determine the effect of ditch spacing and depth on the wetland hydrologic status of forested lands. This analysis was conducted for a Cape Fear sandy loam soil located near Plymouth, North Carolina. Soil property inputs to the model will be discussed in a later section. They include saturated hydraulic conductivity for the various layers of the profile, the relationship between drained water free pore space and water table depth, and several other inputs affecting infiltration, evapotranspiration, surface storage and runoff, and subsurface drainage. Weather data for the 50-year period 1956-2005 were used to simulate the water table depth on a day-by-day basis for a range of drain spacings and depths.

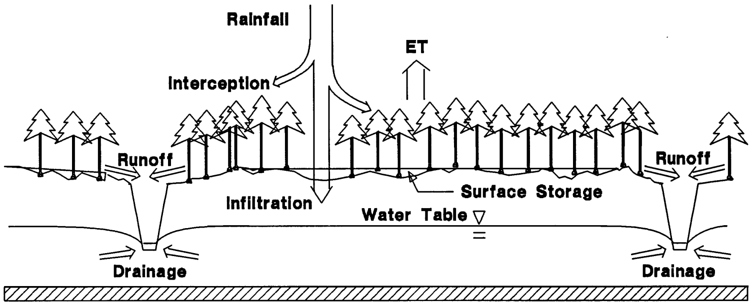

Figure 1. Schematic of parallel ditch drainage for silviculture (after Skaggs et al., 1994).

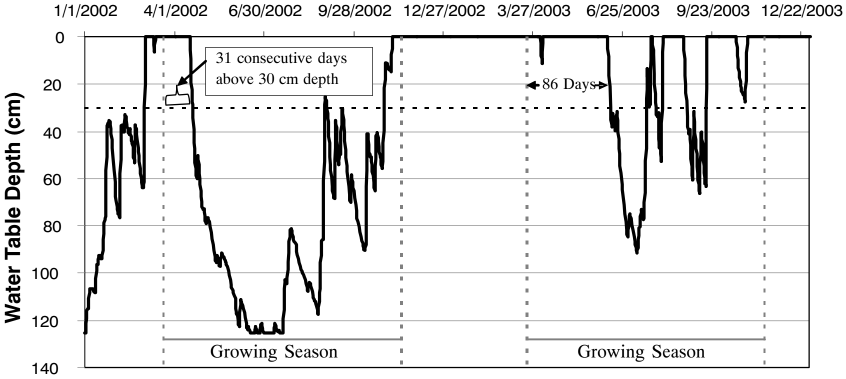

Figure 2. Water table depth predicted by DRAINMOD for locations midway between 0.9 m deep parallel drainage ditches spaced 100 m apart in a Cape Fear sandy loam soil near Plymouth, North Carolina, in 2002-2003.

The typical parallel ditch spacing for silviculture on this soil is 100 m (330 ft). Water table depths predicted by DRAINMOD for ditches 0.9 m (3 ft) deep and 100 m apart are plotted in figure 2 for years 2002 and 2003. The longest continuous period when the water table remained in the top 30 cm of the profile in 2002 was 31 days. Year 2003 was wetter than 2002, especially in the winter and early spring. The water table remained at the surface until about June 1 and was within 30 cm of the surface for a continuous period of 86 days during the growing season, clearly much greater than the 14-day requirement for wetland hydrology. Results of the longest period during the growing season for each year were summarized for all 50 years, and the number of years when that period was greater than or equal to the 14-day threshold was determined. In the case of the 100 m spacing, that number was 47 years. That is, for drains 0.9 m deep and 100 m apart, the water table in the region midway between the drains will satisfy the depth and duration requirements of the hydrologic criterion for wetlands in 47 of 50 years, or 94% of the years. Since this is greater than 50% of the years, the wetland hydrologic criterion is satisfied. The same analysis was conducted for drain spacings varying from 10 to 300 m. Results plotted as a function of drain spacing in figure 3 indicate that the threshold ditch spacing is 25 m. That is, for a 0.9 m ditch depth on this Cape Fear soil at Plymouth, North Carolina, the wetland hydrologic criterion will be satisfied in more than 50% of the years for a ditch spacing greater than 25 m. The criterion will not be satisfied for ditch spacing less than 25 m for these conditions and this location.

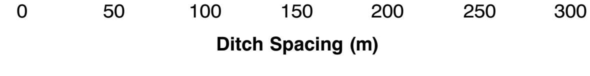

Figure 3. Effect of ditch spacing on number of years wetland criterion for hydrology is satisfied for Cape Fear soil at Plymouth, North Carolina. Ditch depth is 0.9 m (3 ft); surface depressional storage is 5.0 cm.

SELECTION OF BENCHMARK SOILS

A total of 75 soil series, which are commonly forested and are classified as very poorly, poorly, or somewhat poorly drained, were identified as candidates for our study (www.bae.ncsu.edu/soil_water/methods_data.php). In order to select soils for the analyses, an approach based on expert opinion was used. Inquiries were sent to professionals with experience in silvicultural minor drainage in the southeastern U.S. to ascertain the soil series that are typically subject to minor drainage and which ones were predominate. Those responses in conjunction with the intent to cover the range in soil texture provided the basis for identifying eight benchmark soils (table 1) used in the detailed analysis of this study. Since the soils were selected to represent a range in texture and organic matter content among soils that commonly use prescribed minor drainage for silviculture in the Atlantic and Gulf coastal plain, the results from this analysis can be extrapolated to other soil series based on texture, drainage class, and transmissivity of the profile. All soils listed in table 1 are hydric soils and, under natural undrained conditions, would support wetland vegetation. Vegetation on the sites simulated was assumed to be pine or a mixture of pine and hardwood.

SOIL PROPERTIES

Soil property inputs to DRAINMOD are documented in the model and in the DRAINMOD Reference Report available from the USDA Natural Resource Conservation Service (NRCS) Wetland Science Institute. The Reference Report can also be found at: www.bae.ncsu.edu/soil_water/documents/drainmod/chapter5.pdf. A summary of the inputs for the soils selected for this study is given in table 2. Data for three of the soils (Cape Fear, Coxville, and Tomotley) were obtained from our previous research and are given by Skaggs and Nassehzadeh-Tabrizi (1986). Input data for the other five soils were obtained from a database originally developed by Carlisle et al. (1985) and published in a series of Soil Science Research Reports by the University of Florida. These data, which include soil water characteristic (or water release) data for unsaturated conditions, cover most of the soil series in the state of Florida, and, important to this study, all five of the remaining soils in table 1. The Florida soils data are available at: http://flsoils.ifas.ufl.edu/index.asp.

One of the most important DRAINMOD inputs is the saturated hydraulic conductivity (*K*) of each layer of the profile. These values are given in table 2 for each soil in units of cm h^{-1}, which are the units required in the model. Also given are

Table 1. Benchmark soil series selected for DRAINMOD simulation analyses. All of these poorly drained soils are common to the Atlantic and Gulf coastal plains.

Drainage Class	Subsoil Texture Clays (C, SiC, SC)	Clay Loams (CL, SiCL, SCL)	Loams (Si, L, SiL, SL)	Sands (LS, S)
Very poorly drained	Cape Fear	Pantego	Torhunta	Pamlico
Poorly drained	Coxville	Tomotley	Plummer	Leon

Table 2. Summary of soil property inputs for DRAINMOD for the soils considered in this study.[a]

Soil	Drainage Class	Profile Depth (cm)	Bottom Depth (cm) of Layers 1 to 4				Conductivity (cm h^{-1}) of Layers 1 to 4				T (cm^2 h^{-1})	Θ_s (cm^3 cm^{-3})	Θ_{ll} (cm^3 cm^{-3})	f (cm cm^{-1})
			1	2	3	4	1	2	3	4				
Cape Fear	VPD	300	41	122	300	--	10	0.3	8.2	--	473	0.48	0.22	0.057
Pantego 1	VPD	203	30	43	178	203	3.7	4.8	0.1	0.2	192	0.53	0.25	0.021
Pantego 2	VPD	300	36	175	300	--	8.2	3.2	8.2	--	1765	0.53	0.26	0.021
Torhunta 1	VPD	215	43	58	91	183	6.4	13.2	17.3	5.7	1751	0.42	0.17	0.024
Torhunta 2	VPD	300	28	127	300	--	3.2	10	15	--	3675	0.42	0.17	0.024
Pamlico 1	VPD	152	38	84	109	152	45	27	15	6.2	3594	0.86	0.6	0.12
Pamlico 2	VPD	300	69	300	--	--	8.2	32.5	--	--	8073	0.86	0.6	0.12
Coxville	PD	200	20	120	200	--	5	0.75	1	--	188	0.45	0.22	0.023
Tomotley	PD	170	100	170	--	--	1	3	--	--	310	0.46	0.2	0.022
Plummer 1	PD	132	56	109	132	--	9.3	3.1	5.5	--	812	0.42	0.16	0.024
Plummer 2	PD	300	71	300	--	--	15	3.2	--	--	1798	0.42	0.16	0.024
Leon 1	PD	183	99	122	152	183	11	3.8	2.1	0.7	1261	0.56	0.29	0.055
Leon 2	PD	300	41	86	150	300	15	8	8	8	2718	0.56	0.29	0.055

[a] T = transmissivity, Θ_s = saturated water content, Θ_{ll} = lower limit water content, and f = drainable porosity for water table depth range of 0 to 30 cm.

values for volumetric soil water contents of the surface horizon at saturation and at the lower limit available to plants (estimated as permanent wilting point in most cases). The horizontal hydraulic transmissivity of the profile, which is the sum of the product of K and depth of each soil layer, is not a DRAINMOD input but is an indicator of the potential rate of subsurface drainage, and is given in table 2 for reference. Note that there are two entries for five of the eight soils. The first entry (e.g., Pantego 1) reflects data from the research reports or the online database. The second entry (e.g., Pantego 2) estimates the saturated hydraulic conductivity (K) by soil horizon or layer based on data provided in the NRCS Soil Survey for the specific soil series. A range of K values for each horizon is given in the soil survey. The values in table 2 are midrange or average values for each case. Depth to the restrictive layer is not always clear from published soil property data. Where that was the case, the depth from the soil surface to the restrictive layer was assumed to be 300 cm (about 10 ft). In most cases, this depth would be deeper than the actual depth of a restrictive layer and will provide an indication of the maximum effect of drainage on wetland conditions for these soils. Note that there is considerable difference between the first and second entries for the K values and thickness of soil layers for some of the soils. This reflects variability within the soil series. Analyses were conducted for both cases to reflect the variability of the impact of minor drainage that can be expected within a soil series.

The relationship between the "drained to equilibrium" water-free pore space (V_d, cm [cm^3/cm^2]) and water table depth (cm) is an important DRAINMOD input. This pore volume (V_d) is the depth (or volume per unit surface area) of water that would be drained if the water table were lowered from the surface to a given depth. The relationship is calculated from the soil water characteristics of the profile layers and is given in figure 4 for the eight soils considered in this study. The slope of this curve is the drainable porosity (f).

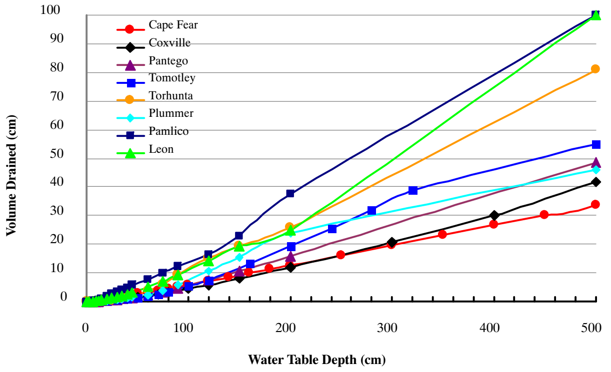

Figure 4. Relationship between drained volume (per unit surface area) in profile and water table depth (under "drained to equilibrium" conditions) for eight benchmark soils of the Atlantic and Gulf coastal plains.

Soil water characteristic data for the surface horizon are required DRAINMOD inputs and are given for all profile layers of the eight soils, along with tabular relationships between water table depth (WTD), V_d, and maximum steady upward flux (UPFLUX) in the appendix to the final report (www.bae.ncsu.edu/soil_water/methods_data.php). Simulations were conducted for ten locations distributed from Norfolk, Virginia, in the east to Baton Rouge, Louisiana, in the west to represent the effect of different weather conditions and growing seasons. The locations along with weather and growing season parameters are summarized in table 3. The eight soils considered in this analysis naturally occur in most, but not all, of the ten locations. There are soils at all of the ten locations with a similar range in properties to the eight soils in table 1. Analyses were conducted for drainage ditch depths ranging from 0.6 to 1.2 m (2 to 4 ft) in 0.15 m (0.5 ft) incre-

Table 3. Summary of climate and growing season parameters for sites where the effect of minor drainage on wetland hydrology was simulated in this study. The growing season was defined by the average last date of -2°C (28°F) air temperature in the spring to the average first date in the fall or winter.

Location	Latitude (°)	Longitude (°)	Annual Averages (mm) Rainfall	PET	Average Daily Temp. (°C)	Growing Season Start	End
Norfolk, Virginia	36.9	76.19	1163	909	15.5	March 3	Dec. 5
Nashville, Tennessee	36.12	86.69	1217	892	15.2	March 26	Nov. 13
Plymouth, North Carolina	35.87	76.66	1298	945	16.2	March 21	Nov. 15
Wilmington, North Carolina	34.27	77.9	1412	1006	17.6	March 1	Dec. 3
Charleston, South Carolina	32.9	80.04	1334	1161	18.6	Feb. 17	Dec. 13
Savannah, Georgia	32.13	81.21	1260	1115	19.1	Feb 17	Dec. 15
Jacksonville, Florida	30.5	81.69	1349	1199	20.4	Feb. 6	Dec. 23
Tallahassee, Florida	30.39	84.35	1631	1128	19.7	Feb. 28	Nov. 26
Mobile, Alabama	30.69	88.25	1671	1044	19.7	Feb. 15	Dec. 14
Baton Rouge, Louisiana	30.54	91.15	1506	1067	19.8	Feb. 8	Dec. 11

ments for each soil at all locations. Ditches may be cleaned periodically to maintain their original depth, or sometimes allowed to silt in over the course of a 25 to 35 year rotation. Results for the range of depths considered herein will allow determination of the effect of drainage on wetland hydrology at all stages.

RESULTS AND DISCUSSION

Predicted threshold ditch spacings are summarized in table 4 for ditch depths ranging from 0.6 to 1.2 m (2 to 4 ft) for all soils at Wilmington, North Carolina. Similar results for all ten locations in the south and southeast are available in Skaggs et al. (2009). Saturated hydraulic conductivity was determined from two sources for five of the soils, so threshold spacings were determined for 13 soil profiles at each of the ten locations. Wetland hydrology would be removed from the site for ditches spaced closer than the spacings given in table 4. As expected, threshold spacings increase with drain depth and with hydraulic transmissivity of the profile. For example, the threshold spacing for the Cape Fear soil at Wilmington increases from 14 m for a 0.6 m ditch depth to 23 m for a 1.2 m depth. Ditches for silviculture are almost never closer than 100 m (330 ft), so ditches would remove wetland hydrology from only a small strip adjacent to the ditch from this soil. On the other end of the spectrum, the threshold spacing for Pamlico 2 muck for the same location was predicted to be 114 m for a 0.6 m ditch depth and 204 m for a 1.2 m deep ditch. Hydraulic transmissivity for this fibrous organic soil is very high ($T = 8073$ cm^2 h^{-1}), so a 100 m (330 ft) ditch spacing would remove wetland hydrology from the site. However, ditches spaced at 100 m would not be required for silviculture for this soil, which could be adequately drained with ditches at much wider spacings.

Results for all soils at all ten locations for ditch depths of 0.6, 0.9, and 1.2 m (2, 3, and 4 ft) are given in table 5. These results show that the threshold ditch spacing varies with location, but differences between locations were not as great as might be expected. In terms of wetland hydrology, the wettest location of those considered, as indicated by the smallest threshold ditch spacing, is Mobile, followed closely by Tallahassee and Baton Rouge, and then, in order of threshold ditch spacing, Wilmington, Charleston, Jacksonville, Savannah, Norfolk, Plymouth, and Nashville.

For a given location and surface depressional storage, threshold spacings were affected more by the hydraulic transmissivity (T) of the profile than by any other factor. This seems reasonable, as precipitation and potential evapotranspiration are the same for all soils at the same location, and T is the soil property most closely related to the rate at which water would drain laterally from the profile. The T value is given for each soil in table 2. Threshold drain spacings are plotted as a function of T for ditch depths of 0.6, 0.9, and 1.2 m (2, 3, and 4 ft) for the Wilmington, North Carolina, location in figure 5. Note that for a given depth (D), points on the plots represent different soil profiles. A power function was fitted to the points to give an equation that could be used to estimate the threshold spacing in terms of T. The equation may be written as:

$$L_T = CT^E \tag{1}$$

where L_T is the threshold ditch spacing (m), T is hydraulic transmissivity of the profile (cm^2 h^{-1}), and C and E are equation coefficients. Similar analyses were conducted on results for all ten locations. As shown in figure 5, the power function did not predict the threshold spacing without error. R^2 values ranged from about 0.82 to 0.95 across all ditch depths and locations. Other factors such as drainable porosity, and soil properties influencing infiltration and evapotranspiration, affect the threshold spacing and are not considered by this sim–

Table 4. Predicted threshold ditch spacing (m) for benchmark soils at Wilmington, North Carolina. Surface storage is 5 cm. Ditch spacing closer than the threshold spacing will remove wetland hydrology from the site.

Soil	Ditch Depth 0.6 m (2 ft)	0.75 m (2.5 ft)	0.9 m (3 ft)	1.05 m (3.5 ft)	1.2 m (4 ft)	T (cm^2 h^{-1})	$\sqrt{T}$
Cape Fear	14	16	18	20	23	473	21.7
Coxville	24	27	29	31	32	188	13.7
Leon 1	49	56	62	68	71	1261	35.5
Leon 2	72	86	99	108	118	2687	51.8
Pamlico 1	68	76	84	90	96	3594	59.9
Pamlico 2	115	137	161	182	204	8073	89.8
Pantego 1	20	22	24	26	27	192	13.9
Pantego 2	66	75	84	90	96	1765	42.0
Plummer 1	41	46	49	51	52	812	28.5
Plummer 2	65	75	82	90	98	1798	42.4
Tomotley	28	30	33	35	37	310	17.6
Torhunta 1	76	86	100	110	118	1751	41.8
Torhunta 2	98	112	132	142	156	3675	60.6

Table 5. Predicted threshold ditch spacings (m) for three ditch depths at all locations and for all soils. Surface depressional storage is 5 cm.

Soil	Norfolk, Va.	Plymouth, N.C.	Wilmington, N.C.	Charleston, S.C.	Savannah, Ga.	Jacksonville, Fla.	Tallahassee, Fla.	Nashville, Tenn.	Mobile, Ala.	Baton Rouge, La.
Ditch depth = 0.6 m (2 ft)										
Cape Fear	17	17	14	14	15	14	12	20	11	12
Coxville	25	27	24	24	25	24	21	29	20	21
Leon 1	54	56	49	53	55	51	43	63	39	45
Leon 2	84	84	72	81	84	79	65	93	58	65
Pamlico 1	80	80	68	78	79	72	59	88	53	63
Pamlico 2	146	141	115	144	146	138	100	155	95	106
Pantego 1	21	22	20	20	21	21	18	25	17	17
Pantego 2	70	75	66	69	73	71	59	82	55	59
Plummer 1	40	47	41	43	45	43	37	51	35	37
Plummer 2	70	73	65	69	73	71	57	81	53	57
Tomotley	29	31	28	27	30	29	25	33	23	25
Torhunta 1	82	87	76	80	86	81	66	94	61	68
Torhunta 2	106	114	98	106	110	105	85	121	79	89
Ditch depth = 0.9 m (3 ft)										
Cape Fear	23	25	18	20	21	19	17	29	15	17
Coxville	31	33	29	30	31	29	26	35	24	26
Leon 1	69	73	62	70	73	64	53	78	49	55
Leon 2	108	118	99	112	116	106	82	122	76	87
Pamlico 1	106	101	84	102	105	92	73	110	68	77
Pamlico 2	201	192	161	220	224	208	133	214	130	147
Pantego 1	27	27	24	24	25	25	22	30	20	21
Pantego 2	89	95	84	90	93	89	74	102	67	76
Plummer 1	53	57	49	51	53	51	43	61	39	45
Plummer 2	92	97	82	90	93	90	73	102	67	75
Tomotley	37	39	33	34	36	34	30	41	27	30
Torhunta 1	107	115	100	113	112	103	84	124	77	87
Torhunta 2	142	152	132	148	146	133	112	159	100	114
Ditch depth = 1.2 m (4 ft)										
Cape Fear	29	33	23	26	29	25	22	39	19	22
Coxville	37	37	32	33	35	33	29	41	27	30
Leon 1	79	84	71	82	84	74	59	86	55	61
Leon 2	138	138	118	148	139	132	99	144	92	102
Pamlico 1	119	113	96	118	118	106	80	122	77	86
Pamlico 2	248	252	204	284	278	282	165	254	154	182
Pantego 1	30	30	27	27	28	28	24	33	23	24
Pantego 2	109	113	96	106	110	103	86	118	77	88
Plummer 1	57	61	52	57	57	53	47	65	42	47
Plummer 2	107	113	98	113	113	104	86	120	77	87
Tomotley	42	45	37	40	42	37	33	47	31	34
Torhunta 1	133	138	118	136	142	128	99	142	93	101
Torhunta 2	176	179	156	186	190	176	132	186	122	130

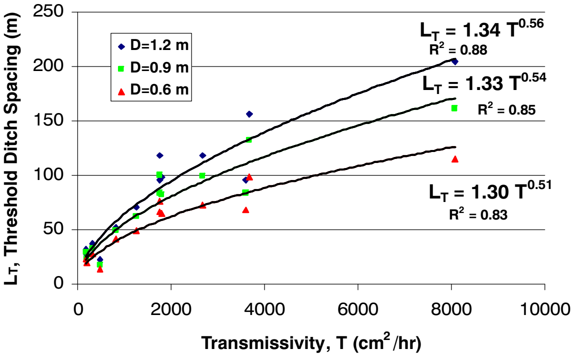

Figure 5. Effect of hydraulic transmissivity (*T*) of soil profile on threshold ditch spacing for three ditch depths at Wilmington, North Carolina. Surface depressional storage is 5 cm.

ple equation. Nevertheless, the equation provides an easy means of estimating the threshold ditch spacing (the spacing that would remove wetland hydrology) once the equation coefficients are defined. Examination of results for all ditch depths and locations indicated that the exponent in equation 1 was close to 0.5 in all cases. This is consistent with drainage theory, as the drain spacing required to maintain a minimum water table depth under steady rainfall conditions, as predicted by the Ellipse or Hooghoudt equations (van der Ploeg et al., 1999), is proportional to $T^{0.5}$.

In order to further simplify the equation, a separate analysis was conducted to fit the following equation to the data in table 4:

$$L_T = C\sqrt{T} \tag{2}$$

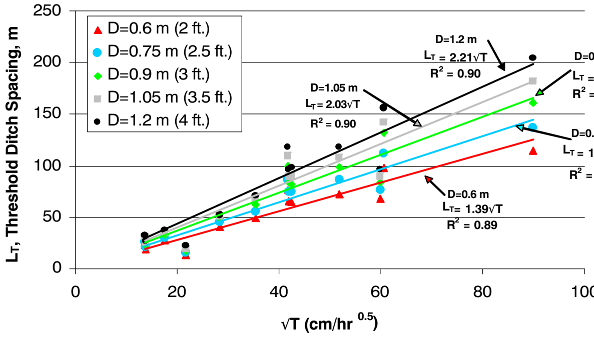

Figure 6. Effect of square root of transmissivity (*T*) on threshold drain spacing (L_T) for wetland hydrology for different ditch depths at Wilmington, North Carolina. Surface storage is 5 cm.

The results are shown in figure 6 for the Wilmington, North Carolina, location. Similar results were obtained for all other locations (not shown). Values for the coefficient *C* are given in table 6 for all ditch depths and all locations considered.

The results in tables 5 and 6 can be used to estimate the effect of minor drainage for silviculture on wetland hydrology for forested soils in the south and southeast. For the specific soils analyzed in this study, table 5 can be used directly to determine threshold ditch spacings that would remove wetland hydrology. For example, the results in table 5 for the Cape Fear, Coxville, and Tomotley soils indicate threshold ditch spacings of less than 40 m for all ditch depths considered. Thus, conventional silviculture ditch spacings of 100 to 200 m would remove wetland hydrology from only a relatively narrow strip of the landscape adjacent to the ditch. On the other hand, 1.2 m deep ditches spaced 100 m apart would remove wetland hydrology from soils with higher transmissivities, such as the Torhunta and Pamlico soils. Adequate drainage for silviculture can likely be provided with ditch spacings of 300 m or wider for these soils. As discussed previously, hydraulic conductivities and profile transmissivities vary substantially within soil series. Threshold ditch spacings for the soils represented in table 5, but having different layer depths and hydraulic conductivities, can be determined by interpolation using equation 2. For soils not considered directly herein, and therefore not represented in table 5, threshold ditch spacings can be estimated using equation 2 with the appropriate *C* value from table 6.

EXAMPLE

Consider a sandy loam soil located near Norfolk, Virginia, with the following layers and lateral *K* values:

Layer 1: 0 to 40 cm, $K = 10$ cm h^{-1}
Layer 2: 40 to 100 cm, $K = 3$ cm h^{-1}
Layer 3: 100 to 250 cm deep, $K = 6$ cm h^{-1}
Layer 4 is a restrictive layer with $K < 0.1$ cm h^{-1}.

Estimate the spacing of ditches 0.9 m (3 ft) deep that would remove wetland hydrology from the site. First determine the *T* value for this soil. *T* is the sum of the products of lateral *K* and the thickness of the layer. In this case, $T = (10 \times 40) + (3 \times 60) + (6 \times 150) = 1480$ cm^2 h^{-1}. From table 6 for Norfolk, Virginia, and a ditch depth of 0.9 m, the threshold spacing (L_T) can be estimated from *T* as:

$$L_T = 2.13\sqrt{T} \tag{3}$$

Substituting $T = 1480$ cm^2 h^{-1} into the equation gives L_T = 82 m. The same soil at Baton Rouge would have a threshold spacing of 75 m. The coefficients given in table 6 can be used with equation 2 to estimate threshold ditch spacings for any soil for which the transmissivity (*T*) can be determined.

SURFACE DEPRESSIONAL STORAGE

The results given above were obtained for fields with surface depressional storage of 5 cm (2 in.). The depth of surface depressional storage indicates the average depth of water that is stored on the surface before runoff occurs. Surface storage is important for silviculture because most plantation forests on poorly drained soils are bedded to establish a well drained zone for young seedlings. The furrows between the beds are not typically connected, resulting in a rough surface with a relatively large amount of surface storage, especially compared to agricultural lands. Surface storage depths on forested wetlands vary from about 2.5 cm (1 in.) for lands that are not bedded to as much as 10 to 15 cm for intensively bedded lands. For some soils, and especially for relatively smooth surfaces with few or shallow depressions, the depth of surface storage may have a substantial effect on the threshold ditch spacing. The effect of surface depressional storage on threshold ditch spacing is shown in figure 7 for the Tomotley, Leon 1, and Pamlico 1 soils. These results show that the threshold ditch spacing for wetland hydrology increases as surface storage decreases. This is especially the case for Tomotley, as the threshold spacing increases sharply with a decrease in surface storage to less than about 2.5 cm. Differ-

Table 6. Effect of location and ditch depth on the coefficient *C* in the equation $L_T = C\sqrt{T}$, where L_T is threshold ditch spacing (m) and *T* is hydraulic transmissivity of the soil profile (cm^2 h^{-1}). Surface depressional storage is 5 cm.

Location	Annual Precipitation (mm)	Ditch Depth 0.6 m (2 ft)	0.75 m (2.5 ft)	0.9 m (3 ft)	1.05 m (3.5 ft)	1.2 m (4 ft)	R^2
Norfolk, Va.	1163	1.60	1.89	2.13	2.36	2.58	0.94
Plymouth, N.C.	1299	1.64	1.91	2.18	2.43	2.63	0.92
Wilmington, N.C.	1402	1.39	1.61	1.85	2.02	2.21	0.90
Charleston, S.C.	1269	1.58	1.92	2.21	2.48	2.75	0.92
Savannah, Ga.	1254	1.63	1.97	2.25	2.49	2.75	0.92
Jacksonville, Fla.	1349	1.54	1.81	2.07	2.33	2.61	0.91
Tallahassee, Fla.	1631	1.22	1.42	1.57	1.71	1.86	0.89
Nashville, Tenn.	1209	1.79	2.10	2.34	2.55	2.73	0.93
Mobile, Ala.	1690	1.13	1.31	1.46	1.60	1.72	0.91
Baton Rouge, La.	1506	1.26	1.47	1.65	1.81	1.94	0.92

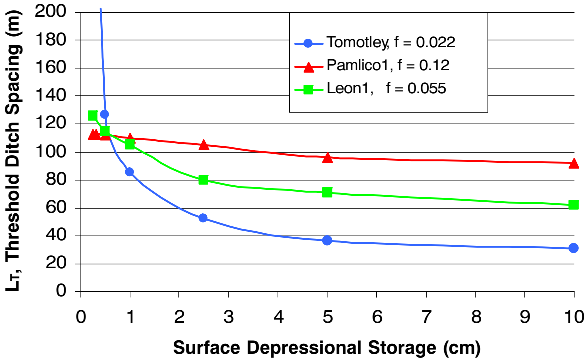

Figure 7. Effects of surface depressional storage on threshold ditch spacings for wetland hydrology (Wilmington, N.C., ditch depth is 1.2 m).

ences in the responses to surface storage between the three soils are primarily due to differences in drainable porosity. Tomotley has a drainable porosity in the top 30 cm of the soil profile of only 0.022, or 2.2%. This means that after the water on the soil surface is removed by drainage and/or evaporation, only 0.022 × 30 cm = 0.66 cm of water must be removed from the soil profile to lower the water table from the surface to a depth of 30 cm. Thus, wide drain spacings and very low drainage rates may be sufficient to remove wetland hydrology if surface depressional storage is small.

Indeed, the results for Tomotley indicate that shallow water tables necessary to sustain wetland hydrology would not exist for surface depressional storage of 0.25 cm or less, regardless of ditch spacing. That is, even for a zero drainage rate, evapotranspiration would be sufficient to lower the water table such that the wetland hydrologic criterion will not be satisfied for this soil. Similar results (not shown) were obtained for the other soils in table 2 with drainable porosities in the range of 0.021 to 0.024. These small drainable porosities are common when the water table is in the top 30 cm of the profile for mineral soils. Threshold drain spacing was not nearly as sensitive to surface depressional storage for the Pamlico 1 soil ($f = 0.12$). In this case 0.12 × 30 = 3.6 cm of water would have to be removed from the profile by drainage and evaporation to lower the water table from the surface to a depth of 30 cm, so having a relatively large amount of water stored on the surface following heavy rainfall events is not as critical to maintaining wetland hydrology as it is for soils with low drainable porosities. Results for the Leon 1 soil, with a drainable porosity of 0.055, fell between those for the Tomotley and Pamlico, as expected (fig. 7).

Most plantation forests on poorly drained soils will have surface depressional storage greater than the 5 cm assumed in this study. This means that the threshold drain spacings given in table 5 and predicted by equation 2 will be somewhat wider than the spacing required to remove wetland hydrology from most plantation forested sites. For example, the threshold spacing for Leon 1 with surface depressional storage of 10 cm is 62 m, compared to 72 m for a depressional storage of 5 cm (fig. 7).

Lateral Effect of a Single Drainage Ditch

The results presented herein can be used to determine ditch spacings and depths that would remove wetland hydrology from the field between parallel drainage ditches. The center portion of the field (midway between and farthest from the ditches) is in most cases the wettest area in the field, so conditions at the midpoint determine the threshold ditch spacing. In some cases, it will be important to know the lateral effect of a single drainage ditch, or in the case of widely spaced parallel ditches, the width of a strip adjacent to the ditch from which wetland hydrology will be or has been removed. A method was developed in previous work (Skaggs et al., 2005) to predict the lateral effect of a drainage ditch. The method is based on findings that threshold conditions for wetland hydrology may be characterized in terms of the rate of water table drawdown when the water table is near the surface. Specifically, the threshold drawdown rate may be defined by the time T_{25} required for the water table to be drawn down by drainage to a depth of 25 cm (10 in.). The T_{25} values are calculated by first determining threshold ditch spacings, as discussed herein and given in table 4. Then drainage theory is used to calculate the time required to lower the water table at a point midway between the ditches from the surface to a depth of 25 cm. This time is the T_{25} value for the given soil, ditch depth, location, and surface depressional storage. Then drainage theory for a single ditch can be used to calculate the distance from the ditch to the point where the water table will be lowered from the surface to a depth of 25 cm in time T_{25} (Skaggs et al., 2005). The wetland hydrologic criterion will be barely satisfied at that location, and the distance is defined as the lateral impact of the ditch on wetland hydrology. Results from initial studies indicated that T_{25} values for a given location, drain depth, and surface depression storage are relatively constant among different soil series. DRAINMOD analyses were conducted for a range of soils for all 100 counties in North Carolina, and software was developed to solve the Boussinesq equation to automatically calculate the lateral effect in terms of ditch depth and soil properties. The T_{25} values were determined for ditch depths from 30 to 180 cm and surface storage depths of 2.5 and 5 cm. The method and the software can be downloaded at: www.bae.ncsu.edu/soil_water/projects/lateral_effect.html.

The threshold ditch spacings determined in this study (tables 4 and 5) were used to calculate T_{25} values for ditch depths ranging from 0.6 to 1.2 m for all locations and all soils. The values are summarized in table 7. The T_{25} values for a given location and ditch depth were similar for six of the soils (Cape Fear, Coxville, Pantego, Plummer, Torhunta, and Tomotley) and could be represented by a single value equal to the average. The T_{25} values for the Leon and Pamlico soils, which had a combination of both high drainable porosities and high profile transmissivities compared to the others, were of nearly equal magnitude and significantly larger than the other six soils. The average of values for the Leon and Pamlico soils are listed separately in table 7.

The T_{25} values in table 7 were used with the software referenced above to determine lateral effects for a 0.9 m (3 ft) deep drainage ditch for all soils and locations considered herein. Results given in table 8 indicate that a 0.9 m (3 ft) deep drainage ditch will lower the water table such that wetland hydrology will be removed for a distance varying from 8 to 55 m from the ditch for the soil profiles considered in this study. The distance that wetland hydrology would be removed, or the lateral effect, is based on the current criterion for wetland hydrology (given herein). It varies over a relatively wide range due to differences in soil properties (hydraulic conductivity, profile transmissivity, and drainable porosity) and growing season and weather variables, as affected by geographic location. Surface depressional storage may have a big effect on lateral impact, as discussed above (fig. 7). The results in table 8 were obtained for surface storage of 5 cm. The lateral impact of a drainage ditch would increase as surface storage is reduced, and vice versa. This effect could be dramatic for small surface storage values, as discussed previously.

The results in tables 5 and 8 present multiple examples of the nonlinear nature of lateral impacts of drainage ditches. For example, a reviewer pointed out that the lateral effects given in table 8 for Pamlico 1 and Torhunta 1 were similar, yet the drainable porosity of Pamlico (0.12) is 5 times that of Torhunta (0.024) (table 2). How can that be the case? The processes governing drainage, water table drawdown, and lateral impacts are both nonlinear and transient, and their interactions, which are considered by DRAINMOD and the method used to calculate lateral impacts, are not obvious. However, this apparent anomaly can be partly explained by examining the amount of water that would have to be drained to lower the water table to a depth of 30 cm. Assuming that the 5 cm deep surface depressions are initially half full (that is, water is initially ponded on the surface to a depth of 2.5 cm), the amount of water that would have to be drained from the Pamlico profile to lower the water table to a depth of 30 cm would be $V_P = 2.5 + (30 \times 0.12) = 6.1$ cm. For Torhunta, the amount would be $V_T = 2.5 + (30 \times 0.024) = 3.22$ cm, so nearly twice as much water would have to be drained from Pamlico 1 as from Torhunta 1 to lower the water table to a depth of 30 cm. However, the transmissivity of Pamlico 1 (3600 $\text{cm}^2\ \text{h}^{-1}$) is about twice that of Torhunta 1 (1750 $\text{cm}^2\ \text{h}^{-1}$) (table 2); therefore, under similar conditions, the drainage rate for Pamlico is about twice that of Torhunta. Thus, it seems reasonable that the drawdown rate and lateral impact could be roughly the same. The processes are transient and variable. Sometimes water may be ponded at a depth of 5 cm after rainfall, and other times less than 1 cm, or none at all. These factors are considered in the long-term DRAINMOD simulations conducted to determine the T_{25} values. These simple calculations indicate that the differences between lateral impacts for the two soils would be expected to increase as the surface depressional storage becomes smaller. This was confirmed by additional simulations (results not shown).

Table 7. Summary of average T_{25} values (days) for ten locations and five ditch depths for surface depressional storage of 5 cm.

	Ditch Depth				
Location	0.6 m (2 ft)	0.75 m (2.5 ft)	0.9 m (3 ft)	1.05 m (3.5 ft)	1.2 m (4 ft)
Cape Fear, Coxville, Pantego, Plummer, Torhunta, Tomotley					
Norfolk, Va.	2.6	2.9	3.0	3.2	3.4
Plymouth, N.C.	2.9	3.1	3.4	3.6	3.9
Wilmington, N.C.	2.2	2.2	2.4	2.4	2.6
Charleston, S.C.	2.4	2.5	2.7	2.9	3.2
Savannah, Ga.	2.7	2.8	2.9	3.2	3.5
Jacksonville, Fla.	2.5	2.5	2.6	2.7	2.8
Tallahassee, Fla.	1.7	1.8	1.9	1.9	2.1
Nashville, Tenn.	3.6	3.9	4.0	4.4	4.7
Mobile, Ala.	1.5	1.5	1.5	1.6	1.7
Baton Rouge, La.	1.7	1.8	1.9	2.0	2.1
Pamlico and Leon					
Norfolk, Va.	7.4	8.0	8.8	9.3	10.1
Plymouth, N.C.	7.3	8.0	8.6	9.4	10.1
Wilmington, N.C.	5.2	5.5	6.1	6.5	7.0
Charleston, S.C.	7.1	8.4	9.3	10.4	11.6
Savannah, Ga.	7.4	8.9	9.9	10.4	11.2
Jacksonville, Fla.	6.4	7.0	8.0	9.2	10.2
Tallahassee, Fla.	4.0	4.2	4.3	4.5	4.8
Nashville, Tenn.	8.9	9.6	10.2	10.6	10.9
Mobile, Ala.	3.3	3.6	3.9	4.1	4.2
Baton Rouge, La.	4.4	4.7	5.0	5.3	5.5

There is evidence that soil properties, including infiltration capacity, hydraulic conductivity, and profile transmissivity, depend on land use (Shirmohammadi and Skaggs, 1984; Skaggs et al., 2011). It is generally assumed that the *K* values in databases reflect agricultural land uses. Forested soils would most closely approximate this condition during, and for a few years following, site preparation and planting. For plantation forests, higher *K* values may develop as the stand matures (Skaggs et al., 2011). This would result in increased lateral impacts on wetland hydrology. Natural sloughing and clogging of ditches would tend to counteract such effects. However, there are currently not sufficient data, on either the change of *K* with time or on changes in the effective depth of drainage ditches due to sloughing, clogging, etc., to predict their impacts on wetland hydrology.

Table 8. Predicted lateral effect of a single drainage ditch (0.9 m deep) on wetland hydrology for ten locations in the Atlantic and Gulf coastal states for surface depressional storage of 5 cm.

Soil	Norfolk, Va.	Plymouth, N.C.	Wilmington, N.C.	Charleston, S.C.	Savannah, Ga.	Jacksonville, Fla.	Tallahassee, Fla.	Nashville, Tenn.	Mobile, Ala.	Baton Rouge, La.
Cape Fear	13	13	11	12	12	12	10	15	9	10
Coxville	12	12	10	11	12	11	9	14	8	9
Leon 1	28	28	23	28	30	27	20	30	19	21
Leon 2	44	44	37	46	47	42	17	48	30	34
Pamlico 1	30	30	25	31	32	29	21	33	20	23
Pamlico 2	52	52	44	54	55	50	37	56	35	39
Pantego 1	11	11	10	10	10	10	8	12	8	8
Pantego 2	34	36	31	32	33	32	27	39	24	27
Plummer 1	18	19	16	17	18	17	14	21	13	14
Plummer 2	32	34	29	31	32	30	26	37	23	26
Tomotley	13	14	12	13	13	12	11	15	9	11
Torhunta 1	28	30	25	26	27	26	22	32	20	22
Torhunta 2	46	49	41	44	45	43	37	53	33	37

SUMMARY

A simulation study was conducted to determine the effects of minor drainage for silviculture on wetland hydrology of poorly drained forested soils in the Atlantic and Gulf coastal states. Long-term (50-year) DRAINMOD simulations were conducted to determine whether parallel open ditch drains, at depths and spacings commonly used for silviculture, remove wetland hydrology from forested wetlands. The analysis was conducted for eight poorly and very poorly drained soil series commonly used for forest production. Two profile depths were considered for five of the soils, so the analysis was conducted for a total of 13 soil profiles. Published soil property values were used to determine DRAINMOD inputs. In order to consider the effect of variation in climate over the region, analyses were conducted using weather data from ten locations scattered from Norfolk, Virginia, to Baton Rouge, Louisiana. Threshold ditch spacings for wetland hydrology were determined for all soil profiles at all locations for ditch depths of 0.6, 0.75, 0.90, 1.05, and 1.2 m (2, 2.5, 3, 3.5, and 4 ft). Wetland hydrology would be removed from the site for ditches placed closer together than the threshold spacing, which serves as a benchmark for determining the effects of drainage on wetland hydrology. Results indicated that the threshold spacing could be approximated as a function of the square root of the profile hydraulic transmissivity. Proportionality constants required to estimate the threshold spacing were determined as a function of ditch depth and are given for all locations considered.

In many cases, drainage for silviculture is accomplished with very widely spaced ditches, or single ditches placed in the wettest locations on the landscape. The threshold spacings determined herein were used in combination with methods developed in a previous study to determine the lateral impacts of a single ditch on wetland hydrology. The T_{25} values required by the methods were determined for all locations, ditch depths, and soils considered. These values can be used, together with software available for download, to calculate the lateral impacts of a single drainage ditch. Results are tabulated in this article for all locations and soils analyzed for a ditch depth of 0.9 m (3 ft).

In conclusion, the methods and results presented in this article can be used to determine the threshold ditch spacings and the lateral impact of drainage ditches on wetland hydrology for the poorly drained forested soils and conditions in the south and southeast. Direct use of the methods is confined to sites with surface depressional storage of 5 cm or greater, typical of forested wetlands. Additional work is needed to determine the T_{25} values necessary to use the methods for other surface storage depths, including the smaller values needed for agricultural cropland.

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