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SILVICULTURE IN FORESTED WETLANDS

Effects of Drainage for Silviculture on Wetland Hydrology

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Abstract

Wetland silviculture on the Southeastern Coastal Plain attempts to balance competing objectives of draining topsoils sufficiently to provide access and promote tree growth while maintaining hydric soil characteristics in compliance with the Clean Water Act. This balancing act is dynamic as soil hydraulic properties, and thus water table regimes, change over the stand rotation cycle. Previous studies have defined threshold ditch spacings that would sustain wetland hydrology on a wide range of poorly drained coastal plain soils in US southeast. There is strong evidence that the hydraulic conductivity (K) and transmissivity (T) of the soil profile increase as trees mature. Such changes increase drainage rates, lower water tables, and potentially remove wetland hydrology from drained sites. Results from a long term forested watershed study showed that T of the profile decreased from 50 m^2/d under a mature loblolly pine plantation to 5.5 m^2/d after harvest and site preparation for regeneration, and then increased to 34 m^2/d by 8 years after replanting. Based on these results, a modeling case study was conducted to determine the effects of changes in soil properties on wetland hydrology for a pine plantation. Results showed that 90 cm deep drainage ditches would have to be more than 62 m apart in a young plantation (YP) to sustain wetland hydrology on a site with 15 cm of surface storage. Increases in K and T as the plantation matures increased the predicted threshold spacing (L_T) for wetland hydrology from 62 m for YP to 290 m for a mature plantation (MP). For ditch spacings greater than L_T, wetland hydrology will be sustained in a broad center section midway between ditches, with the width of the wetland section dependent on ditch depth, spacing and soil properties. Methods developed to estimate the lateral effect of a single ditch on wetland hydrology were used to determine the width of a strip adjacent to the ditch where wetland hydrology is not sustained, and, thereby the percentage of wetland loss from the plantation. Depending on ditch depth, wetland hydrology will not be sustained on 14 to 27% of the land area for a 200 m ditch spacing on the young plantation of the case study. As the plantation matures (to MP), wetland hydrology will not be sustained for normal ditch spacings (100 to 200 m) on these soils. More research is needed to determine effects of stand age and production practices on hydraulic conductivity for a wide range of drained soils. Wetland hydrology can be enhanced by limiting depth and increasing spacing of drainage ditches, by use of control structures in some cases, and by allowing field ditches to fill naturally as plantations mature.

Keywords Forest drainage · Forest hydrology · Hydraulic conductivity · Forest soil properties · DRAINMOD · Wetland hydrology · Lateral effects

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Introduction

This study examines the effect of tree growth on soil hydraulic properties and how these soil dynamics alter the effects of silvicultural drainage practices on the hydrology of wetland forests. Minor drainage for silviculture is permitted under certain conditions in the U.S., but is limited to measures that maintain wetland hydrology. Most studies of effects of drainage on the hydrology and wetland status of forested wetlands have treated soil hydraulic properties as static. In this study, results of long term field research on a drained pine plantation watershed were used to quantify changes in soil hydraulic properties over an 18 year period from prior to harvest through harvest, regeneration, and growth to maturity. The effect of changes in soil properties on the hydrology and wetland hydrologic status of drained forested wetlands were then analyzed in a process based modeling case study.

On a global basis, drainage has been used since the mid-eighteenth century to enhance tree growth and provide timely access to forested lands with poor natural drainage (Paavilainen and Päivänen 1995). Historically such drainage activities were viewed as beneficial and promoted by government programs to improve agricultural and silvicultural production (Lilly 1980). With recognition in the latter part of the twentieth century of the ecological and water quality functions and values of wetlands, such programs have been either phased out, regulated, or terminated in most countries, to protect forested wetlands. Drainage is still needed to provide access and protect the soil resource, and minor drainage for silviculture continues under guidelines to maintain the hydrology and wetland characteristics of the watershed. Research is needed to inform such efforts/policies.

Drainage and associated practices affecting wetland hydrology vary depending on the type of forested wetlands. Williams et al. (2016) used a simple water balance to characterize forested wetlands as three basic types: (1) rain-fed, (2) groundwater-fed, and (3) surface water-fed. Drainage is rarely used on surface water-fed forested wetlands, which are typically in riverine settings with flooding determined by upstream hydrology or downstream backwater or tidal effects. The hydrology of these wetlands may be affected by flood control practices, such as construction of upstream reservoirs, or levees along the stream, but infrequently by drainage. Drainage ditches have been used to intercept seepage from upslope to lower the water table to improve trafficability and growing conditions in groundwater-fed forested wetlands. The greatest application of drainage for silviculture in the U.S. has occurred in the rain-fed forested wetlands on broad flats between widely spaced and relatively shallow natural streams in the coastal plains of the south and southeast. Average annual precipitation (P) in this region exceeds potential evapotranspiration (PET) by 150 to 650 mm, depending on location (Skaggs et al. 2011a). Thick restrictive layers cause deep seepage to be small in most locations (Heath 1975; Daniels et al. 1978), so annual drainage is, on average, about equal to the difference between P and evapotranspiration (ET). Under natural conditions, drainage on these relatively flat lands occurs mostly as shallow subsurface flow and surface runoff (Amatya et al. 2019) with wetland hydrologic conditions (defined below) during much of the year. Results presented herein are directly applicable to these lands.

Recognition of the substantial positive effects of drainage on tree growth and silviculture in the south and southeast had its roots in a drainage project in the Hoffman Forest in eastern NC in the 1930s (Miller and Maki 1957, Maki 1960, 1971; Klawitter et al. 1970; Fox et al. 2007). A review by Terry and Hughes (1975) showed drainage increased tree growth by 80 to 1300%. Further studies documented as much as 10 times greater wood production on drained compared to undrained loblolly pine plots (Campbell and Hughes 1980). This early work resulted in the implementation of drainage practices and programs that produced significant increases in the productivity of wetland forests and silviculture (Campbell 1976; Terry and Hughes 1978).

The greatest limitation to establishing adequate drainage for agriculture and forestry in the lower coastal plains of the southern U.S. was the lack of adequate drainage outlets. Outlets are provided by natural streams, but, in large poorly drained areas, such streams are too far apart, too shallow, or of insufficient capacity to remove excess water at a rate that would permit agriculture, or even the less intensive drainage needs of forestry. In areas with well-defined natural drainage patterns, sufficient drainage for silviculture can be provided by cleaning out natural drainage ways and, in some cases, the addition of ditches through wet areas (Terry and Hughes 1978). In the broad, flat, poorly drained areas, a pattern drainage system is typically used with outlets provided by the construction of drainage canals. Depending on the land form (e.g., broad flats, pocosins, Carolina bays) and local conditions, the canals may vary in orientation, size and length. A schematic of a pattern drainage system for silviculture, consisting of main drainage canals (1.6 km apart), collector canals spaced 0.8 to 1.6 km apart, and field ditches, is shown in Fig. 1a. The canals are usually designed to remove water from the watershed at a specified rate, called the drainage coefficient, DC. Depending on crops and soils a DC of 10 to 25 mm/d is typically recommended for agricultural cropland (USDA-NRCS 2001). Drainage requirements are less intensive for silviculture and are most critical during the harvesting and re-establishment period. Based on trafficability requirements, a DC of 5 to 8 mm/d appears to be sufficient for silviculture in NC (Skaggs et al. 2016). The collector canals are generally road canals that collect water from the field ditches and conduct it to the main canals. Field ditches are commonly spaced at 100 or 200 m, with the closer spacings required for soils with lower hydraulic conductivity (Terry and Hughes 1978).

The goal of silvicultural drainage is to promote tree growth while maintaining wetland forest hydrology. Wetland hydrology is characterized by sustained saturated conditions in the upper part of the soil profile. The criterion may be expressed as follows: wetland hydrology exists on a site if, during the growing season, the soil profile is normally saturated within 30 cm of the surface for a continuous duration of at least 14 days (USACE 2005). The growing season (GS) was

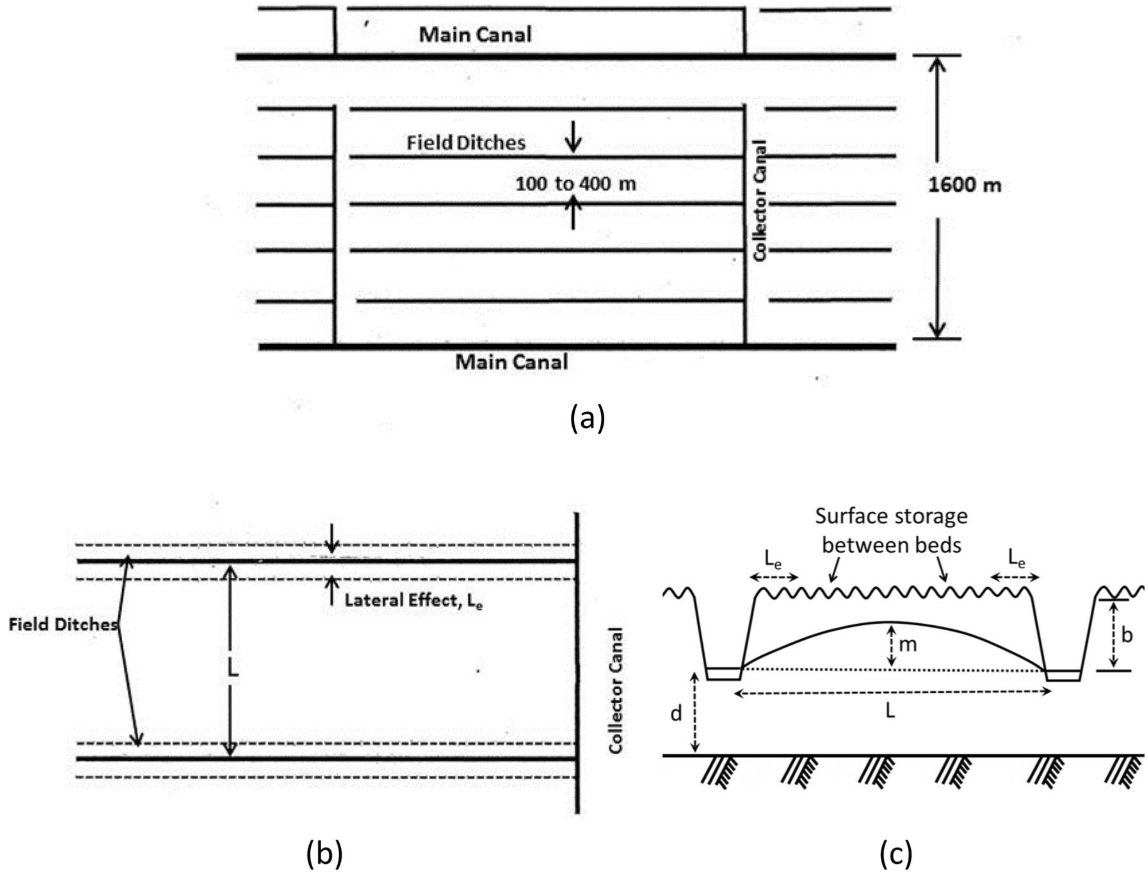


Fig. 1 (**a**) Schematic of pattern drainage system consisting of main drainage canals, collector canals and field ditches. (**b**) Details of parallel field ditches showing strip near the ditch where wetland hydrology may be removed by the ditch. (**c**) Elevation view of field ditches showing surface storage between furrows

defined by US Army Corps of Engineers (USACE 2005) and by USDA-Natural Resources Conservation Service (NRCS) as the period with air temperatures above 28 °F (−2.2 °C) for 50% of the years. Finally, the term "normally" in the criterion is defined as meaning the water table conditions satisfying the criterion occur in 50% of the years, or once in two years on average (USACE 2005). This criterion is used herein to define wetland hydrology. It is noted that the growing season has been defined differently in the Regional Supplement to the Corps of Engineers Wetland Delineation Manual (USACE 2010). Methods proposed therein extend the growing season throughout the year (365 days) for portions of the coastal plain from Virginia to Texas (Seybold et al. 2002; Burdt et al. 2005; Miller and Bragg 2007). Use of this definition of the GS would substantially reduce saturation requirements for wetland hydrology (Skaggs 2012); it was not used in this analysis.

Whether or not wetland hydrology is sustained on a drained site depends on factors related to drainage system design (depth and spacing of ditches, bedding and surface storage), soil properties that control subsurface drainage and water table drawdown (hydraulic conductivity, hydraulic transmissivity of the profile, drainable porosity), weather (precipitation and evapotranspiration, ET), and outlet conditions at the watershed scale (DC). The rate that water drains from the profile to parallel field ditches may be approximated for both steady state and extended drawdown events by the Hooghoudt equation (Bouwer and van Schilfgaarde 1963; Skaggs 2017):

$$q = 4K_e m(2d_e + m)/L^2 \quad (1)$$

where, referring to Fig. 1c, q is drainage rate, K_e is equivalent saturated horizontal hydraulic conductivity of the soil profile, d_e is the equivalent depth from the water level in the ditch to the restrictive layer, L is the ditch spacing, and m is the elevation of the midpoint water table above the ditch water level. For open ditches d_e is usually assumed equal to d. The soil profile is generally composed of two or more horizons or layers with K_e defined as, $K_e = (K_1 t_1 + K_2 t_2 + K_3 t_3 + \ldots)/(t_1 + t_2 + t_3 + \ldots)$, where $K_1, K_2, \ldots$, and $t_1, t_2, \ldots$ are respectively, saturated hydraulic conductivities and thicknesses of the layers below the water table, 1,2,3,…. The subsurface drainage intensity (DI) may be defined as the drainage rate, q, when the water table midway between the drains is coincident with the surface (i.e., m = b, Fig. 1c) (Skaggs 2017):

$$DI = 4K_e b(2d + b)/L^2 \quad (2)$$

DI and DC quantify key drainage rates for a site and are useful indicators of the hydrology of drained lands.

In most cases, the wettest areas in drained fields are those farthest from the drains. For parallel ditches (Fig. 1) this would be the area midway between ditches. Conversely, the most intensively drained areas are immediately adjacent to the ditches and canals. Depending on ditch depth, the water table may be lowered in a strip near the ditch such that the wetland hydrologic criterion will not be satisfied, regardless of ditch spacing. That is, wetland hydrology may not be sustained in a strip of width L_e on both sides of the ditch, as indicated in Figs. 1b, c, while the criterion is satisfied and wetland hydrology exists in the broad center section of the field. The width of the strip, L_e, where wetland hydrology is not sustained, is defined as the lateral effect of the ditch. In addition to location, which affects weather variables (P and ET), L_e depends on the ditch and soil profile depths, and the soil properties mentioned above. Methods for estimating the lateral effect were developed by Skaggs et al. (2005) and field tested by Phillips et al. (2010).

Another factor affecting the hydrology of poorly drained forested lands is surface storage. Surface storage may be due to naturally occurring shallow depressions which must be filled before surface runoff can occur. Water remains ponded in such depressions until it drains through the profile or is removed by ET. In silviculture plantations, surface storage may be substantially impacted by the practice of bedding (Figs. 1c & 2) for the purpose of creating an elevated soil zone to protect tree seedlings from waterlogging stresses during wet periods. Similar bedding is often used in agricultural croplands on these soils. For croplands, the furrows between beds are typically connected with the field ditches by the construction of shallow transverse surface trenches (hoe drains) to remove the surface water. In contrast, the furrows between beds for silviculture drainage are not usually connected with drainage ditches (Fig. 2). Young trees can tolerate saturation for longer periods than agricultural crops, so it is not as important to quickly remove standing surface water. Unconnected furrows increase surface storage and thus reduce both surface runoff and silting of drainage ditches. Beds such as shown in Fig. 2 result in average surface storage of 5 to more than 15 cm, as compared to less than 2 cm for most agricultural cropland.

A simulation analysis to determine the effects of minor drainage on the hydrology of forested wetlands was conducted in a previous work (Skaggs et al. 2011a). Long term simulations were conducted with the process based DRAINMOD model (described below) for 10 locations in the Atlantic and Gulf coastal states for a wide range of ditch spacings to determine threshold drainage intensities that would remove wetland hydrology from forested wetlands. The threshold drainage ditch spacing (L_T) is defined as the largest spacing that would remove wetland hydrology from the entire field. Wetland hydrology would be sustained in the center section midway between adjacent ditches for ditch spacings greater than L_T, with the width of the section dependent on L_e, ditch spacing and depth, surface storage, and soil properties. Threshold spacings were determined for five ditch depths on 13 soil series and profile combinations at 10 locations from Norfolk, VA to Baton Rouge, LA. Except for the strip of width, L_e, next to the ditch, predicted water table depths would satisfy the criterion for wetland hydrology in the broad center section of the field for ditch spacings greater than L_T. Results indicated that L_T varied widely among soil series because of variability of soil properties, specifically the hydraulic conductivity, K, which varies by layer within the profile. The overall impact of K on drainage rates is indicated by the profile hydraulic transmissivity, $T = K_1\ t_1 + K_2\ t_2 + K_3\ t_3 + ... = K_e(t_1 + t_2 + t_3 + \ldots)$. The profile transmissivities varied from 0.5 to 19 m^2/d among the 13 soil series and profile combinations considered. Corresponding L_T values at Wilmington, NC for a ditch depth of 0.9 m, for example, varied from 18 to 161 m. Threshold spacing may also vary widely within soil

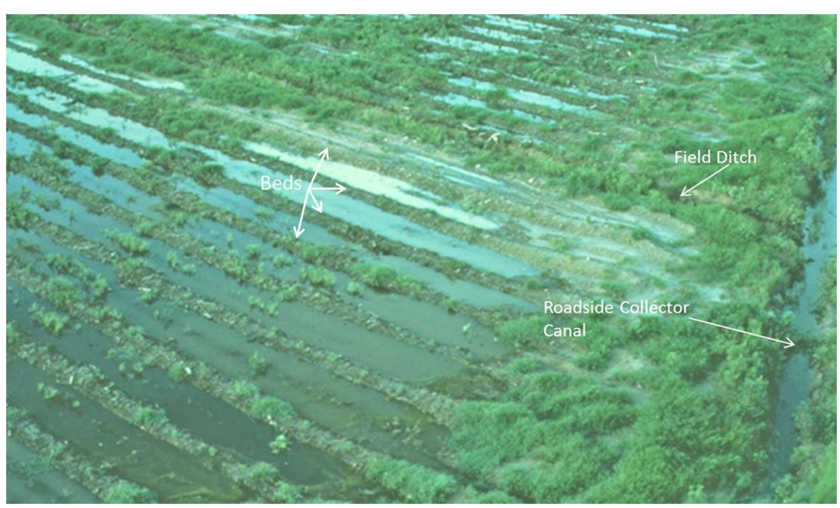


Fig. 2 Bedded recently planted pine plantation in eastern NC. Note furrows between beds not connected to field ditch nor roadside collector ditch on right resulting in significant surface storage following large rainfall events. (photo by Joe Hughes, 1981)

series so it is not possible to reliably estimate L_T based on soil series alone. Attention must also be given to soil properties (K and T) specific to the site. Analysis of results for all locations and ditch depths showed that threshold ditch spacing, L_T, could be approximated as $L_T = CT^{0.5}$ where units for L_T are meters, C is a coefficient dependent on ditch depth and geographic location and T is hydraulic transmissivity of the soil profile in cm^2/h.

One of the objectives of the study described above was to provide guidelines for designing minor drainage systems that would facilitate silviculture operations while maintaining wetland hydrology on the site. For example, the results showed that, for a ditch depth of 60 cm, about 40% of the soils /sites analyzed had L_T less than 50 m. For those soils and conditions, a ditch spacing of 100 m, which is a typical spacing for the tighter soils in the NC coastal plain, would seem to be a reasonable recommendation that would sustain wetland hydrology in a broad center section between ditches. Over 88% of the cases considered had predicted L_T less than 100 m with the largest 161 m. So a recommendation of 200 m spacing for those sites with 50 m < L_T < 150 m would seem to be an appropriately safe ditch spacing that would maintain wetland hydrology in those sites.

While it is generally recognized that K and other soil properties may vary both within and between different soil series, it is usually assumed they are independent of land use and static. Scientists have long recognized the fallacy of such assumptions (Wilson and Luxmoore 1988), but the lack of information to quantify effects of land use on soil properties and their temporal variation has limited our ability to assess the impacts. Research in recent years (Chandler et al. 2018; Hassler et al. 2011; Price et al. 2010; Bonell et al. 2010; Skaggs et al. 2008;) has shown that the hydraulic conductivity of the upper part of the profile under a mature stand of trees may be substantially greater than that occurring under pasture, agricultural crops, or recently planted silviculture plantations. Thus, a ditch spacing and depth that would sustain wetland hydrology on a young plantation may provide sufficient drainage intensity to remove wetland hydrology after the plantation matures and the hydraulic conductivity of the upper part of the profile increases. Here, we present two complimentary studies, separately providing methods, results and discussion for each. The first presents results from a long term field study in eastern North Carolina that demonstrates effects of silviculture practices and stage of growth on saturated hydraulic conductivity and profile transmissivity. The second, a simulation modeling case study, is then presented to examine the effects of changes in soil properties on wetland hydrology of silviculture plantations.

Field Study: Methods

Effects of stand age and management practices on equivalent saturated hydraulic conductivity, K_e, were determined in a long term forest drainage study on the Carteret 7 research site in eastern North Carolina. Three watersheds (D1, D2, and D3), each approximately 25 ha planted to loblolly pine (*Pinus taeda* L.), were instrumented to measure and record drainage rate, water table depth, rainfall and meteorological data (Fig. 3). The soil, Deloss fine sandy loam (fine-loamy, mixed, thermic Typic Umbraquults), is classified as very poorly drained with a shallow water table under natural conditions; the topography is flat. Each watershed is drained by four parallel lateral ditches about 1.2 m deep, spaced 100 m apart. Drainage outflow was continuously measured at the outlet of each watershed by recording the water level upstream from a 120° V-notched weir, with the bottom of the "V" about 1 m below average soil surface elevation. Water table elevations were continuously recorded at two locations midway between the field ditches. McCarthy et al. (1991) and Amatya et al. (1996) describe the site in detail. Data collection began in 1988 when the trees were 15 years old. Studies have been conducted to determine hydrologic impacts of a range of practices since 1988. The observations reported in this paper are limited to watershed D2, which was harvested in July 1995 at a stand age of 22 years. The watershed was bedded and prepared for planting in October 1996, replanted February 1997 (Blanton et al. 1998; Amatya et al. 2006), and continuously monitored for weather, rainfall, water table, and drainage outflow until mid-2016 (Amatya et al. 2006; Beltran et al. 2010; Muwamba et al. 2015).

Drainage and water table records were analyzed to determine K_e and K by soil layer prior to harvest, after harvest prior to bedding, and in years following bedding and replanting. Relationships between the drainage rate, q (cm/d), and the elevation of the water table above the water level in the ditch at the midpoint between the ditches, m (cm), were plotted using the field data for different time periods. The resulting q(m) relationships were then compared to theoretical relationships predicted by the Hooghoudt equation as discussed above (Eq. 1). The Hooghoudt equation was derived for steady state conditions, but can be used to approximate the Main Drainage Curve (MDC) relating drainage rate, q, to water table elevation, m, as the water table falls from the surface to drain depth (Bouwer and van Schilfgaarde 1963; Skaggs 2017). However, the analysis of q(m) data to define the MDC must be done carefully as there are times when the drainage rate, q, may be significantly greater than indicated by the MDC and the Hooghoudt Eq. (1). Typically this happens when rainfall occurs during a drawdown event, causing the water table to reverse course, rise, and change shape. The flowrate and water table elevation may increase for a period, depending on the rainfall amount and duration, but, in the absence of additional

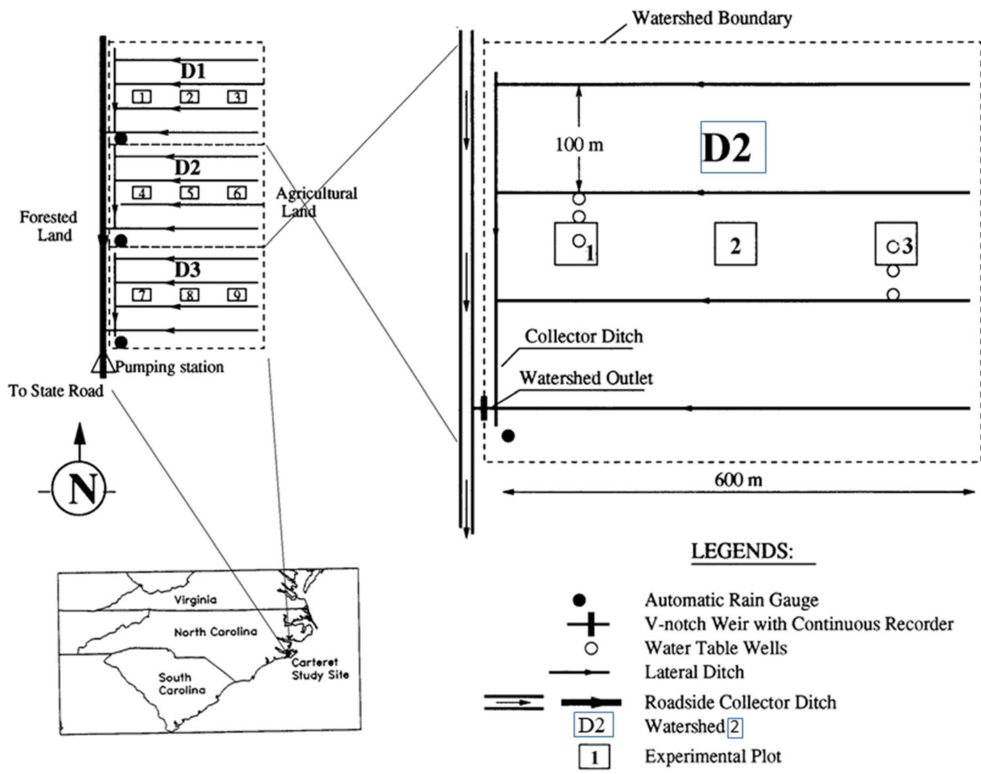


Fig. 3 Location map of experimental watershed with detailed layout of monitoring stations on watershed 2, Carteret County, NC (After Amatya et al. 1996)

rainfall, will fall back to the MDC. Methods for analyzing q(m) data to remove the effects of such transient periods in defining the MDC and to determine the field effective lateral hydraulic conductivity of the profile, K_e, were presented by Skaggs et al. (2008). Once the MDC was determined from measured values of q vs m, K_e was calculated from the Hooghoudt equation for a range of water table depths. The profile at Carteret 7 was analyzed as consisting of three layers, with the conductivity of the individual layers determined from K_e values, starting at the bottom of the profile. Data were analyzed for only the dormant season months of November–March to minimize the effect of ET on the MDC. It is well understood that K varies from point-to-point in the field and that determining a field effective K from small scale measurements is challenging (Brooks et al. 2004). The methods used defined a field effective saturated K by layer based on measured drainage rates at the field scale that included the effects of macropore flow.

Field Study: Results and Discussion

Measured drainage rate, q, is plotted as a function of measured water table elevation midway between parallel drainage ditches, m, in Fig. 4 for 5 periods: (1) the pre-harvest period in 1994 and 1995 (harvest in July, 1995); (2) post-harvest from October 1995 through October 1996, when the site was bedded and prepared for replanting; (3) post-bedding, October 1996 through March, 1997; (4) year 2005, 8 years after replanting, and (5), year 2012, 15 years after replanting. A thinning operation in early 2009 could have affected results for period 5 (Ssegane et al. 2013). A cursory review of Fig. 4 indicates that the q(m) relationship changed substantially as a result of harvest, site preparation (bedding) and regeneration of a new pine plantation. The measured data (individual data points, Fig. 4) were used with Eq.1 to calculate the field effective hydraulic conductivity by layer for each of the five periods (Table 1). The curves plotted in Fig. 4 represent the q(m) relationship predicted by the Hooghoudt equation using K values in Table 1 for each layer. The range of K values given by the county Soil Survey (USDA-SCS 1978) for the Deloss soil series is included in Table 1 for reference.

Field effective K of the top 80 cm of the profile prior to harvest of mature pine was 55 to 60 m/d (Table 1). This is 20 to 30 times greater than published values for the Deloss soil (USDA-SCS 1978). The high K values are attributed to the presence of macropores and preferential flow resulting from tree roots and biological activity that was uninterrupted for over 20 years prior to site preparation (bedding) in 1996. Similar high K values were reported by Grace III et al. (2006) for an organic soil and by Diggs (2004) for both mineral and organic soils under pine plantation. Noguchi et al. (1997) attributed similar K values, (35 m/d at 10 cm depth, declining to 5 m/d at 80 cm) in a Malaysian tropical rain forest, to macropores and preferential flow caused by decaying and living roots. The development and presence of macropores in

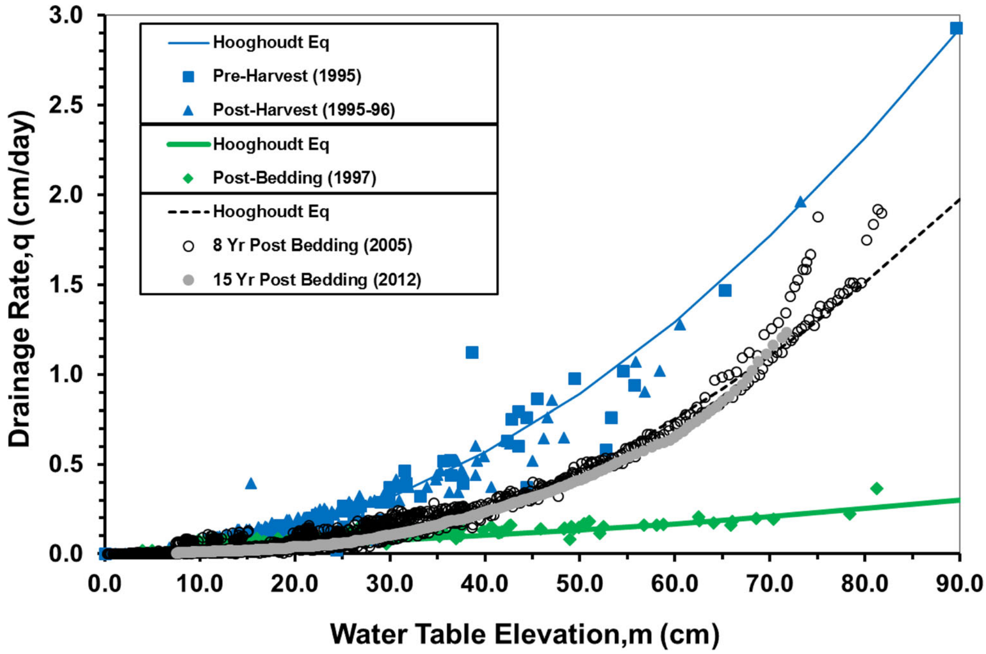


Fig. 4 Measured drainage rate, q, and water table elevation above water level in ditch, m, at Carteret 7 watershed D2 for pre-harvest and various times post harvest. Curves predicted with the Hooghoudt Eq. are shown using hydraulic conductivity values from Table 1. (modified from Skaggs et al. 2008)

forest soils and their importance to subsurface hydrology has long been recognized (Gaiser 1952; Aubertin 1971; Wilson et al. 1990; Messing et al. 1997). Wilson and Luxmoore (1988) stated that macropore and mesopore processes substantially control subsurface flow in forested watersheds.

The harvest process did not have an apparent effect on the pore structure as the q(m) relationship (Fig. 4) and the K values (Table 1), after harvest and prior to bedding, were the same as prior to harvest. This is in contrast to the findings of Grace III et al. (2007) that timber harvesting substantially reduced saturated K. However, the organic soils of that study are more susceptible to compaction than the mineral soils of the Carteret site. Drainage rates after bedding were clearly reduced for water table elevations greater than m = 15 cm (Fig. 4). For example, the measured drainage rate, q, for m = 60 cm was 1.3 cm/d prior to bedding, but only 0.16 cm/d after bedding and replanting. This is reflected by the K values in the top 50 cm, which were reduced from 60 to 3.6 m/day, and in the 50 to 80 cm depth where K was reduced from 55 to 1.6 m/d (Table 1). Flow rates calculated by the Hooghoudt equation, using the high end of the range of K values given in the Soil Survey (Table 1), agreed with observations for post-bedding condition (Fig. 4). Apparently the bedding process destroyed and/or interrupted the continuity of macropores in the upper part of the soil profile, such that K in those layers was similar to that given in the soil survey, which are typically estimated for agricultural land uses. These data indicate that it was not the harvesting process that reduced the K values in the top part of the profile, but the bedding process prior to replanting.

The q(m) data for 2005 indicate that drainage rates were increased compared to the post-bedding and replanting stage, but had not risen to the rates measured prior to harvest for the higher water table elevations (larger m values, Fig. 4). K values computed from observed data for the top 50 cm (Table 1) were nearly the same as prior to harvest (50 m/d versus the 60 m/d) but only 20 m/d for the 50 to 80 cm depth. This may indicate that the macropores responsible for high K values prior to harvest had not had time by 2005 to fully redevelop in the 50 to 80 cm depth range. However, results for 2012, 15 years after planting, and 2 years after thinning, were similar to those measured for 2005. Thus it is not clear how long it will take for the hydraulic conductivity to return to the values measured in 1995 prior to harvesting the 22 year old stand of loblolly pine, or if it will. It is clear that the hydraulic conductivity and transmissivity of the soil profile of these mature pine plantations is much greater than for young plantations. This means that drainage and water table drawdown rates of a mature forest will be increased compared to conditions at planting and in young plantations.

Effects of land use and production practices on saturated K of surface layers of shallow water table forested soils (Table 1) are similar to those reported in previous studies in some respects, but different in others. As noted above, our research on other drained forested sites (Diggs 2004; Grace et al. 2006; Skaggs et al. 2011b) reported K values similar to those given in Table 1 (one to two orders of magnitude greater than K values published in USDA soil surveys for the respective soil series). A large body of research to determine the effects of land use and management practices on hydraulic conductivity and other soil properties has been conducted on forested uplands where drainage systems are unnecessary. Much of this work has been focused on defining stormwater pathways in forested lands. Results for a wide range of locations are

Table 1 Field effective hydraulic conductivity (m/d) by layer for the soil profile on Carteret 7 watershed prior to and following harvest, bedding and planting. Values published in county soil survey for Deloss soil are given for reference. (modified from Skaggs et al. 2011b)

Layer Depth (from surface)	Hydraulic Conductivity, m/d			Transmissivity, m^2/d
	0–50 cm	50–80 cm	80–280 cm	0–280 cm
Pre-Harvest,1994–1995 (Age 22Y)	60	55	1.6	50
Post-Harvest, 1995–1996	60	55	1.6	50
Post-Bedding, 1996–1997	3.6	1.6	1.6	5.5
8 Yr. Post-Planting, 2005	50	20	1.6	34
15 Yr. Post Planting, 2012	50	20	1.6	34
K, Deloss from Soil Survey	1.2–3.6	0.36–1.6	0.36–1.6	1.4–5.5

summarized in Table 2 (after Agnese et al. 2011). Included are measured values for field saturated K for forested conditions and the ratio of that value to K of an alternative land use, which was pasture in most cases. K of the surface layer under forest was generally 3 to more than 25 times greater than that for pasture, cropland, or degraded forest on nearby sites and similar soils. The depth that K was impacted by surface cover was found to be 6 to 12 cm in some studies (Agnese et al. 2011; Hassler et al. 2011; Godsey and Elsenbeer 2002) and limited to about 25 cm for the remainder. An exception was reported by Bonell et al. (2010) who found a reduction in K of degraded forest compared to undisturbed forest, at depths of 60 and 150 cm, although reasons for the reduction were not clear. Godsey and Elsenbeer (2002) concluded that pasture, cropping, and recovering systems seem to have K values distinct from primary forests at shallow depths, but may be considered similar to forests at depths greater than 20 cm. This was not the case for the drained soils of this study where K at depth 50 to 80 cm under a mature pine plantation was reduced by more than a factor of 30 following harvesting, bedding, and replanting (Table 1). Differences in the response of K to harvesting and regeneration of drained pine plantations (Table 1) compared to harvesting or deforestation and changes in land use of upland forests (Table 2) may be due to both the methods used to measure K, and, in the case of plantation pine, to changes in soil properties caused by management or production practices. Most of the K measurements in studies on upland soils were point (or small-scale) measurements made on soil cores, or conducted in situ above the water table with permeameters of various types (Amoozegar and Wilson 1999). A weakness of the permeameter methods is that K is determined from inflow or infiltration measurements where air may be entrapped behind the wetting front and the soil not completely saturated. This results in values that are less than saturated K by as much as a factor of 2 (Bouwer 1966; Talsma 1987; Zimmermann et al. 2006; Bonell et al. 2010). Soil water contents below the water table under drainage conditions (Fig. 2) are likely closer to saturation. A more important reason is that the point scale K measurements of Table 2 do not adequately reflect the impacts of macropore flow which may be a substantial fraction of total subsurface flow at field and hillslope-scales (Brooks et al. 2004; Beven and Germann 1982). A clear discussion of the limitations of small-scale measurements of K for describing field or hillslope-scale processes was presented by Brooks et al. (2004). K values in Table 1 are based on measured drainage rates at the field scale and include effects of macropore flow.

Modeling Case Study: Effect of Drainage System Design on Wetland Hydrology at Plymouth, NC

The effect of substantial temporal changes in soil properties during the forest management cycle (tree harvest, site preparation (which includes bedding), planting, and tree growth to maturity) complicates the analysis of effects of drainage on wetland hydrology. A simulation study was conducted to determine the effects of silvicultural drainage on wetland hydrology of a pine plantation and how those effects change in response to changes in K. The hypothesis was that drainage systems, originally designed to sustain wetland hydrology, may fail to satisfy that objective after some years because of increases in K as the plantation matures.

Modeling Case Study: Methods

The Deloss soil on the field study site at Carteret did not provide an opportunity to test the hypothesis and was not selected for this case study. Ditches installed at a spacing of 100 m in the early 1970s drained the site such that it does not satisfy the wetland hydrologic criterion. Analysis of continuous water table measurements on the D2 site over the 1988–2008 period showed that the wetland criterion was not satisfied for a single year of the 21 year record (Amatya et al. 2019). This included the YP years following harvest, bedding and replanting when K was at a minimum (Table 1) and wetland conditions most likely to occur. Since ditches at a conventional 100 m spacing did not sustain wetland hydrology at the site preparation and planting stage there was no opportunity to test the hypothesis. A site on a Cape Fear loam soil near Plymouth, NC was selected for the model case study. Previous field and modeling studies had documented hydraulic properties of the soil for both pasture and forested land uses (Burchell et al. 2005; Liu 2017; Diggs 2004). Simulations

Table 2 Measured field saturated K of forest soils $\mathbf{K_{fs,F}}$ and ratios between $\mathbf{K_{fs,F}}$ and field saturated K of pasture or degraded forest ($K_{fs,P}$) soils from the literature. (Modified from Agnese et al. 2011)

Reference	Site	$K_{fs,F}$ (m/d)	$K_{fs,F}$/ $K_{fs,P}$	Depth (cm)	Notes
Alegre and Cassel (1996)	Peru	10	10	Surface	Infiltration rates-Forest/pasture
Godsey and Elsenbeer (2002)	Brazil	7	70	12.5	Compared to degraded pasture
Sauer and Logsdon (2002)	Arkansas	3	1.1 (ns*)		Stony soils
Celik (2005)	Turkey	0.35	1.2	0–10	Differences ns 10–20 cm layer
Zimmermann et al. (2006)	Brazil	4.9 0.9	6 3.7	12.5 20	K under forest compared to pasture and other (not shown)
Zimmermann and Elsenbeer (2008)	Ecuador	3.2–18 2.2–3.1 0.3–4.3	9.5–53 5.4–7.6 1 (ns)	12.5 20 50	Compares K under natural forest and grazed pasture in disturbed lands (landslides, etc)
Ande and Jide (2009)	Nigeria	4.1	2.3	0–20	Cores; Secondary Forest/Pasture
Hassler et al. (2011)	Panama	5.6 0.6	10 1 (ns)	0–6 6–12	K under 100 yr. Secondary Forest /Pasture
Bonell et al. (2010)	India, Western Ghats	2.6 1.0 0.7 0.5	6.7 7.2 5.5 12	0 10 60 150	Ratio of K under Forest compared to degraded forest Effects on other land uses also considered
Price et al. (2010)	*N. Carolina*	1.5	6.4	0–25	K under Forest/Pasture & Lawns
Agnese et al. (2011)	Sicily	3–22	2–12		5 forest species/pasture
Archer et al. (2013)	Scotland	0.2–4.2	5–8	4–15	Broadleaf Forest/grazed grasslands
Chandler et al. (2018)	Scotland	30 9	38 12	3–7 3–7	Scots pine /grazed pasture Sycamore/grazed pasture

ns, no significant difference

were conducted for a young pine plantation (YP) (0–5 years after bedding and planting) when the soil properties are expected to be similar to those measured under pasture, and for a mature pine plantation (MP) with K of the surface layers increased based on results from the field study discussed above and from a field and modeling study by Diggs (2004) on a nearby pine forested watershed. The hydraulic transmissivity of the Cape Fear soil under pasture is 2 m^2/d compared to 5.5m^2/d under YP for the Deloss soil of the field site (Table 1, post bedding), so we expected wetland conditions to be sustained under YP for conventional drain spacings on the Cape Fear.

The water balance in the soil profile was simulated with the model DRAINMOD (Skaggs 1982; Skaggs et al. 2012). The model predicts, on a continuous basis, water table depth, subsurface drainage, ET, deep and lateral seepage, and surface runoff for given weather and site conditions. Daily predicted water table depths were used to determine whether the wetland hydrologic criterion would be satisfied for a given site. Reliability of the model for predicting water table depths and the hydrology of artificially drained agricultural and forested lands, and wetlands, has been verified in extensive field studies and experiments (Skaggs 1982; Broadhead and Skaggs 1989; McCarthy et al. 1992, Borin et al. 2000; Amatya and Skaggs 2001; He et al. 2002; Vepraskas et al. 2004; Diggs 2004; Caldwell et al. 2007; Tian et al. 2012; Liu 2017). Inputs defining the wetland hydrologic criteria (critical water table depth (30 cm), growing season dates, and duration of saturation) are used together with daily predicted water table depths to determine if the wetland hydrologic criterion is satisfied in the center section of the field on an annual basis. Growing season dates at Plymouth are March 21 to November 15 based on median dates of 28 °F air temperature. Methods developed by Skaggs et al. (2005) and Phillips et al. (2010) were used to estimate the lateral effect, L_e, where wetland hydrology is not sustained near the ditch.

Soil properties for a Cape Fear loam were determined in research studies on an agricultural field site on the Tidewater Experiment Station near Plymouth, NC. Field effective saturated hydraulic conductivities (K), as a function of profile depth, were determined for this site by Burchel et al.(2005), Poole (2006), and Liu (2017) from continuous measurements of water table depth and drainage rate on a drained pasture. Results of the field study indicated that hydraulic conductivity under young pine (YP) is about the same as for agricultural uses so the K values given in Table 3 for YP are based on values determined by Liu (2017) in the calibration of DRAINMOD for the pasture site. Soil layers deeper than 100 cm were assumed to be unaffected by the plantation, so K values for MP were taken to be the same as for YP at those depths (Table 3). K values for the surface 100 cm of the profile for a mature pine plantation on this same site were estimated based on results obtained by Diggs (2004) in the calibration of DRAINMOD for a drained Cape Fear soil on an MP site located 6 km from the pasture site, and on results of the field study (Table 1). The K of 60 m/d for the 80 cm deep surface layer for MP (Table 3) is less than the equivalent K_e of 88 m/d reported by Diggs (2004) for MP on the other Cape Fear site, and somewhat greater than the equivalent K_e for MP on the Deloss soil (Table 1). The more conservative 60 m/d value was chosen because of concern that limited data for water table depths less than 40 cm deep in the Diggs (2004) study may have caused K in the surface layer to be overestimated. Volume drained and drainable porosity as a function of water table depth (Table 4) are based on values given by Liu (2017) and Diggs (2004) for YP and MP, respectively.

In addition to soil properties, there were also differences in inputs required to calculate ET for YP and MP. Daily ET is determined from potential evapotranspiration (PET) which may be read as input data or, in this case, estimated with the Thornthwaite (1948) method based on measured daily air temperatures and monthly correction factors developed from long-term analyses with the Penman- Monteith (PM) equation (Amatya et al. 1995). Domec et al. (2012) and Ge Sun et al. (2010) found PET for MP near Plymouth was 12–15% higher than estimated by the FAO Penman-Montheith equation for YP, which, in turn, was assumed to be the same as for grass. The difference was due to a much lower albedo for mature compared to young pine. Results were consistent with those presented by Amatya et al. (2002) who found PET for MP about 9% higher than YP for a site in the same area. Standard monthly based correction factors (Amatya et al. 1995) were used in this analysis for YP; they were increased by 10% for MP. Weather data from the Tidewater Experiment Station near Plymouth NC for the 50 year period (1965–2014) were used to simulate the hydrology of both YP and MP plantations for a range of ditch spacings, depths, and surface storages. Results were analyzed to determine how changes in field effective soil K and T affect wetland hydrology as pine plantations mature.

Table 3 Field effective saturated hydraulic conductivity (K) by layer and profile transmissivity (T) for Cape Fear Loam (based on Liu (2017) for YP and values in Table 1 and by Diggs (2004) for MP)

Young Plantation (YP)		Mature Plantation (MP)	
Depth (cm)	K(m /d)	Depth (cm)	K (m/d)
0–36	2.4	0–80	60
36–75	0.77	80–100	2
75–100	0.096	100–175	0.14
100–175	0.14	175–300	0.6
175–300	0.6		
T	2 m^2/d		49 m^2/d

Results and Discussion: Modeling Case Study

Daily predicted mid-field water table depths for YP and MP are plotted for a range of ditch spacings in Fig. 5 for the three-year period 2011–2013. The spacings of 62 and 290 m are threshold ditch spacings (L_T), based on results for the 50-year simulation period, for 90 cm deep ditches in the Cape Fear soil under YP and MP, respectively. The wetland hydrologic criterion would not be satisfied and wetland hydrology not sustained anywhere in the field for ditch spacings less than L_T. When the ditch spacing is greater than L_T, wetland hydrologic conditions will be satisfied in the center section of the field midway between the ditches. The 100 m and 200 m ditch spacings are commonly used for silviculture on Cape Fear and similar soils in NC, while a spacing of 400 m represents the upper end of the range that might be used for field ditches. Thus, the water table plots (Fig. 5) are representative of wetland hydrologic conditions for all five ditch spacings for YP, and for spacings of 290 and 400 m for MP. Annual rainfall depths for the 3-years (1406, 1295, and 1281 mm, respectively) were close to average for the 50-year simulation period (1293 mm). The impact of changes in soil properties on water table and wetland hydrology is substantial as shown by results for L62 (L = 62 m) where the predicted water table for YP was in the top 30 cm of the profile for over 60 consecutive days during the growing season (GS) in 2011, but only entered that zone for two days during the three years for MP. The differences are even more stark for L = 200 m where the predicted mid-field water table for YP was at the surface for continuous periods of more than 80 days in each of the three years, but only rose above the 30 cm depth twice during the three years for MP.

The effect of ditch spacing and depth on percentage of years satisfying the water table criterion for wetlands (i.e., water table continuously within 30 cm of the surface for a period of at least 14 days during GS) is shown in Fig. 6. Wetland hydrology exists when that criterion is satisfied in 50% of the years (25 out of 50 in this case), or more, so threshold ditch spacings are defined by the intersection with the 50% line in Fig. 6 for both YP and MP. Threshold spacings (L_T) are summarized in Table 5 for surface storage depths of 2.5, 5, and 15 cm and ditch depths ranging from 60 to 150 cm. There was not much difference in results for storages of 5 and 15 cm because rainfall conditions resulting in surface storage greater than 5 cm rarely occurred. L_T increased with ditch depth for both YP and MP, as expected from drainage theory, but the more important result is the change in wetland hydrologic status caused by the much greater profile hydraulic transmissivity and increases in ET of the mature plantation. Predicted threshold spacings (L_T) for MP were roughly four times greater than for YP for all ditch depths (Table 5). Using a ditch depth of 90 cm and surface storage of 15 cm as an example, the water table was within 30 cm of the surface for a continuous period of 14 days or more in at least 50% of the years for ditch spacings greater than $L_T = 62$ m for YP. To get the same results for MP, the ditch spacing would have to be 290 m or greater (Table 5, Fig. 6). Consider the impact for the 100 m ditch spacings often used in this region for silvicultural drainage of fine textured soils (Terry and Hughes 1978). For YP profile conditions, the shallow water table requirement for wetland hydrology would be satisfied in 92% of the years on average for a ditch depth of 90 cm, and 74% of the years for a ditch depth of 150 cm (Fig. 6). These results are predicted for soil conditions that exist during the first 5 years or so after site preparation and planting. The much greater hydraulic transmissivity of the profile by 8 years after planting (Table 3), coupled with increases in ET, caused the wetland hydrologic status to be much different. For a 100 m ditch spacing under those conditions, the water table criterion for wetland hydrology was not satisfied in a single year of the 50 year simulation for all ditch depths considered (Fig. 6). Thus, parallel ditches at 100 m spacing sustained wetland hydrology in the center section between ditches early in the plantation when drainage requirements are most critical, but failed to satisfy the wetland hydrologic criterion for the mature plantation. The difference is mostly due to the increase of hydraulic conductivity in the upper part of the profile, rather than to increases in ET. This is illustrated by the broken curve in Fig. 6 which plots results of simulations conducted for MP soil properties with YP inputs for PET. That is, the increases in PET as the plantation matures were not considered in this hypothetical case. Failure to consider changes in ET as the plantation matures would have increased the predicted percentage of years satisfying the wetland hydrologic criterion by 7 to 10% (Fig. 6) for this example. Overall, changes in the soil properties that occurred as the plantation matured caused the threshold ditch spacing, $L_{T,}$ to increase from 62 m (YP) to 260 m (MP, broken curve, Fig. 6). Increases in ET due to changes in the vegetation added another 30 m so that L_T determined for the MP stage is 290 m. The effects of ET are important and ET from a forest may be substantially greater than the normal potential ET (PET) based on a grass reference (Sun et al. 2010, 2011; Domec et al. 2012; Katerji and Rana 2011; Rao et al. 2011; Oliveira et al. 2018). However, differences in wetland hydrologic status between YP and MP shown in Fig. 6 and Table 5 are mostly due to increases in subsurface drainage intensity caused by changes in soil properties and, to a lesser extent, by increases in ET.

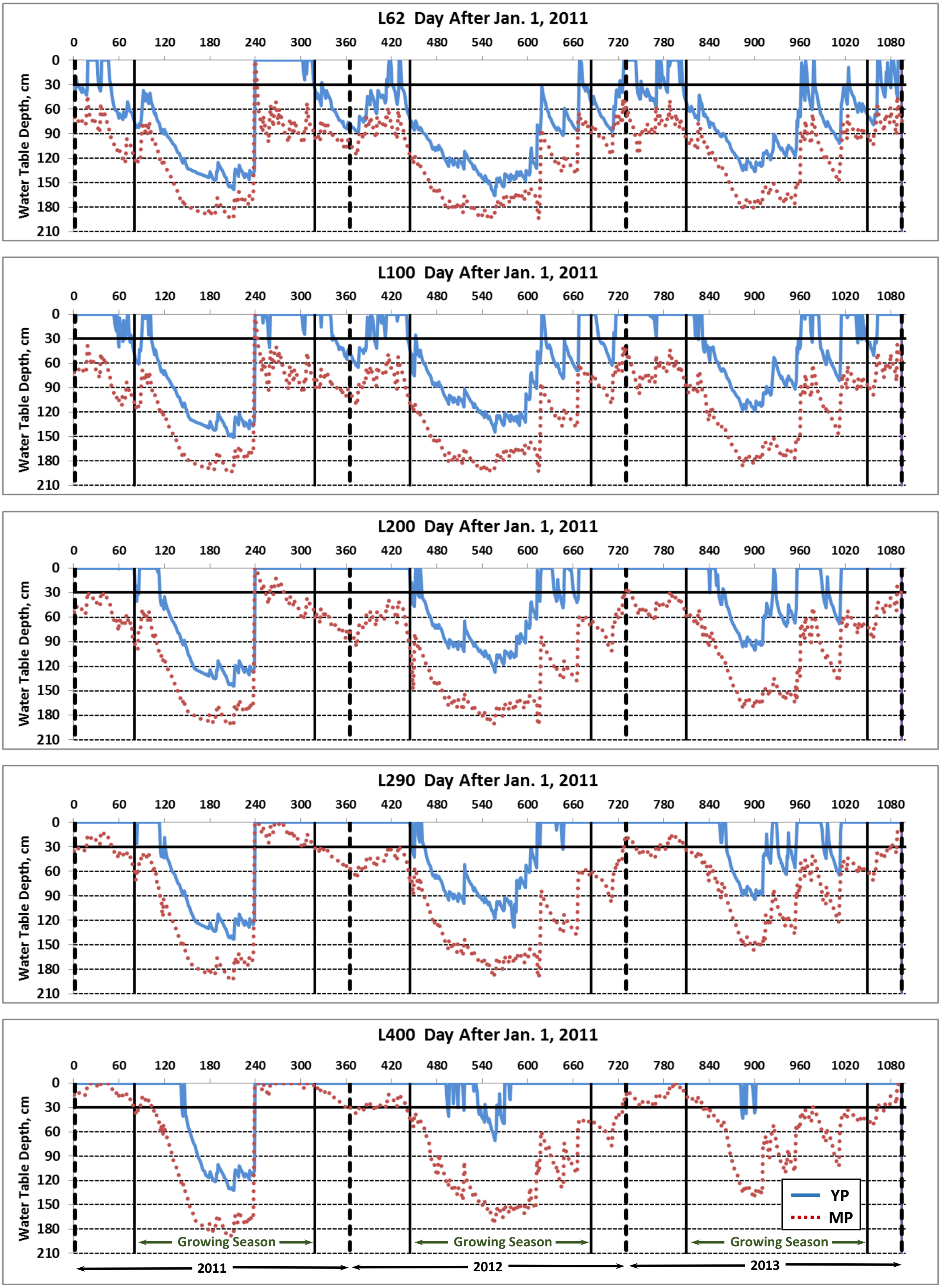
The drainage intensity (DI, Eq. 2) corresponding to the threshold ditch spacing may be defined as the threshold drainage intensity (DI_T), and is included in Table 5. DI_T varied from 1.3 to 4.4 mm/d across the ditch depths, surface storages, and plantation soil conditions (YP and MP) considered (Table 5). Wetland hydrology would not be sustained at any point in the field for DI greater than DI_T. Generally DI_T decreased with ditch depth and increased with surface storage with average values around 3 mm/d for YP and 4 mm/d for MP for normal silviculture surface storages (5 to 15 cm).

Depending on the ditch spacing and soil properties, the lateral effect (L_e) of the ditches may remove wetland hydrology from a relatively large percentage of the field (Table 6). For example the L_e for 90 cm deep ditches was predicted to remove wetland hydrology from 20 m on both sides of the ditch for YP, or 40% of the field for 100 m ditch spacing, and 20% of the field for 200 m spacing. The predicted lateral effect for MP conditions is larger, but is not relevant for the 100 and 200 m spacings as they are less than L_T and wetland hydrology is removed from the entire field (Table 5). While wetland hydrology would be sustained midway between widely spaced ditches for MP (Table 5), L_e would be large. Depending on ditch depth, wetland hydrology would not be sustained in a strip 51 to 99 m wide on either side of the ditch for MP conditions, (Table 6). This amounts to between 26 and 49% of the field area for a ditch spacing of 400 m (MP400, Table 6).

The Drainage Coefficient (DC) assumed for results presented above was 2.5 cm/d which is typically recommended for agricultural drainage in the area (USDA-NRCS 2001) and greater than needed for silviculture drainage in most cases. This means that drainage flow rates in the above results were limited by the rate water could drain through the profile to the ditches, not by the hydraulic capacity of the ditches and outlet canals. Changes in DC had little impact on wetland status for DC values greater than 0.6 cm/d for a mature plantation (Fig. 7). DC values of 0.2 cm/d or less would sustain

Table 4 Volume drained (water free pore space) when water table is lowered from the surface to depths shown. Drainable porosity in percent is given in (). Modified from Liu (2017) for young plantation (YP) and Diggs (2004) for mature plantation (MP)

Water Table	Volume drained, cm (drainable porosity)	
Depth, cm	Young Plantation (YP)	Mature Plantation (MP)
0	0 (2%)	0 (24%)
30	0.7 (6.6)	7(21)
60	2.6 (5.3)	12(5)
90	4.2(5.3)	14.4(5.3)
120	5.3(5.3)	15.6(4.7)
150	6.5(2.5)	16.5(6.0)


L62 Day After Jan. 1, 2011
L100 Day After Jan. 1, 2011
L200 Day After Jan. 1, 2011
L290 Day After Jan. 1, 2011
L400 Day After Jan. 1, 2011
0 60 120 180 240 300 360 420 480 540 600 660 720 780 840 900 960 1020 1080
Water Table Depth, cm
0 30 60 90 120 150 180 210
YP
MP
Growing Season
Growing Season
Growing Season
2011
2012
2013

◀ **Fig. 5** Predicted Water table depths for young (YP———) and mature (MP- - - - - -) pine plantations over the 3-year period 2011–2013 for a range of ditch spacings on a Cape Fear loam near Plymouth, NC. Solid horizontal black line denotes 30 cm water table depth criterion for wetland hydrology. Ditch depth is 90 cm and surface depressional storage 15 cm. Annual rainfall of 1406, 1295, and 1281 mm, respectively, are close to the 50-yr. long term average of 1293 mm

wetland hydrology for all cases considered. Similar results were predicted for YP soil conditions (not shown). The DC may be limiting and result in wetland hydrology where outlets reduce flow capacities because of design, plugging, or obstructions in the ditch.

Flow frequency diagrams (Fig. 8) are plotted for a DC of 2.5 cm/d for a range of ditch spacings that would result in satisfying the criterion for wetland hydrology for some cases (solid curves), and not for others (dashed curves). Drainage rates are limited by drainage intensity (DI) as affected by ditch spacing and stand age (YP or MP). The shapes of the flow frequency relationships are similar for the 90% of days having the lowest flows for all cases (whether or not they satisfy wetland hydrologic criterion, Fig. 8). Predicted outflows for this range were less than 0.3 cm/d. The percentage of days with no outflow varied from 30% for L100YP to 56% for L100MP; no outflow was predicted on 38% of the days for the threshold ditch spacings (L62YP and L290MP). The flat portions designated as "aa" in each curve represent conditions when the predicted water table was at the surface with drainage rate equal to DI. Flow rates less than those values were simulated when the midpoint water table elevation, m, (Fig. 1) was below the surface. Outflow rates greater than DI occurred when the surface became ponded from ditch-to- ditch and surface runoff occurred. Daily outflows greater than DI were predicted for fewer than 3.9% of the days for L100YP, 0.6% for L62YP, and 0.1% for L100MP, L200MP, and L290MP.

This modeling case study illustrates how minor drainage for silviculture can result in the loss of wetland hydrology, even if the drainage system is specifically designed to avoid that result. Based on published values of soil properties and current practice in the area, the threshold spacings for 60 to 90 cm deep ditches on the Cape Fear soil of this study would be 47 to 65 m for a bedded plantation (Table 5). The beds would provide a drained micro-environment for seedlings during their most vulnerable stage, so it would be logical to install ditches at 100 to 200 m spacings to provide a low DI (3 mm/d or less) to maintain wetland hydrology in the broad center section between ditches (Table 6). To minimize the lateral effect of the ditch on the % of land with wetland hydrology, the ditches should be as shallow and the spacing as wide as possible (Table 6). However, long term field research has shown that effective K of the soil profile increases by an order of magnitude or more (Table 1) due to the development of macropores, resulting in a substantial increase in DI and failure to sustain wetland hydrology as the plantation matures (Table 5, Fig. 6). While the effect of trees, root growth, and development of macropores on K is well recognized (Wilson and Luxmoore 1988; Brooks et al. 2004), there are few data on the rate of change, and the effects of harvesting and regeneration on soil properties. More research is needed for a range of soils and conditions. The impacts of such changes are important, as shown here, but are not generally considered in assessing hydrologic impacts of drainage. In addition to the negative effects that increases in K and DI have on maintaining wetland hydrology, they may also reduce water availability for silviculture production. Greater than necessary DI will result in excess drainage of

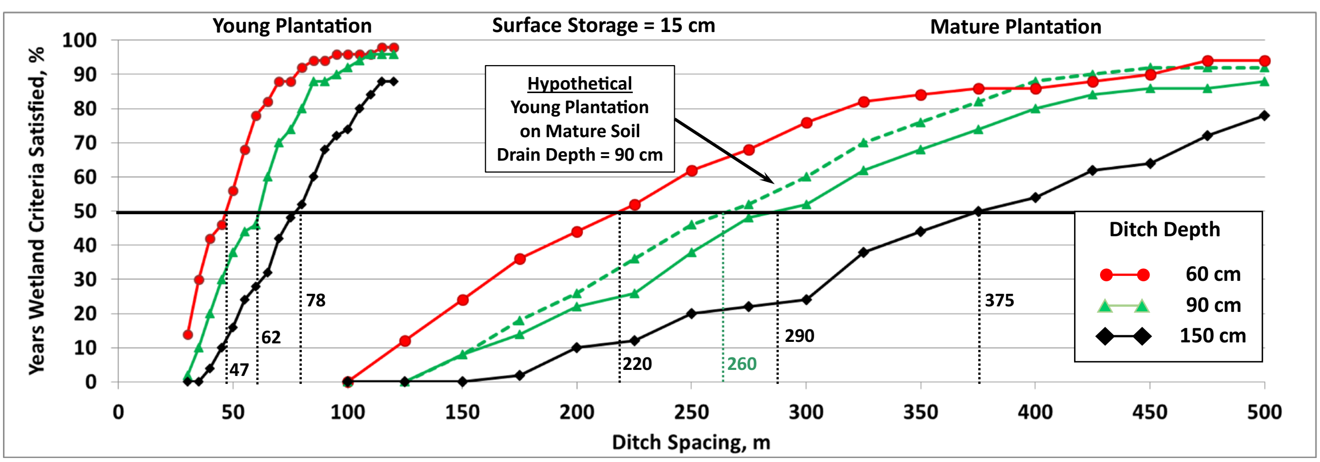


Fig. 6 Percentage of years (out of 50) predicted water table was above the 30 cm depth for 14 or more continuous days during the growing season as affected by ditch spacing and depth for young (YP) and mature (MP) pine plantation near Plymouth, NC. Broken curve shows relationship when increased ET of mature pine is not considered. Wetland hydrology exists when % Years Criterion Satisfied is greater than 50%

Table 5 Threshold ditch spacing, L_T (m), as affected by ditch depth and surface storage for young (YP:0–5 yrs) and mature (MP:>8 yrs) pine plantations on Cape Fear soil, Plymouth, NC. The subsurface drainage intensity, DI (mm/d) is given in ()

Surface Storage, cm	2.5	5	15	2.5	5	15
Ditch Depth, cm	Young Plantation (0–5 yr.)			Mature Plantation (> 8 yr.)		
60	72 (1.7)	51 (3.3)	47 (4.2)	227 (4.1)	220 (4.4)	220 (4.4)
90	89 (1.5)	65 (3.0)	62(3.5)	293 (3.5)	290 (3.6)	290 (3.6)
120	103 (1.5)	78 (2.6)	70 (3.2)	350 (3.1)	340 (3.3)	335 (3.4)
150	119 (1.3)	87 (2.4)	78 (3.0)	380 (3.1)	380 (3.1)	375 (3.1)

water that could otherwise be used by the trees to satisfy ET requirements, potentially reducing growth compared to what would occur with smaller DI. In this respect objectives for maintaining wetland hydrology are coincident with those of drainage water management for production.

Options to minimize the effects of silviculture drainage on wetland hydrology include (1) use of shallow field ditches (60 to 90 cm) to limit drainage beyond the 90 cm depth and DI to 3 to 4 mm/d, (2) beds to minimize surface runoff and protect seedlings from waterlogging stresses, so that (3) ditches can be spaced as widely as possible. (4) Control structures or gates can be used in relatively flat lands to raise water levels in collector canals and field ditches. The weir elevation can be increased over time to counter effects of increasing K and maintain a DI in the 3-4 mm/d range. This reduces the effective depth of the ditch and drainage rates, raises water tables, and conserves water (Amatya et al. 1996, 2000). (5) The orifice weir control structure (Amatya et al. 2003) could be used after year 5 or so to reduce drainage rates by both raising the effective ditch depth and reducing the DC. (6) A passive method that could be effective in some cases is to simply allow field ditches to fill naturally (Campbell and Hughes 1991). The most intensive drainage needs are in the early stages of plantation, and at harvest. By not cleaning the ditches from planting to just prior to harvest, natural sloughing and filling processes could counter some of the increases in DI resulting from changes in K. (7) Another option is to simply plug some of the ditches (e.g., one out of two, or two out of three ditches) to reduce drainage intensity after about year 5 following planting.

Table 6 Lateral effect, L_e (m), as a function of ditch depth for 15 cm surface storage on young (< 5 yrs) and mature (> 8 yrs) pine plantations on Cape Fear soil, Plymouth, NC

Ditch	Lateral Effect		Lateral Effect			
Depth (cm)	(m)		(As % of Field Area)			
	*YP	*MP	YP100	YP200	YP400	MP400
60	14	51	28%	14%	7%	26%
90	20	74	40	20	10	37
120	24	87	48	24	12	44
150	27	99	54	27	14	49

*YP and MP mean young and mature pine plantations, respectively; YP100 and YP200 mean young plantation with 100 m and 200 m ditch spacing, respectively

Summary

Long term field research on a drained pine plantation watershed in eastern NC showed that field effective saturated hydraulic conductivity (K) of the top 80 cm of the profile under a mature pine plantation (MP) was over 20 times greater than under a young plantation (YP). K for YP was close to values published in the USDA NRCS Soil Survey for the soil series. The difference, which is attributed to development of macropores in the profile of the mature forest, resulted in hydraulic transmissivity of the profile of 50 m^2/d compared to 5.5 m^2/d for YP. Measured K and profile transmissivity (T) were not changed by tree harvest, but were reduced to expected values for the soil series after site preparation and bedding during regeneration of the

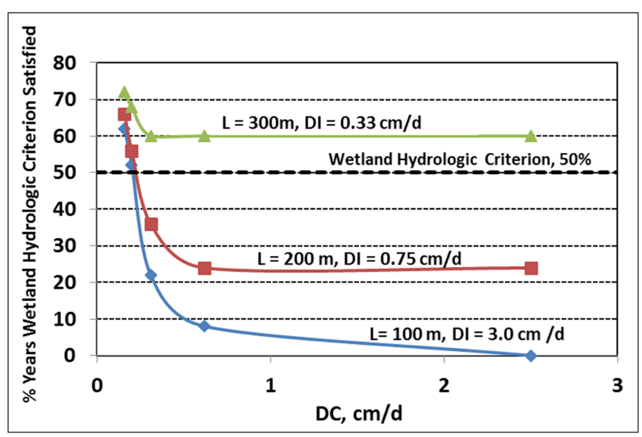


Fig. 7 Effect of drainage coefficient (DC) on % years water table criterion for wetland hydrology is satisfied for drained Cape Fear Soil on a mature pine plantation near Plymouth, NC. Wetland hydrology exists when the percentage is greater than 50%

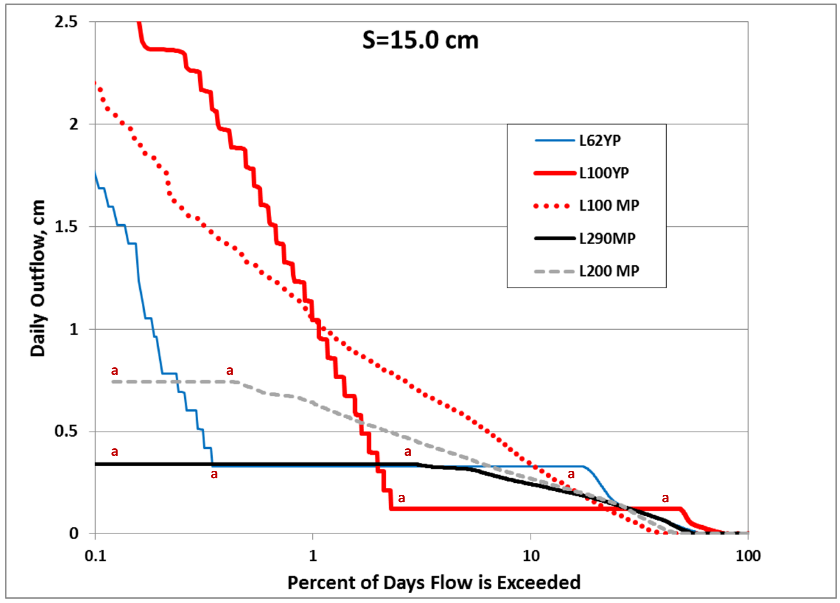


Fig. 8 Frequency of predicted daily outflows from a Cape Fear soil near Plymouth, NC for ditch depth 90 cm, surface storage of 15 cm, and a range of ditch spacings: L100YP means ditch spacing L = 100 m on young plantation (YP); L200MP means L = 200 m on a mature plantation (MP), etc. Wetland hydrologic criterion satisfied for solid curves, not for dashed curves

plantation. By eight years after planting, K of the top 40 cm had nearly returned to pre-harvest values. A modeling case study was conducted to determine effects of such changes in soil properties on wetland hydrology. It showed that increased K and T caused ditch spacings required to sustain wetland hydrology for MP to be about 4 times greater than required for YP. Even for ditch spacings wide enough to sustain wetland hydrology in the broad center section between ditches, the water table in a strip near the ditch may be lowered such that wetland hydrology is removed. The case study showed that lateral effects of drainage ditches, typically small for YP, may be much greater when the trees mature (MP), resulting in failure to sustain wetland hydrology near the ditches on a significant percentage of the plantation. This raises questions about spatial extent of wetland conditions necessary to consider a site a wetland.

What do changes in soil properties under a maturing forest mean in terms of meeting requirements of the Clean Water Act's 404(f) exemption? Our results show that drainage ditches, typically spaced at 100 or 200 m to provide sufficient drainage intensity (DI) for establishment and survival of a young pine plantation, will satisfy the wetland hydrologic criterion on most of the site for the first five years or so after planting. Increases in soil K and profile T as trees mature may result in failure to sustain wetland hydrology by about year 8 after planting. The limited research evidence currently available indicates that soil properties return to original values when trees are harvested and fields are prepared for planting and regeneration. More research is needed to determine the range of soil conditions under which this occurs and the rates that field effective values of soil properties change. The changes causing removal of wetland hydrology are not permanent, but are part of the production cycle with wetland hydrology existing during the early years after planting, but not during the later years. Methods discussed herein can be used to reduce drainage intensity (DI), conserve drainage water, and potentially sustain wetland hydrologic conditions as the trees mature.

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