A Method to Determine Lateral Effect of a Drainage Ditch on Wetland Hydrology: Field Testing

B. D. Phillips, R. W. Skaggs, G. M. Chescheir

Abstract. *An approximate method was previously developed to predict the lateral effect of a drainage ditch on wetland hydrology. The method predicts the lateral distance of influence of a single ditch constructed through, or adjacent to, a wetland in terms of T_{25} values, which are dependent on climatological conditions. The lateral effect, or distance of influence, is defined as the width of a strip adjacent to the ditch that is drained such that it no longer satisfies wetland hydrologic criteria. T_{25} represents the time required for the water table to be drawn down by drainage from the surface to a depth of 25 cm at the location on the landscape that will just barely satisfy the wetland hydrologic criterion. Data to test the method were collected at two wetland mitigation sites in eastern North Carolina: Mildred Woods in Edgecombe County and ABC near Pinetown in Beaufort County. The approximate method predicted lateral effects of 42.6, 7.2, and 14.1 m for Mildred Woods, ABC shallow ditch, and the ABC deep ditch, respectively. Compared to direct interpolation of 3-year average field results for Mildred Woods (41 m) and the deep ditch (12 m), the method performed well. The lateral effect predicted by the method for the shallow ditch at the ABC site was at least two times that measured in the field (<3.75 m). In this case, the ditch was located in a tight clay layer, which substantially reduced the effective transmissivity of the profile and the lateral effect of the ditch on the hydrology of adjacent wetlands.*

Keywords. *Drainage, DRAINMOD, Hydric soils, Lateral effect, Mitigation, Restoration, Water table, Wetland drainage, Wetlands.*

The U.S. Army Corps of Engineers (COE), under authority of the Environmental Protection Agency (EPA) and through Section 404 of the Clean Water Act (CWA), regulates jurisdictional wetlands by controlling the discharge of dredged or fill materials into wetlands. In 1987, the COE's Environmental Laboratory issued a Wetlands Delineation Manual, commonly referred to as the 87 Manual (COE, 1987), as a guide to define a jurisdictional wetland. As stated in the 87 Manual, jurisdictional wetlands are:

"Those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas" (COE, 1987. p. 12).

The 87 Manual's delineation procedure is based on the so-called three-parameter approach, which holds that, in order to be a wetland, a site must satisfy three parameters: wetland hydrology, hydric soils, and conditions that would support a dominance of hydrophytic vegetation. Of these, wetland hydrology is the most important, as neither hydric soils nor hydrophytic vegetation could be sustained without hydrologic conditions characteristic of wetlands. For the purposes of this research, wetland hydrology will be based on the 87 Manual and summarized as follows:

> "Wetland hydrology exists if, during the growing season, the water table is normally within 30 cm (1 foot) of the soil surface for a continuous period of at least 5% of the growing season" (NRC, 1995, p. 75).

In order to fully quantify the above criteria, definitions must be set for the growing season and for "normally." The growing season is usually defined as the period between the average last day having an air temperature of -2°C (28°F) in the spring and the first day having an air temperature of -2°C (28°F) in the fall (50% probability of recurrence). Data for the growing season length can be found in published Natural Resources Conservation Service (NRCS) county soil surveys or from the internet at the NRCS Water and Climate Center. "Normally" is defined for this purpose by the COE as occurring in half of the years on average; that is, the water table would be within 30 cm of the surface for at least 5% of the growing season in 50% of the years on average. New regional COE supplements for determining hydraulic status of wetlands use 14 days, rather than 5% of the growing season, as the minimum threshold for continuous saturation. This change is consistent with recommendations by the National Research Council report on characterizing wetlands (NRC, 1995). The work reported in this article was done prior to the change and used 5% of the growing season as the threshold. The change will not affect the validity of the method, nor of

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the results presented herein to test its reliability, as will be discussed in a later section.

Wetland hydrology is generally considered to be the most difficult of the three parameters or factors to quantify (Owen, 1995; NRC, 1995, 2001). In order to determine the existence of wetland hydrology from on-site measurements, long-term water table data are required. Often these records are either unavailable or are available for only short durations. Therefore, regulatory judgment as to whether a site meets the jurisdictional wetland criteria is often based on presence of hydric soils, dominant hydrophytes, and hydrologic indicators. This issue was addressed by a committee of the National Research Council (NRC, 1995) in a comprehensive study of the characteristics and definitions of wetlands. The committee concluded that soils and plants are reliable indicators of wetland hydrology for cases where the hydrology has not been modified. However, when the hydrology has been modified, the presence or absence of wetland hydrology must be determined independently.

Drainage ditches constructed through or adjacent to wetlands will modify the hydrology of the wetland to some extent. For purposes of both wetland delineation and restoration, there is a need for a sound method of quantifying the lateral effect of a drainage ditch on the hydrology of adjacent wetlands. The lateral effect of a drainage ditch or other drain or similar structure may be defined as the width of a strip of land adjacent to the ditch which is drained such that it no longer satisfies the wetland hydrologic criterion.

One method that has been used to determine the lateral effect of a roadside drainage ditch on adjacent wetland hydrology is based on the "Scope and Effect Guide" for North Carolina hydric soils (NRCS, 1998). The guide groups together soils of similar soil properties and estimates the lateral effect of a particular drainage ditch depth and soil group combination. The method is based on the ellipse equation for flow to parallel drains with several simplifying assumptions. It does not consider a number of factors affecting wetland hydrology, including the dynamics of water table rise and fall in response to rainfall, drainage and evapotranspiration, the fact that the lateral effect of a single ditch is less than that of parallel drains, and the effects of surface depressional storage.

An approximate method was presented by Skaggs et al. (2005) to estimate the lateral effect of a drainage ditch on adjacent wetland hydrology. The method was adopted by the North Carolina Department of Transportation (NCDOT) and is available on their website (www.ncdot.org/doh/Operations/dp_chief_eng/roadside/fieldops/downloads/). The method is based on the time required for water table drawdown in an initially saturated profile with the water table coincident with the surface. DRAINMOD (Skaggs, 1978) simulation analyses showed that sites barely satisfying the wetland hydrologic criterion will have drainage intensities that provide water table drawdown from the surface to a depth of 25 cm in a specific time. This threshold drawdown time, T_{25}, was found to depend moderately on ditch depth but was nearly constant among soils having a wide range of profile transmissivities and drainable porosities. T_{25} was found to depend strongly on surface depressional storage, decreasing as surface storage increased. T_{25} also depended strongly on geographic location, which affects both the growing season and weather variables. Because they are determined from DRAINMOD simulations, the T_{25} values consider the effect of both precipitation and ET on water table dynamics. Once the T_{25} values are determined, published solutions to the Boussinesq equation for water table drawdown due to a single drain (Skaggs, 1976) can be used to estimate the lateral effect of a drainage ditch or subsurface drain on wetland hydrology. The purpose of this study was to test the validity of the approximate method.

The solutions developed by Skaggs (1976) are presented as nondimensional plots, which are applicable to most situations involving a single drain. Application of the approximate method involves some manipulation of the nondimensional solutions. While the application is relatively straightforward, it does require graphical lookup and interpolation. A computer model based on the original numerical solution of the Boussinesq equation and associated software to simplify its application were developed in this study and were used in testing the method.

Objectives

1. Measure the lateral effect (location of boundary between upland and wetland conditions) of drainage ditches adjacent to wetlands at three locations.
2. Compare lateral effects predicted by the approximate method with values determined from field data.

Study Sites

Field testing of the method was conducted at two wetland mitigation sites in eastern North Carolina. These sites are managed by the North Carolina Department of Transportation's Office of Natural Environment. The first study site is located in Edgecombe County at the Mildred Woods mitigation site (35.87° N, 77.48° W; NCDOT, 2001), approximately 5 km east of the town of Tarboro. The second study site is located in the town of Pinetown, Beaufort County, at the ABC mitigation site (35.62° N, 76.86° W; NCDOT, 2002).

Transects of seven water table wells were installed perpendicular to drainage ditches at the sites. A graphical depiction of the wells along a generalized transect is shown in figure 1. Transects were installed adjacent to two drainage ditches at the ABC site and adjacent to one ditch at the Mildred Woods site. Lengths of transects and distances between the wells varied depending on the ditch dimensions and soil type.

The sites were instrumented in late 2001, with data recording and collection beginning early 2002 and continuing until May 2005. Both manual and recording wells were used to determine water table depth. The wells were made of slotted 102 mm (4 in.) PVC pipes and installed to a depth of 1.5 to 2.0 m. Weatherproof instrument boxes were placed atop the recording wells. Elevations, in reference to the ditch bottom, were recorded at the top of the well and at ground surface.

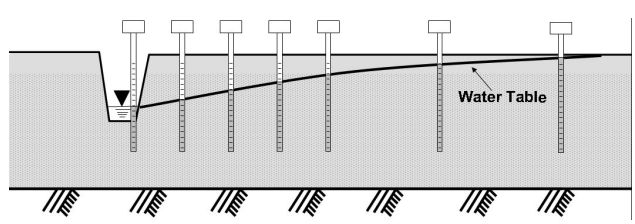

Figure 1. Generalized view of a transect of wells.

Table 1. Soils and site parameters at study sites.

Site	Soil Series	Depth (m)	Top Width (m)	Bottom Width (m)	Sideslope (H:V)	Depth to Impermeable Layer (m)	Normal Depth to Water in Ditch (m)
Mildred Woods	Cape Fear, Roanoke	1.2	9.1	6.1	2:1	4.8	0.9
ABC shallow ditch	Leaf	0.9	2.3	1.0	1.1:1	6.0	0.8
ABC deep ditch	Leaf	1.4	4.0	1.3	1:1	6.0	1.2

The recording wells included a float/counterweight pulley system coupled to a potentiometer. Voltages through the potentiometer were monitored and recorded by a data logger (HOBO H8, Onset Computer Corp., Bourne, Mass.) on an hourly basis. Collection of data from the field involved visiting each site on a regular basis, every 2 to 4 weeks depending on weather conditions. During each visit, a manual depth to the water table was recorded at each of the seven wells on each transect, and voltage data were offloaded to a computer. Paired values for the manually measured water table depth and the voltage were recorded for each automatic recording well. Data for each visit were entered into a spreadsheet, and a linear regression line was fitted to the updated data set to develop an equation for the relationship between voltage and measured water table depth. This relationship was then used to convert measured voltage data to water table depths for each recording well. Coefficient of determination (R^2) values for the relationship of water table depth and voltage for each recording well were typically greater than 0.95 during the monitoring period.

One manual rain gauge and one recording rain gauge were located at the transect site. The tipping-bucket rain gauge (Onset Computer Corp.) recorded the time of each 0.254 mm (0.01 in.) tip. During each field visit, the manual rain gauge was read and data from the recording rain gauge were downloaded. The reading from the manual rain gauge was compared to that of the recording rain gauge, and the data were adjusted if necessary. The manual rain gauge almost always recorded higher rainfall than the tipping-bucket rain gauge due to small losses of rainwater during the tipping process. On an annual basis, precipitation measured by the manual gauge was between 3% and 5% greater than that measured by the tipping bucket.

Mildred Woods Site

The Mildred Woods Mitigation Site was constructed in 1995 and is approximately 340 ha. One well transect was installed perpendicular to a main north-to-south drainage ditch that had a free-flowing outlet. Transect wells were located at 0 (located in the ditch), 7.5, 15, 30, 45, 60, and 90 m away from the ditch. The wells located at 7.5 and 90 m were manual observation wells. Wells located at 0, 15, 30, 45, and 60 m were instrumented with automatic recorders. Two dominant soil series are located within the transect area. Close to the drainage ditch, the soil series is Cape Fear (clayey, mixed, Typic Umbraquults). Beginning at approximately the midpoint of the transect, the soil series is Roanoke (clayey, mixed, thermic Typic Ochraquults). The Cape Fear series is classified as very poorly drained, and the Roanoke series is classified as poorly drained.

ABC Site

The ABC Mitigation Site was constructed in 2001 and is approximately 75 ha. Two main ditches are located on the ABC site. The ditches are not connected and had free-flowing outlets during the monitoring period. A shallow north-to-south ditch is located on the western edge. The shallow ditch flows to a southern perimeter canal adjacent to an agricultural field. A deeper ditch is located on the northern side and runs east to west. Water from the deep ditch flows east toward a tributary of Pungo Creek. The tributary is of low order and is 14.5 linear km (9 linear mi) from Pungo Creek. Tidal influences were not observed during monitoring of the deep ditch water levels. Transect wells located at the shallow ditch were at 0 (in the ditch), 3.75, 7.5, 11.25, 15, 22.5, and 30 m away from the ditch. The well located at 30 m was a manual well. The remaining wells were recording wells. Transect wells located at the deep ditch were at 0 (in the ditch), 7.5, 15, 22.5, 30, 45, and 60 m away from the deep ditch. The wells located at 7.5 and 60 m were manual, and the remaining wells were automatic recording wells. The dominant soil series in both transect areas was the Leaf series (clayey, mixed, thermic Typic Albaquults), classified as poorly drained.

Auger hole tests to determine lateral hydraulic conductivity (van Beers, 1970) were performed on both sites in March 2004. Soil cores were collected from both sites in May 2004 to determine soil-water characteristics curves and vertical hydraulic conductivity (Klute, 1986). Soil borings to determine the depth to the impermeable (or restrictive) layer (marine clay) were conducted at each site in September 2004. A layer was considered impermeable, or restrictive, if its hydraulic conductivity was less than 10% of the layers above it. Physical parameters of the three ditches are listed in table 1.

Results

Rainfall

The annual rainfall for the study period ranged from 1110 mm in 2004 to 1418 mm in 2003 at Mildred Woods (table 2). The long-term average (1971-2000) annual rainfall (1157 mm) and 30th and 70th percentiles (1031 and 1235 mm, respectively) were determined from records at the COOP weather station in Tarboro (near Mildred Woods). Annual rainfall at Pinetown ranged from 1098 to 1556 mm; the long-term average (1971-2000) at nearby Belhaven was 1266 mm. Year-to-year variability of rainfall for each month was greater on a percentage basis than year-to-year variability of annual rainfall. For example, rainfall for July at Mildred Woods ranged from 65 mm in 2004 to 216 mm for 2002 compared to the long-term average of 113 mm. High year-to-year variability of monthly rainfall is typical for eastern North Carolina; this variability causes difficulty in determining hydrologic status of wetlands.

Mildred Woods Site

Water table depths measured at both sites fluctuated with rainfall events and evapotranspiration (ET). Water table depths at Mildred Woods ranged from at or above the soil sur-

Table 2. Monthly rainfall (mm) at the Mildred Woods and ABC sites.

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Mildred Woods													
2002	139	38	108	36	32	62	216	140	136	171	116	96	1290
2003	45	131	97	151	135	44	148	191	207	104	44	122	1418
2004	29	80	53	73	125	152	65	244	126	54	79	31	1110
Avg. (3 years)	71	83	86	87	97	86	143	191	156	110	80	83	1272
Avg. (30 years)	108	90	107	78	95	95	113	122	125	81	65	78	1157
30th percentile	83	66	83	51	66	63	74	85	70	45	43	51	1031
70th percentile	125	107	129	102	109	111	131	145	154	111	78	96	1235
ABC													
2002	122	50	167	70	56	72	75	145	89	104	125	96	1171
2003	19	121	111	141	222	34	174	133	252	107	72	170	1556
2004	44	98	52	104	95	150	46	196	132	47	90	46	1098
Avg. (3 years)	62	90	110	105	124	85	98	158	157	86	96	104	1275
Avg. (30 years)	108	78	105	81	114	121	140	148	129	87	74	81	1266
30th percentile	83	54	79	49	71	90	104	93	75	37	52	55	1164
70th percentile	125	95	122	105	138	138	163	179	152	107	87	100	1337

face after heavy rainfall events or wet periods, particularly during the winter months, to more than 1.3 m deep in June 2002. Water table elevation is plotted in figure 2 as a function of distance from the ditch for five dates in 2003. Water table depth generally decreased as the distance of the monitoring well from the ditch increased. For most of the observations, the water table was deepest at 7.5 m from the ditch and shallowest at 90 m. The water table depths at 45 m were usually close to those measured at 90 m. Water table depths at the 15 m well were rarely less than 30 cm deep, while water table depths at the 45 and 90 m wells were frequently less than 30 cm deep.

The water level in the ditch (as depth below the soil surface at the top of the bank) also fluctuated with rainfall and ET. The water level in the ditch was usually between 0.8 and 1.0 m below the top of the bank. There were periods during the 3-year study when the water level in the ditch was impacted by a downstream beaver dam. Beaver activity was evident during the fall and the winter of 2002. During much of this period, the level in the ditch was 0.6 to 0.7 m below the top of the bank. The water level in the ditch is assumed to influence the water table depths measured in the well transects, particularly in the wells close to the ditch.

Water table elevation (expressed in fig. 2 as elevation above the bottom of the ditch) usually increased with distance from the ditch, consistent with the theoretical shape (fig. 1). Note that when the water table is high (e.g., March 31) it is relatively flat beyond 45 m. The water table shape near the ditch sometimes differed from the theoretical shape (see Nov. 11), but this was likely due to the fluctuating water level in the ditch. Normal fluctuations of the ditch water levels caused by rainfall and ET would likely not affect the methods developed in the study.

Fluctuations in ditch water levels caused by beaver dams, however, would affect the accuracy of the methods. In this case, the lateral effect would be less than that predicted by the methods. The water table shape on July 31 occurred when the water table fell below the water level in the ditch during high ET summer conditions, producing a subirrigation effect. Visual inspection of figure 2 indicates that the lateral effect

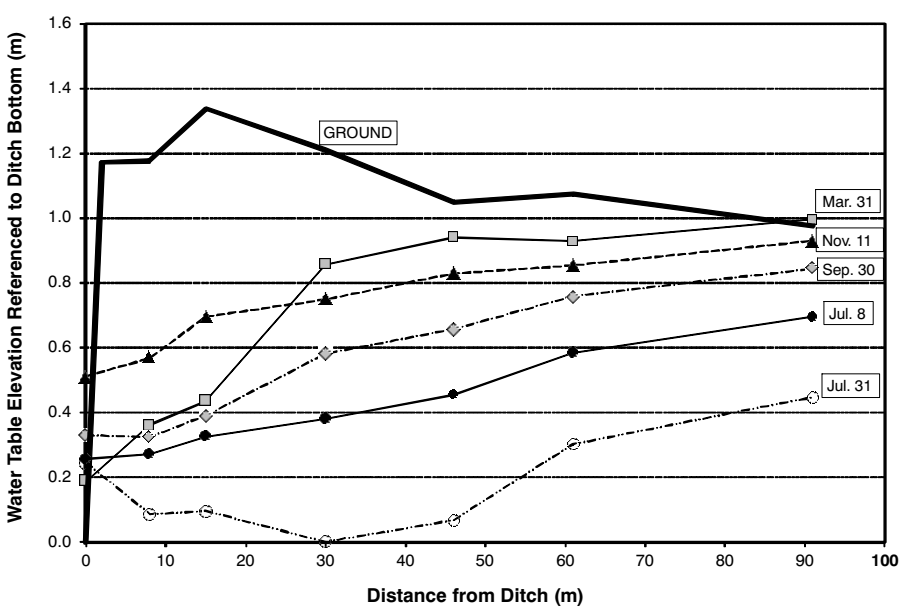

Figure 2. Observed water table elevations along a transect perpendicular to the ditch at the Mildred Woods site in 2003. Observations at $x = 0$ correspond to water level elevation in the ditch. All elevations are referenced to the elevation of the bottom of the ditch.

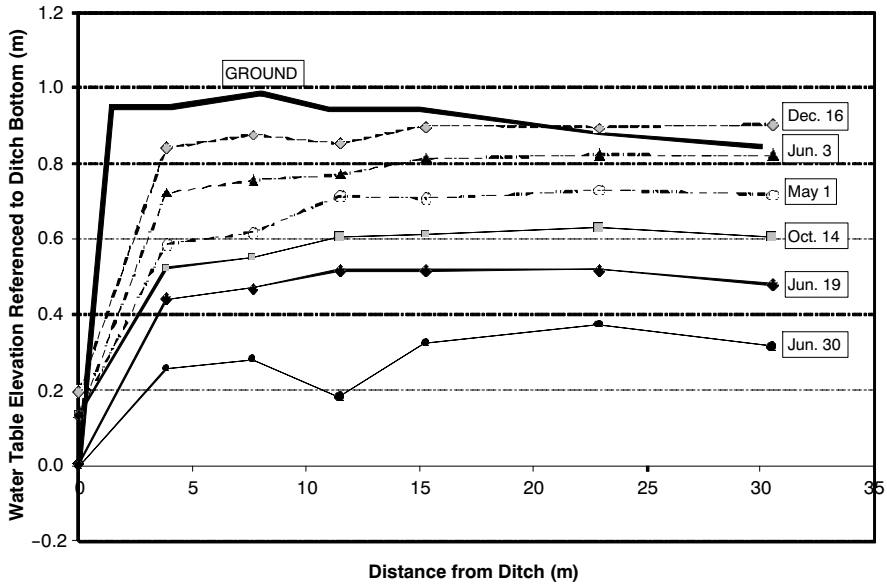

Figure 3. Water table elevations observed on specific dates in wells along a transect perpendicular to the shallow ditch at the ABC site in 2003. All elevations are referenced to the elevation of the bottom of the ditch. Distances of the wells from the ditch are shown.

of the drainage ditch at Mildred Woods is between 30 and 45 m. An analysis of the data to make a more definitive estimate will be presented in a later section.

ABC Site

Shallow Ditch Transect

Water table depths measured on the shallow ditch transect at the ABC mitigation site ranged from a maximum of 1.1 m in August 2004 to at or above the soil surface after rainfall events during the winter months. Water table depth generally decreased as the distance of the monitoring well from the ditch increased (fig. 3). For most of the observations, the water table was deepest at 3.75 m and shallowest at 30 m. The water table depths at 11.25 m and 15 m were usually between those at 3.75 and 30 m. Water table depths were often less than 30 cm deep for all of the wells in this transect.

The water level in the ditch fluctuated with rainfall and ET, but there was no evidence of beaver activity in the ditch during the study period. Changes in water level in the ditch were temporary and not likely to influence the water table depths measured in the well transects.

Water table elevations (expressed in fig. 3 as elevation above the bottom of the ditch) increased with the distance of the well from the ditch, as expected. However, the water table rise between 3.75 and 7.5 m was very small. The water table was mostly flat from 7.5 m to 30 m. Based on these data, it appears that the lateral effect of the ditch is less than 7.5 m, and possibly less than 3.75 m. The shape of the water table was consistent with the theoretical shape, but there were an insufficient number of points to define the shape of the curve near the ditch.

Deep Ditch Transect

Water table depths ranged from a maximum of 1.7 m in August 2004 to at or above the soil surface after rainfall events during the winter months. As with the other transects, water table depth generally decreased with distance from the ditch (fig. 4). For most of the observations, the water table was deepest at 7.5 m and shallowest at 45 m. Water table depths at the 7.5 m well were rarely less than 30 cm deep, while water table depths at the 22.5 and 45 m wells were frequently less than 30 cm deep. The water level in the ditch, as with the shallow ditch, fluctuated with rainfall, but there was no evidence of beaver activity during the study period.

Water table elevation increased with distance from the ditch up to 30 m. Most of this increase occurred within 15 and 22.5 m, especially during wet periods when the water table was shallow. The water table was mostly flat from 30 to 60 m; however, the water table elevation at the 60 m well was less than at the 30 m well when conditions were dry. The shape of the water table was consistent with the theoretical shape shown in figure 1, except when the water table at 60 m was lower during dry conditions. The shape of the water table was well defined by the measurements near the ditch. Visual inspection of figure 4 indicates that the lateral effect of the ditch is less than 30 m, and possibly less than 15 m.

Determining the Lateral Effect Based on Field Data

The data for all sites were analyzed to determine the maximum duration that the water table stayed above the 30 cm depth during the growing season. Results varied from year-to-year (as expected) because of weather variability. Maximum durations for each observation well at Mildred Woods are plotted in figure 5. The critical duration at this site (5% of the growing season) is 12 days; so the lateral effect of the drainage ditch (called x for convenience) is the distance from the ditch where the water table is within 30 cm of the surface for 12 consecutive days in 50% of the years. For any given year, the water table at x may remain in the top 30 cm for more or less than 12 days, depending on weather conditions. So it is not possible to simply compare the measured number of consecutive days plotted in figure 5 with 12 to determine the lateral effect, x. In order to define a reference duration for each year of observation, DRAINMOD was used to determine a threshold drain spacing for conditions at this site following procedures described by Skaggs et al. (2005). Simulations were conducted for the 54-year period (1951-2004) of local weather data for multiple drain spac–

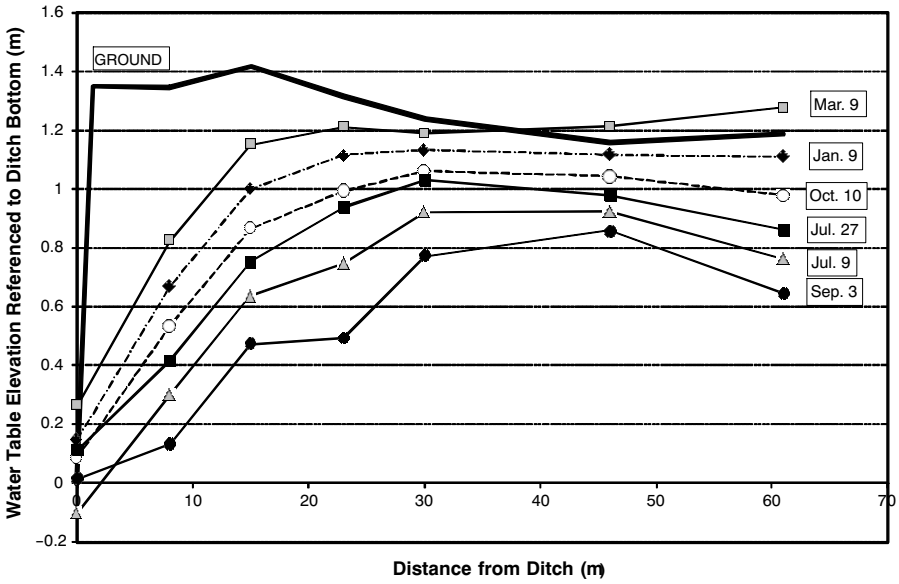

Figure 4. Water table elevations observed on specific dates in wells along a transect perpendicular to the deep ditch at the ABC site in 2003. All elevations are referenced to the elevation of the bottom of the ditch. Distances of the wells from the ditch are shown.

ings. The threshold spacing for the Mildred Woods site was determined to be 96 m. This means that the land midway between ditches 96 m apart would satisfy the criterion in 50% of the years. Next, DRAINMOD was used with the threshold ditch spacing and depth, along with recorded rainfall data for 2002-2004, to predict the maximum consecutive duration that the water table would be above the 30 cm depth for those specific years. Those durations are plotted as "threshold condition" in the bar plot of figure 5.

Using these values as a reference, the durations plotted in figure 5 can be analyzed to estimate the lateral effect. For example, the duration predicted for threshold conditions for 2002 was 20 days. This means that a site that would barely satisfy the wetland hydrologic criterion in 50% of the years over a 54-year period would have the water table within 30 cm of the surface for 20 consecutive days during the growing season in 2002. This is very close to the measured duration at a distance of 45 m from the ditch in 2002 (fig. 5). So, based on data from 2002, we estimate the lateral effect x = 45 m.

Results in figure 5 may be plotted by year, as shown in figure 6, for easy determination of the lateral effect. Once the measured duration versus distance from the ditch is plotted for a given year, the lateral effect can be estimated as the intercept of that curve and the duration predicted for the threshold ditch spacing for that year (fig. 6). Application of this method resulted in estimated lateral effects at Mildred Woods of 37 m and 41 m based on data from 2003 and 2004, respectively (fig. 6). The same methods were applied to the two ABC sites. Results are summarized in table 3.

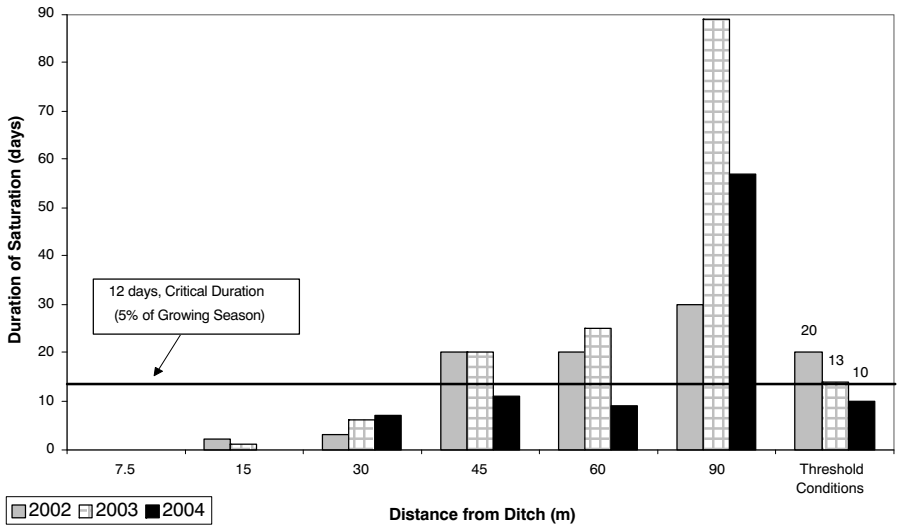

Figure 5. Observed number of consecutive days when water table was within 30 cm of the surface during the growing season plotted by year for the Mildred Woods site. Threshold conditions (bars on the right) represent the predicted number of days, in each year observed, for a site that barely satisfies the wetland hydrologic criterion.

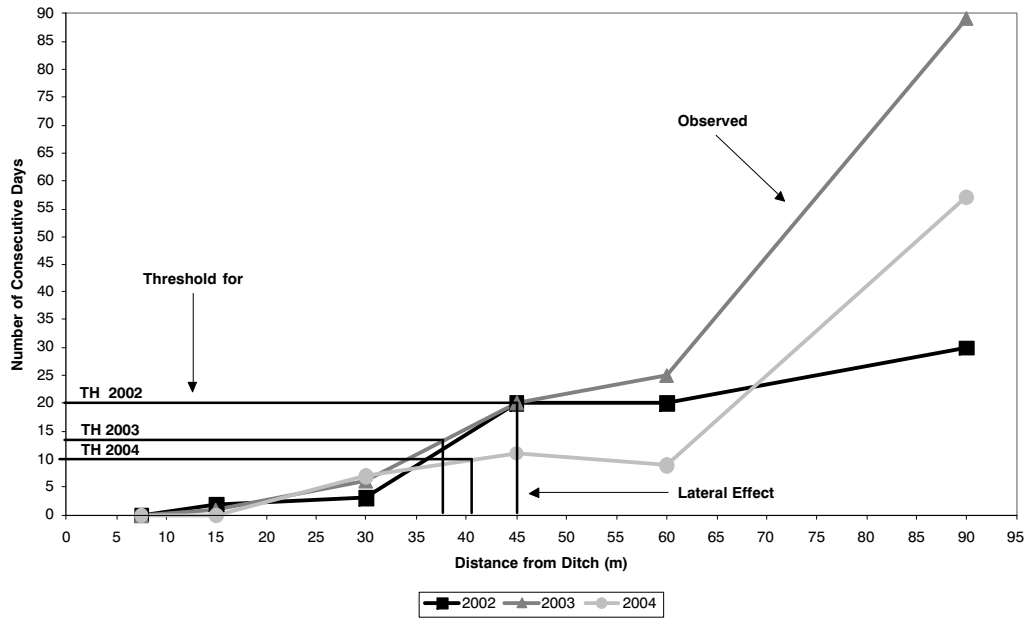

Figure 6. Observed consecutive number of days with water table within 30 cm of surface as a function of distance from ditch at Mildred Woods. Threshold (TH) values are the number of consecutive days that a site which barely satisfies the criterion would have in each year.

Calculating the Lateral Effect Using the Approximate Method

Skaggs et al. (2005) determined that sites that barely satisfied the wetland hydrologic criterion had characteristic water table drawdown rates that depended on local weather conditions, surface depressional storage, and ditch depth, but were relatively independent of soil type. The characteristic drawdown rate was quantified as the threshold time, T_{25}, required for the water table to be drained from the surface to a depth of 25 cm. T_{25} values were determined and published (www.bae.ncsu.edu/soil_water/projects/lateral_effect.html) for a range of ditch depths for all 100 North Carolina counties. The lateral effect of a ditch may be estimated as the distance from the ditch where the water table, in an initially saturated profile, will be drawn down by 25 cm after a time of T_{25}. This distance may be calculated with numerical solutions to the Boussinesq equation (Skaggs, 1976). These solutions are plotted in nondimensional form in figure 7.

Example Using the ABC Deep Ditch

Site parameters and soil physical properties for the ABC deep ditch are listed in table 4. Depth from the soil surface to the water level in the ditch is 1.2 m, and the depth of the impermeable layer is 6.0 m. The method assumes that the water table is initially at the surface and determines the distance, x, at which the water table will be drawn down by 25 cm after a time of T_{25}. Refer to the inset diagram in figure 7 for definitions of variables (h_o = 6.0 m, and d = 6.0 - 1.2 = 4.8 m). After 25 cm of drawdown, $h = h_o$ - 0.25 = 6.0 - 0.25 = 5.75 m. This results in a nondimensional water table depth of H = 5.75/6.0 = 0.96 and a nondimensional ditch water elevation of D = 4.8/6.0 = 0.80. Referring to figure 7 with these values of H and D gives an intercept on the abscissa of $1/\eta$ = 0.62. Rearranging the terms in the definition of $1/\eta$ in figure 7 gives:

$$x = \frac{\sqrt{\left[\frac{K}{f}\right] * h_o * t}}{\frac{1}{\eta}} \tag{1}$$

Substituting $t = T_{25}$ = 7.6 days, and the values for h_o, K, and f from table 4 gives the following estimate for the lateral effect:

$$x = \frac{\sqrt{\left[0.0042\,\mathrm{m\,h^{-1}} \times \frac{24\,\mathrm{h\,d^{-1}}}{0.060}\right] \times 6.0\,\mathrm{m} \times 7.6\,\mathrm{d}}}{0.62} = 14.1\,\mathrm{m} \tag{2}$$

A computer program was developed to facilitate the calculation of the lateral effect. The program uses the original numerical solutions to the Boussinesq equation to calculate the lateral effect directly, rather than interpolating from the plotted solutions in figure 7. In fact, the same numerical method used for generating the solutions plotted in figure 7 is used to predict the lateral effect directly. Figure 8 shows a screenshot of inputs to the program.

Table 3. Summary of results for lateral effect at drainage ditches based on three years of observations.

	Mildred Woods		ABC Shallow Ditch		ABC Deep Ditch	
Year	Threshold Condition (d)	Lateral Effect (m)	Threshold Condition (d)	Lateral Effect (m)	Threshold Condition (d)	Lateral Effect (m)
2002	20	45	13	<3.75	13	<7.5
2003	13	37	16	<3.75	18	15
2004	10	41	5	7	6	14
Average		41		5		12

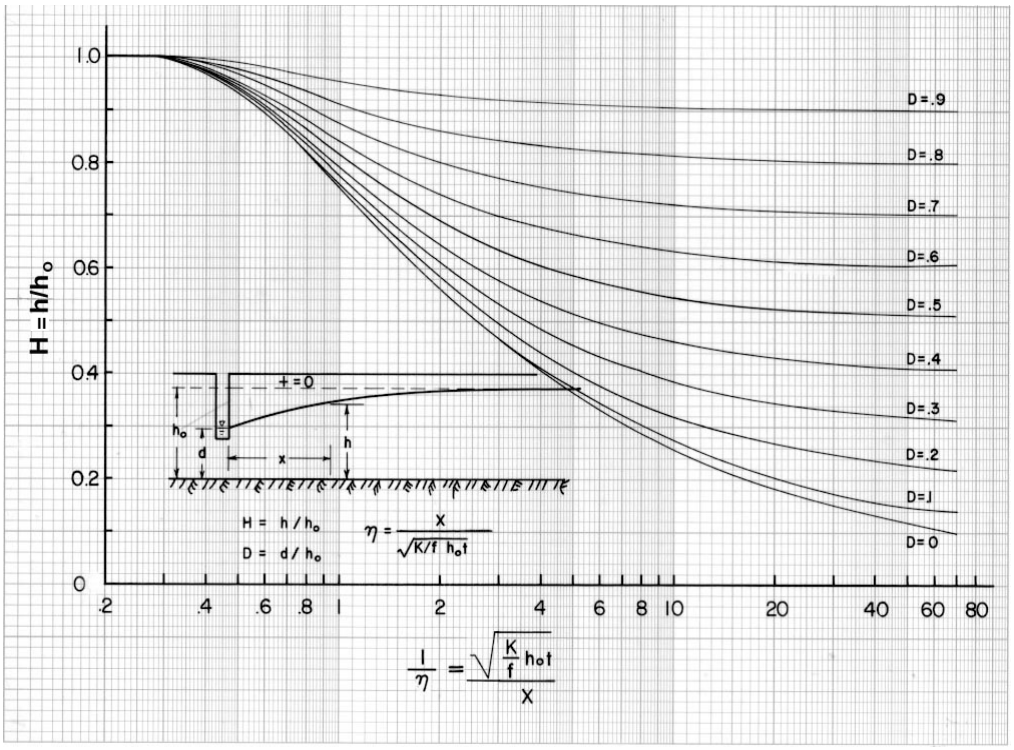

Figure 7. Nondimensional solutions to the Boussinesq equation for water table drawdown due to drainage to a single ditch (after Skaggs, 1976).

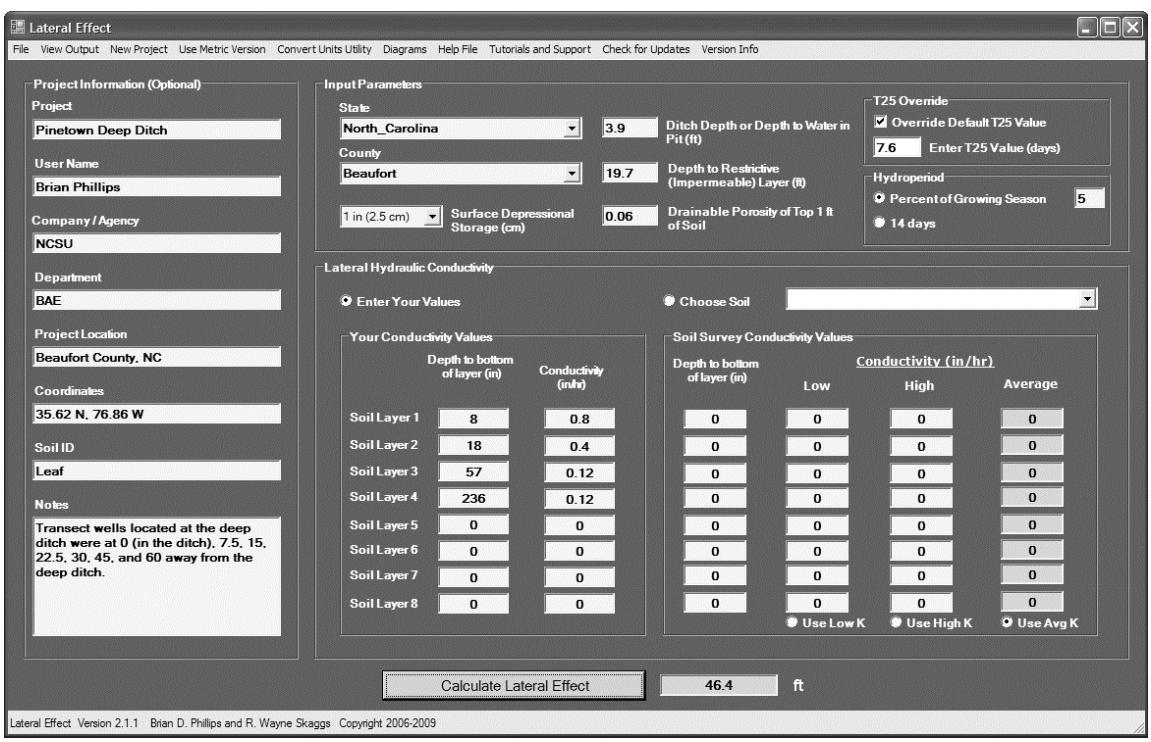

Figure 8. Screenshot of computer program for calculating the lateral effect based on the approximate method.

Calculations of Lateral Effect Method for Field Sites

The approximate method for calculating the lateral effect was applied to each of the three field transects. Ditch depth, surface storage, and effective lateral conductivity were measured onsite. Drainable porosity was determined from soil-water characteristics curves. T_{25} values for all North Carolina counties had been previously calculated. Inputs for each site are listed in table 5.

Table 4. Site parameters and soil property inputs for the ABC deep ditch.

Input Parameter	Value
Location	Beaufort County
T_{25}	7.6 d[a]
Ditch depth	1.20 m
Surface storage	5.0 cm
Effective horizontal hydraulic conductivity, K	0.0042 m h^{-1}
Drainable porosity, f	0.06
Depth to impermeable layer, h_o	6.0 m

[a] From T_{25} values for Beaufort County, North Carolina (www.bae.ncsu.edu/drainmod/lateraleffect/) for ditch depth = 1.2 m and surface storage = 5 cm.

Table 5. Inputs and results for calculating lateral effect of drainage ditch on field sites by approximate method.

	Mildred Woods	ABC Shallow Ditch	ABC Deep Ditch
Location (county)	Edgecombe	Beaufort	Beaufort
Ditch depth (m)	1.2	0.9	1.2
Surface storage (cm)	5.0	10.0	5.0
K_{eff} (m d^{-1})	0.94	0.10	0.10
Drainable porosity	0.035	0.06	0.06
Depth to impermeable layer (m)	4.8	6.0	6.0
T_{25} (d)	5.6	2.63	7.6
H	0.95	0.96	0.96
D	0.75	0.85	0.80
$1/\eta$ (from fig. 2)	0.63	0.72	0.62
Predicted lateral effect (m)	42.6	7.2	14.1

Table 6. Summary of lateral effects (m) predicted or calculated for all methods presented.

Method	Mildred Woods	ABC Shallow Ditch	ABC Deep Ditch
Field results	41	<3.75	12
Approximate method	42.6	7.2	14.1
Difference	1.6	>3.5	2.1
Ratio, predicted/measured	1.04	>1.92	1.18

A summary of the predicted lateral effects for the two methods presented in this article is given in table 6. The approximate method overestimated the lateral effect in all three cases, with differences ranging from 1.6 to greater than 3.5 m. The predicted lateral effect was 4% greater than measured for the Mildred Woods site, 18% greater for the ABC deep ditch, and 92% greater for the ABC shallow ditch.

Discussion

The approximate method was evaluated by comparing predicted lateral effects for three sites to values determined from three years of water table measurements and long-term simulations. Since the definition of the lateral effect involves conditions that are satisfied on a frequency basis (i.e., in more than 50% of years), it is impossible to measure directly. In this study, the "measured" lateral effect was determined by a direct interpolation for each year of observation (field results in table 3).

The approximate method closely predicted the lateral effect for the Mildred Woods and ABC deep ditch sites as compared to field results, while the method overpredicted the lateral effect for the ABC shallow ditch site. The lateral effect calculated by the approximate method was about 43 m for the Mildred Woods site. Results from direct interpolation of field data indicated that the lateral effect of the ditch had an average value of 41 m. Due to the variability in annual climatic conditions, the "measured" lateral effect values differed from year to year: 45 m, 37 m, and 41 m for 2002, 2003, and 2004, respectively.

The average lateral effect for the 3-year period for the ABC deep ditch was 12 m based on interpolation of the measured data. This is about 14% less than the 14.1 m predicted by the approximate method. However, measured results for 2003 and 2004, 15 and 14 m, respectively, were even closer to the predicted value. Discrepancies in the water table data early in 2002 may have caused the low value (<7.5 m) obtained from the field data for that year.

The lateral effect for the ABC shallow ditch was less than 3.75 m, based on the field data. This is about half of the value (7.2 m) predicted by the approximate method. The bottom of this ditch partially penetrates a tight clay layer between depths of about 0.3 to 1.1 m. Observed water table fluctuations close to the ditch indicate very slow drainage and high head loss in the vicinity of the ditch. The tight clay layer around the shallow ditch apparently restricts water movement through deeper, higher hydraulic conductivity layers that influence the calculation of effective transmissivity for the deeper ditch. In essence, the effective transmissivity, defined as the thickness of the profile multiplied by the effective conductivity, is likely lower than the value used to calculate the lateral effect (table 6). Lowering the transmissivity will decrease the lateral effect predicted by the approximate method. In equation 1, the transmissivity is represented by the product of K and h_o. Any reduction in the transmissivity will reduce the value of x calculated. For example, setting the depth of the impermeable layer to be equivalent to the depth of the ditch and adjusting the effective conductivity results in a calculated lateral effect of 5 m for the shallow ditch. Although still an overprediction, it is closer to the field result of <3.75 m. Additional research is needed to determine how the method should be modified for shallow ditches confined in a low-conductivity layer.

Additional work may also be needed to update the T_{25} values for the 14-day threshold, rather than 5% of the growing season, for the continuous high water table stipulation in the wetland hydrologic criteria. In North Carolina, 5% of the growing season varies by county from a low of 10 to a high of 14 days. The recent change affects the T_{25} values, which need to be recalculated using the 14-day threshold. For those counties in which 5% of the growing season is less than 14 days, application of the method with currently available T_{25} values will result in a slightly greater predicted lateral effect than would be calculate if a 14-day threshold had been used to determine the T_{25} values. However, it is important to note that the results and analyses presented herein to test the validity of the method applied the 5% threshold in both determining the lateral effect from the measured field data and in predicting it with the approximate method. Thus, a change to a 14-day threshold will not affect the validity of the test of the method presented in this article.

Limitations

The approximate method was developed for relatively flat sites that are naturally poorly drained. The dominant source of water is assumed to be precipitation; the method was not developed for, and should not be applied to, sites where

flooding due to upstream conditions is a primary cause of wetland hydrologic status. More research is needed to determine how the method can be adjusted for cases where there are high head losses near the drain, such as the ABC shallow ditch case.

Summary and Conclusions

Data to test an approximate method to calculate the lateral effect were collected at two wetland mitigation sites in eastern North Carolina. One site was at Mildred Woods in Edgecombe County, and the other was near the town of Pinetown in Beaufort County. Water tables were measured at several locations on transects perpendicular to drainage ditches on both sites. Data were collected for the 3-year period 2002-2004 on one transect at the Mildred Woods site and for the 3.5-year period from 2002 to June 2005 on two transects at the ABC site. An analysis of the field data indicated that the lateral effect of drainage ditches was between 37 and 45 m at the Mildred Woods site, less than 3.75 m for the shallow ditch (0.9 m deep) at the ABC site, and about 14 to 15 m at the deep ditch (1.3 m deep) site at the ABC site.

The approximate method provides a theoretically sound approach to calculating the lateral effect of a drainage ditch on adjacent wetland hydrology. The method uses inputs of ditch depth, depth to impermeable layer, effective hydraulic conductivity, drainable porosity, T_{25}, and solutions to the Boussinesq equation to calculate the lateral effect. T_{25} times, based on the drawdown time of several soils at threshold drain spacings, were determined for all 100 counties in the state of North Carolina. Once soil properties and site parameters are known, published numerical solutions to the Boussinesq equation may be used to calculate the lateral effect.

The lateral effect was calculated by applying the approximate method for the three study transects. The method predicted a lateral effect of 42.6, 7.2, and 14.1 m for Mildred Woods, ABC shallow ditch, and ABC deep ditch, respectively. Compared to 3-year average field results for Mildred Woods (41 m) and the ABC deep ditch (12 m), the method performed well. It overpredicted the lateral effect, but by only 4% for Mildred Woods and 17% for the ABC deep ditch. Predicted lateral effect was within 1 m of the measured lateral effects at the ABC deep ditch site for two out of three years of the study. The lateral effect predicted by the method for the shallow ditch at the ABC site was small, 7.2 m, but still about two times that measured in the field. In this case, the shallow ditch did not penetrate the tight clay layer near the surface of the profile, which substantially reduced the effective transmissivity and the lateral effect of the ditch on the hydrology of adjacent wetlands. Additional research is needed to determine how the method should be modified for such situations.

A computer program was developed to facilitate the use of the approximate method. Based on user inputs, the program automatically retrieves T_{25} values for sites in North Carolina and numerically solves the Boussinesq equation to predict the lateral effect of a drainage ditch. For sites outside North Carolina, T_{25} values can be read in directly. A version of the program is available online at no charge at the following website: www.ncdot.org/doh/Operations/dp_chief_eng/roadside/fieldops/downloads/. It may also be accessed at: www.bae.ncsu.edu/drainmod/lateralef fect/.

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