Effects of drainage and forest management practices on hydraulic conductivity of wetland soils

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Summary

Continuous records of water table elevations and flow rates from drained forested lands were analysed to determine field effective hydraulic conductivity (K) of a mineral (Deloss s.l.) and an organic (Belhaven muck) soil. K of the top 90 cm of Deloss under mature pine was 60 m/day, which is 20 to 30 times that published for this series. Harvest had a minor effect on K, but site preparation for regeneration, including bedding, reduced the effective K to values typically assumed for this series, 3.6 m/d for the top 45 cm and 1.6 m/d for deeper layers. After regeneration, K values had nearly returned to original values within 8 years after planting. Similar observations on organic soils indicated that field effective K in drained pine plantations is substantially higher than the same soil under agricultural production.

Key index words: drainage, organic soils, hydraulic conductivity, water table, wetland forest

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Introduction

Long-term field studies were conducted in Carteret and Washington counties in eastern North Carolina to determine the effects of drainage and silvicultural practices on hydrology and drainage water quality (Amatya *et al.*, 2003; Shelby *et al.*, 2005). This paper presents results of the effects of drainage and forest management practices on field effective hydraulic conductivity, K, of mineral and organic soils at two sites. Data were collected from 1988 to 2007 from a drained mineral wetland soil (Deloss s.l.) on the Carteret county site. Drainage rates and water table depths were analysed to determine the evolution of field effective saturated hydraulic conductivity of the profile for stages of the production cycle from a mature plantation through harvest, site preparation, and regeneration of a young plantation. Water table elevations and drainage flow rates were continuously measured for a 6-year period (1996-2001) on a forested Belhaven muck soil at another location. The data were used to determine field effective K of the soil profile.

One of the most striking effects of land use on the hydrology of drained lands is the impact on soil properties. Conventional application of models to describe the effects of land use and management practices on the hydrology at field and watershed scales nearly always assigns soil property values based on soil series, without regard to the effect of land use on those properties. There is a reasonably good understanding and acceptance of the variability of soil properties within a soil series. However, the effect of land use, crop, or vegetation is rarely considered. Years of experience in measuring soil properties of poorly drained coastal plain soils has led to the conclusion that hydraulic conductivity is nearly always larger on forested than on agricultural lands. This difference is very important in the application of simulation models to predict hydrology and water quality on both field and watershed scales.

Methods

Carteret 7.

Three watersheds (D1, D2, and D3), each approximately 25 ha planted to Loblolly pine, were instrumented to measure and record drainage rate, water table depth, rainfall and meteorological data. Deloss fine sandy loam soil (fine-loamy, mixed, thermic Typic Umbraquults) on the site 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 1.5 m deep, spaced 100 m apart. Drainage outflow is 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. A pump in the outlet, downstream from all three watersheds, was installed to reduce weir submergence during large runoff events. Water table elevations were measured by recorders at two locations midway between the field ditches for each watershed. McCarthy *et al.* (1991) and Amatya *et al.* (2003) described the site in detail. Data collection began in 1988 when the trees were 15 years old. Commercial thinning was conducted in 1988 and fertiliser was applied in 1989. Since that time, watershed D1 has been maintained as the control with standard drainage and silvicultural practices. Studies have been conducted to determine the hydrologic and water quality impacts of a range of practices on the other two watersheds since 1988. Watershed D2 was harvested in July 1995 at a stand age of 21 years. The watershed was bedded and prepared for planting in October 1996 and planted in February 1997. Drainage and water table records were analysed to determine field effective K prior to harvest, after harvest prior to bedding, and in years following bedding and planting.

Parker Tract.

Drainage flow rate and water table depth were continuously recorded on a 90 ha drained Bellhaven muck (Loamy, mixed, dysic, thermic Terric Haplosaprists) watershed in Washington county, NC. The topography is flat with parallel drainage ditches 0.75 to 0.9 m deep and 100 m apart. The site was planted to Loblolly pine in 1992; water table measurements began in 1993 and flow measurements in 1996. Methods similar to those described above were used to continuously measure water tables and flow rates. The bottom of the V-notched weir in the outlet ditch was set at a depth of 60 cm below the soil surface so the effective drain depth was 60 cm for this site.

Methods for analysing drainage hydrographs.

Drainage rates for the Belhaven muck site are plotted in Fig. 1 as a function of midpoint water table elevation for 1996. The number of measurements per day varied according to conditions; the data shown represent an average of about two measurements per day. Our objective was use drainage theory to calculate field effective hydraulic conductivity from the relationship between drainage rate, q, and water table elevation, m. However, it is obvious from Fig. 1 that the q(m) relationship is not well defined for this site, as the data are scattered with a range of flow rates for a given water table elevation. Such scatter is not unexpected for field data. It results from a variety of causes, including error in measuring and recording both drainage rates and water table depths. Weirs are occasionally clogged with debris, and may be submerged during periods of high flow. Even though these measurements were made carefully with visits by field technicians to check conditions and maintain the instruments on weekly intervals, it is likely that measurement error contributed to the scatter of the data. Potential errors were identified by the technicians and noted in the field notes in some cases so suspect data can be removed. Inevitably, errors remain undetected in other cases.

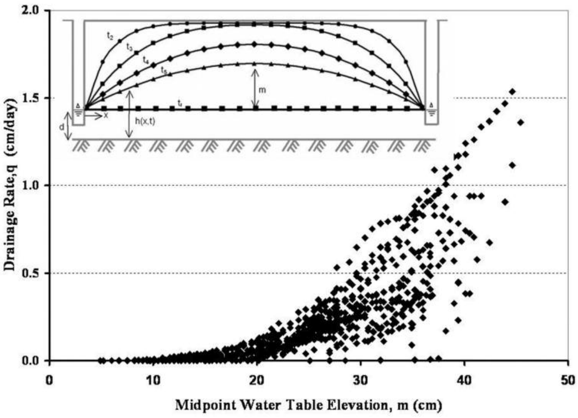

Figure 1. Measured drainage rate, q, and water table elevation above water level in ditch, m, during 1996 for a Belhaven muck on the Parker Tract, Washington County, North Carolina. Inset shows evolution of predicted water table shape with time after rainfall ceased at time, t_2.

A more basic reason for the scatter in Fig. 1 is that the q(m) relationship is not single valued or unique, but depends on recent and current rainfall and evapotranspiration (ET). An example of the effect of recent rainfall on water table profiles is depicted in the inset in Fig. 1. At time t_1 when rainfall began, the water table was horizontal at the depth of the drain. After a period of rainfall the water table rose to the position shown as t_2 when rainfall ceased. Note that the water table at t_2 is relatively flat in the middle part of the profile but the gradient near the drain, which controls the rate water flows to the ditch, is steep and the drainage rate is high. By time t_3 the water table had adjusted to the typical drainage profile, and gradients near the ditch and drainage rates had decreased compared to t_2. But the water table elevation at the midpoint, m, had not changed. Thus, the relatively high drainage rate at t_2 and the lower gradient and drainage rate at t_3 both occurred for the same m. Assuming no additional rainfall, the water table will continue to fall due to drainage to the positions shown for t_4 and t_5. Once the drainage profile is developed (at t_3 in this case), and in the absence of rainfall and ET, the q(m) relationship is unique as the water table recedes due to drainage.

Solutions to the Boussinesq equation (Youngs, 1999) were used to analyse the effect of rainfall on the q(m) relationship and to develop a method for analysing field data such as shown in Fig.1. The Boussinesq equation may be written as,

$$f\frac{\partial h}{\partial t} = K\frac{\partial}{\partial x}h\frac{\partial h}{\partial x} + R \qquad [1]$$

where, referring to the inset in Fig. 1, h is the elevation of the water table above the restrictive layer, t is time, x is lateral position, K is saturated hydraulic conductivity, f is drainable porosity and R is the precipitation or ET rate (R is negative for ET). Numerical methods (Skaggs, 1991) were used to solve the equation to determine the effects of rainfall on the relationship between drainage rate and water table elevation, q(m). Results plotted in Fig. 2 were obtained for ditches spaced 30 m apart and 1.0 m deep in a 2.0 m deep profile with K= 5 cm/hr and f=0.05. Solutions for five different drainage/rainfall events are plotted in Fig. 2. In each case the initial water table was assumed to be horizontal and coincident with the surface at m=100 cm. Drainage rates decreased with time, but the midpoint water table remained at m=100 until a water table profile similar to that shown for t_3 (inset Fig. 1) developed. This is shown as the vertical section of the q(m) relationship on the right side of Fig. 2. This thick curve along the right and bottom part of the plot will be referred to herein as the Main Drainage Curve (MDC), which is the q(m) relationship for drainage of this profile in the absence of rainfall. When rainfall begins, both m and q increase along a very different path than the MDC as shown in Fig. 2.

Consider results for event R3. Drainage began at t = 0 and q receded along the MDC until m = 35 cm at t = 88 hrs. At that point 2 cm of rainfall occurred over a 2 hr period and the water table elevation, m, increased to 80 cm and q to 3.3 cm/d. After rainfall ceased, drainage rate, q, fell rapidly, asymptotically approaching MDC at m = 73 cm about 12 hours later. Thus the 2 cm rainfall event caused a significant perturbation in the q(m) relationship, with both q and m rising rapidly during rainfall and then decreasing to the MDC at an m value 38 cm greater than when rainfall began. The whole process took 14 hours (2 hours of rainfall plus 12 hours for the q(m) relationship to return to the MDC). Depending on the frequency of water table and flow rate measurements, these results show how q(m) data can be scattered, even if measurements are made without error.

In order to calculate field effective K for a given site and condition, we needed to determine the MDC. Solutions to the Boussinesq equation for a large number of initial and boundary conditions were studied to develop the following 4-step method for defining the MDC from field data.

1. Plot the drainage hydrograph: q (t) and m(t) for each rainfall/drainage event. Unlike surface runoff hydrographs, the recession limb of the drainage hydrograph may continue for days or even weeks as the water table falls to the depth of the drain.
2. Determine time rainfall ceases, t_s; confine analysis to recession limb of hydrograph.
3. Determine lag time, T_l, required for the q(m) relationship to merge with MDC following rainfall (Fig. 2). T_l may be estimated as, $T_l=0.015fL^2/(Kh_o)$, where f is drainable porosity, L is drain spacing, K is hydraulic conductivity and h_o is the distance from the restrictive layer to the water table when rainfall ceases.
4. Plot q(m) data for times greater than T_l+t_s for multiple events to define the MDC.

This method was used to analyse the data for the 5 rainfall events in Fig. 2. Results in the inset of Fig. 2 show that the above procedures eliminated most of the 'scatter' caused by rising limbs of the drainage hydrographs, and that the remaining MDC is well-defined. Also note that q(m) values predicted by the Hooghoudt equation are somewhat larger (about 5% for large m values), but in reasonable agreement with the MDC. Thus, once the MDC is defined, field effective K values can be calculated using the Hooghoudt equation.

Results and discussion

Carteret 7.

Measured q(m) relationships for watershed D1 are plotted in Fig. 3 for 4 periods: (1) the pre-harvest period in 1994 and 1995 (harvest in July, 1995); (2) post-harvest from fall, 1995 through Oct. 1996, when the site was bedded and prepared for planting; (3) post-bedding, October 1996 through spring, 1997; and (5) year 2005, 8 years after planting. The procedures outlined above were used for defining the main drainage curves (MDC) for each case. Data were analysed for the months of Nov.-March only to minimize the effect of ET on the MDC. Only daily drainage rates and water table depths were available through 1999. Flow rates and water table depths at 12 minute intervals were available for 2005.

A cursory review of Fig. 3 indicates that the q(m) relationship changed dramatically as a result of harvest, site preparation (bedding) and regeneration of a new pine plantation. The relationship between q and m for the MDC can be estimated by the Hooghoudt equation (van der

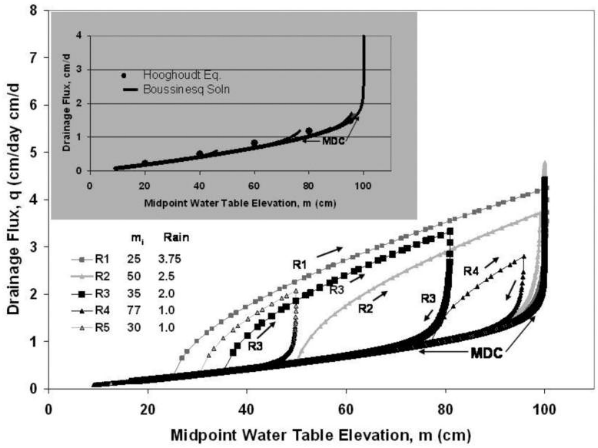

Figure 2. Effect of rainfall on q(m) relationship as predicted by solutions to Boussinesq equation for 5 events with rainfall of the given amounts (cm) starting when the water table was at m_i. Inset shows data for all 5 events when edited according to recommendations.

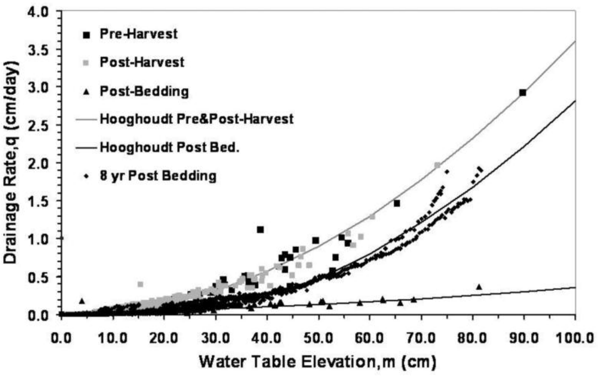

Figure 3. Measured q(m) data for Carteret 7 site D2 at 4 stages during harvest and regeneration of Loblolly pine. Curves predicted with Hooghoudt Eq. using K data in Table 1.

Plough *et al.*, 1999) for the widely spaced (100 m) open ditch drains of this study area as

$$q = 4 K_e m (2d+m)/L^2 \qquad [2]$$

where K_e is the effective or average lateral hydraulic conductivity of the profile, d is the depth from the bottom of the drain to the restrictive layer and L is the ditch spacing. The field effective lateral hydraulic conductivity of the profile, K_e, was calculated from the observed q(m) data using Eq. 2. The profile was divided into 3 layers, and the conductivity of the individual layers obtained from K_e values, starting at the bottom of the profile. Results are given in Table 1 for each of the four periods. The curves in Fig. 3 represent the q(m) relationship predicted by the Hooghoudt equation using the K values in Table 1 for each layer. The range of K values given by the county Soil Survey (SCS, 1978) for the Deloss soil series is included in Table 1 for reference.

Results in Fig. 3 and Table 1 indicate the field effective K of the top 90 cm of the profile is 60 m/d under mature pine. This is 20 to 30 times higher than values published in the Soil Survey for the Deloss soil. The high K values are attributed to the presence of large pores that result from tree roots and biological activity that was uninterrupted for over 20 years. Similar high K values were reported by Grace *et al.* (2007) for an organic soil and by Skaggs *et al.* (2004) for a mineral soil under pine plantation forests. The harvest process did not have an apparent effect on the pore structure as the q(m) relationship (Fig. 3) and the K values (Table 1), after harvest and prior to bedding, were about the same as prior to harvest. But drainage rates after bedding were clearly reduced for water table elevations greater than m = 15 cm. For example, the measured drainage rate 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 in the field effective hydraulic conductivity with K values in the top 90 cm reduced from 60 to 3.6 m/day (Table 1). Predictions by the Hooghoudt equation, using the high end of the range of K values given in the Soil Survey (Table 1), agreed very well with observations for post-bedding condition (Fig. 3). Apparently the bedding process destroyed the macro-pores in the surface layers such that the profile had effective K values similar to those given in the soil survey, which were probably 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 larger m values. K values computed from observed data (Table 1) were the same as prior to harvest (60 m/d) for the top 45 cm but only 20 m/d for the 45 to 90 cm depth. This may indicate that the large pores responsible for high K values prior to harvest had not had time by 2005 to fully redevelop in the 45 to 90 cm depth range.

Table 1. Field effective lateral saturated hydraulic conductivity (m/day) by layer of Deloss sandy loam as calculated from measured drainage rates and water table elevations.

	Depth from Surface		
Stage	0-45 cm	45-90 cm	90-280 cm
Pre-Harvest, 1994-1995	60	60	1.6
Post-Harvest, 1995-1996	55	55	1.6
Post-Bedding, 1996-1997	3.6	1.6	1.6
8 Yr. Post-Bedding, 2005	60	20	1.6
K, Deloss from Soil Survey	1.2-3.6	0.36-1.6	0.36-1.6

Parker Tract

Relationships between drainage rate, q and water table elevation above the water level in the ditch, m, are given in Fig. 4 for four years, 1996, 1998, 1999, and 2000. The same methods described for the Carteret 7 data to define the MDC were used, but only daily data were available for most years. Unlike the data from Carteret 7 (Fig. 3) there was no obvious difference between the q(m) relationships from year-to-year. This may have been due to the timing of measurements with respect to field operations. The site was planted in 1992, four years before flow measurements began in 1996. Water table measurements in 1993 (not shown) indicated a shallow, slowly receding water table (slow drainage) during wet periods, but rates were not measured. Apparently K of the organic soil, had recovered by year 4, as there was no obvious change in q(m) over years 4-8 post bedding (1996-2000).

Field effective K for the Belhaven muck soil was high, especially for the surface layers. Even though the ditches were shallow (60 cm to bottom of the V notch weir), the water table rarely rose to within 15 cm of the surface (m=45 cm) because of the rapid drainage rate. Eq. 2 was used to calculate K_e of the profile from data in Fig. 4. The profile was divided into four layers and the K value of each layer computed from K_e (Table 2). K values for each layer were calculated for the range of q values measured. Table 2 reports high, low and median K values for each layer. Relationships for q(m)

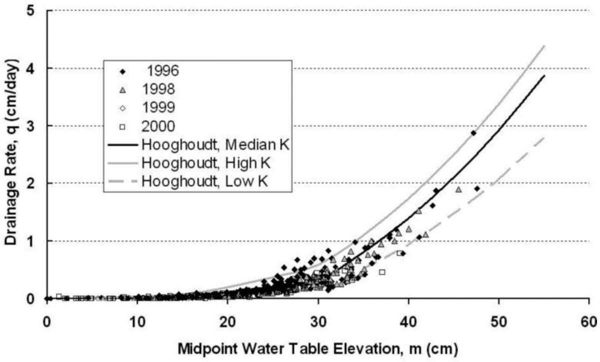

Figure 4. Measured q(m) data from a Belhaven muck soil for years 4-8 after replanting Loblolly pine in 1992. Curves predicted by Hooghoudt Eq. using K data in Table 2.

Table 2. Field effective lateral saturated hydraulic conductivity (m/day) by layer of Belhaven muck as determined form water table depth and drainage rate measurements.

	Saturated Hydraulic conductivity, m/day		
Layer Dept, cm	Low	Median	High
0-30	450	550	600
30-45	60	150	250
45-60	4	9	47
60-240	1.2	1.2	1.2

predicted by the Hooghoudt equation using the low, high, and median K values for each layer are plotted in Fig. 4. Most of the q(m) data are enclosed by the predicted q(m) curves for the high and low K values.

The field effective K ranged from 450 to 600 m/day in the top 30 cm of the profile and from 60 to 250 m/day in the 30 to 45 cm deep layer. These values are more than 25 times higher than expected for this series based on published values in the county Soil Survey. Both layers have an organic matter content of over 90% and have been dried or 'cured' over many wetting and drying cycles since the installation of drainage ditches in the 1970s. K of the third layer (45 to 60 cm deep) was much smaller (4 to 47 m/d) and is reflective of transition between the organic surface and the underlying mineral layers. The field effective Ks of the surface organic layers are about 5 times greater than the largest values determined by Grace *et al.* (2006, 2007) for a nearby Belhaven site on this same Parker Tract. They reported that harvesting reduced K in the 60 cm deep organic surface layer by about a factor of 4; on an adjacent site, thinning reduced K by about a factor of 3. These measurements were conducted on field cores and may not have reflected the influence of interconnected pores or root channels that could be partially responsible for the high K values in Table 2. There may also have been differences in the history of wetting and irreversible drying or 'curing' of the organic surface layers. Such differences could have had substantial effects on the K values.

Conclusions

Field effective hydraulic conductivities (K) of the top 90 cm of a forested mineral soil and the top 45 cm of a forested organic soil were more than 25 times values typically assumed for the respective soil series. Bedding for regeneration in the mineral soil reduced K to published values, but high K in the top part of the profile had returned by 8 years after replanting. The very high K values measured for the top part of the organic soil (Belhaven muck) four years after replanting indicated that it rapidly returned to conditions prior to harvest.

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