

DETERMINATION OF FIELD-EFFECTIVE SOIL PROPERTIES IN THE TIDEWATER REGION OF NORTH CAROLINA

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Abstract—Soils vary spatially in texture, structure, depth of horizons, and macropores, which can lead to a large variation in soil physical properties. In particular, saturated hydraulic conductivity (K_{sat}) and drainable porosity are critical properties required to model field hydrology in poorly drained lands. These soil-property values can be measured by several methods; however, larger scale, “field-effective” values may be needed in developing, calibrating, and validating models, such as DRAINMOD. In this investigation, field-effective soil-property values were estimated from water table and outflow measurements from a 3-year field experiment on poorly drained loblolly pine (*Pinus taeda* L.) plantation watersheds in eastern North Carolina and tested against two additional estimation methods. Field estimates for K_{sat} were compared to estimates determined using the auger-hole method and estimates determined from soil cores by the constant-head method. The field-effective K_{sat} of the surface layer was estimated at 140 and 90 cm/hour for the unthinned and thinned condition, respectively. These values are greater than values obtained from soil cores and not different from values obtained from the auger-hole method which had mean conductivities of 100 and 80 cm/hour for unthinned condition, respectively. The thinned condition had K_{sat} values of 32 and 17 cm/hour based on soil cores and the auger-hole method, respectively. The differences between the field-based values and the constant-head method and auger-hole method may be a result of heterogeneity of soils or overestimations in the field-effective results.

INTRODUCTION

Hydrologic models have, in recent years, received increased utilization as management planning tools to evaluate alternative management scenarios. Models have become essential tools in evaluating and forecasting effects of manmade disturbances, land use changes, and climate change. In the absence of long-term data for a specific scenario, as is typically the case, validated models can provide forest managers vital information to evaluate alternatives. Information attained from model predictions assist in evaluating the effects of changes on attributes ranging from site productivity to water quality (Cho and others 2009, Croke and others 2004, Sun and others 2006). In forest management, hydrologic models have shown promise in predicting hydrology and the influence of forest operations on hydrologic responses (Amatya and Skaggs 2001; Amatya and others 2000, 2004; Lovejoy and others 1997; Parsons and Trettin 2001; Sun and others 1998). However, accurate model predictions are dependent on quality site characterization.

Previous work has shown that site characteristics can greatly influence hydrology and hydrologic responses within a watershed (Detenbeck and others 2005; Lide and others 1995; Sun and others 2001, 2006). Site characteristics such as climate, slope, vegetation, topographic relief, soils, and geographic location affect the hydrograph resulting from a given precipitation event. Among these variables, soil properties are the most difficult to quantify for a given site due to their inherent spatial variability, disturbances associated with land use, and possible errors associated with measurement methods (Grace and others 2006a, Skaggs and others 2008). Soils are highly variable spatially in depth of horizons, structure, texture, organic matter content, and water release or holding properties (Cohen and others

2008, Wei and others 2008). This inherent high variability of soil properties within a watershed is compounded by variability caused by disturbances in the form of mechanized operations. These disturbances can result in compaction and rutting in the areas adjacent to and under tires (Carter and McDonald 1998, Grace and others 2006a) which can account for as much as 20 percent of the disturbed area following operations in a watershed (McDonald and others 1998, Stuart and Carr 1991). Compacted zones can further increase soil variability within the watershed which, in turn, can affect the soil water relationships in the soil.

Soil properties related to soil water movement, such as saturated hydraulic conductivity (K_{sat}), volume drained (V_d), and drainable porosity (f) are especially troublesome to measure *in situ* or by cores in the forested setting due to the existence of roots, voids left from root systems, and buried debris. In addition, hydraulic conductivity is typically measured and modeled as homogenous within layers in the soil profile. Previous work has shown that like most soil properties, K_{sat} and f are highly variable in an area as small as a m^2 (Grace and others 2006a). Consequently, point K_{sat} and f measurements may fail to accurately describe the field conditions from a modeling standpoint due to scaling issues. For example, Bierkens and van der Gaast (1998) presented errors associated with neglecting stochastic upscaling methods. Soil properties are typically determined *in situ* or laboratory determined based on soil cores or measurements collected from randomly selected locations. Core samples and *in-situ* measurements, such as the auger-hole method, are point values that may only represent a small portion of the site under consideration. Soil core samples represent the core scale, and the auger-hole method represents soil properties at the model block scale as described by Bierkens

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and van der Gaast (1998). However, hydrologic modeling is often performed at the local or regional scale which is a considerably larger scale than represented by cores or blocks. This fact presents the need for upscaling, deriving soil properties from smaller scale measurements, or determining soil properties from field hydrologic measurements.

Modeling the hydrology of a site often requires the best possible characterization, or field-effective values, for the soil properties associated with soil water movement for the site under consideration. Soil-property values can be determined from several methods; however, field-effective values are often needed in developing, calibrating, and validating models, such as DRAINMOD. The objective of this paper is to utilize water table and outflow measurements from a 3-year field experiment on loblolly pine (*Pinus taeda* L.) plantation watersheds in eastern North Carolina to estimate K_{sat} , V_d , and f . This alternative procedure and estimates were tested for differences with two alternative estimation methods—estimates determined from the auger-hole method and estimates determined from soil cores by the constant-head method.

METHODS

Site Description

The field experiment was located at approximately 35° latitude and 76° longitude in the Tidewater region near Plymouth, NC. The experiment was conducted on a 56-ha poorly drained loblolly pine plantation watershed owned and managed by Weyerhaeuser Company. The watershed was isolated from the surrounding forest lands by forest roads and a collector ditch. Soils on the study sites are mapped as primarily Belhaven muck soil series, an organic, shallow water table soil. Soils are highly organic with soil organic matter contents of 80 percent or greater in the top soil horizon (O_a horizon). Site elevation was 4.1 to 4.5 m above sea level with an average slope of <0.1 percent. The watershed was delineated into a 40-ha subwatershed (WS5) to receive a thinning treatment and a 16-ha subwatershed (WS2) that served as a control. These watersheds were separated from a hydrologic standpoint using earthen berms in the collector ditch.

Watersheds were instrumented with water table wells, storm water samplers, and up- and downstream stage recorders. The water table was monitored continuously with pressure transducers and hourly measurements recorded using dataloggers for each study watershed. Similarly, discharge was monitored continuously using submerged pressure transducers in combination with Stevens chart recorder. Precipitation information was collected with a tipping bucket rain sensor located within 0.5 km of the study sites. Descriptions of the measurement systems, collected data, and results from the 3-year study period have been reported (Grace and Skaggs 2006; Grace and others 2006b, 2007).

V_d , f , and K_{sat} values determined based on field experimental data were compared to values measured using soil cores and the auger-hole method reported by Grace and others (2007a) using SAS TTEST (alpha = 0.05) procedures (SAS 2004). The hypothesis was that no mean difference exists in soil-property values for the three methods utilized in this work. Subsequent

model predictions based on values determined for the methods were evaluated using the Nash-Sutcliffe model efficiency (ME) coefficient (Nash and Sutcliffe 1970).

Volume Drained

V_d determinations used drainage, water table depth (WTD), and rainfall data collected during the study period from the field experiment. This procedure involved performing a mass balance for rainfall events for the system as the water table changes from time T_1 to time T_2 (fig. 1). The mass balance is given as:

$$\Delta V_a = D + ET - R \quad (1)$$

where

R = rainfall (cm)

D = system drainage (cm)

ET = evapotranspiration losses (cm)

ΔV_a = change in V_d (cm) during the time period.

Record during and surrounding rain events was used in calculations of V_d , ET was assumed to be zero during those times. In addition, deep seepage was assumed negligible and excluded in this determination.

This equation expressed in terms of system flux and f is given by:

$$f \Delta WTD = q \Delta t - R \quad (2)$$

or

$$f = R - \sqrt{\frac{q \Delta t}{\Delta WTD}} \quad (3)$$

where

f = drainable porosity

q = system flux (cm/hour)

Δt = change in time ($T_2 - T_1$)

ΔWTD = incremental change in water table depth at the midpoint from time T_1 to time T_2 (fig. 1)

Determination of the drainable porosity, f , from the equations above assumes the unsaturated zone is drained to equilibrium with the water table at all times. The assumption that the water content distribution at any time is similar to the distribution of the stationary water table and the profile approximately drained to equilibrium has been demonstrated for drained profiles by Skaggs and Tang (1976) and Tang and Skaggs (1978). However, it is understood that representing the water table profile as linear has a degree of error associated with the volume estimates as the water table recedes (development of the elliptical water table profile) i.e., lag time associated with midpoint water table change. This lag time is the period when water stored (bank storage) in the initially flat water table drains before the midpoint water table recedes and takes on the theoretical elliptical shape explained by the relationships. The f values determined from the drainage rate and WTD measurements in the relationships above can be underestimated due to the fact that the difference in V_d as the midpoint water table recedes under theoretical elliptical profile (fig. 2A) is < V_d calculated

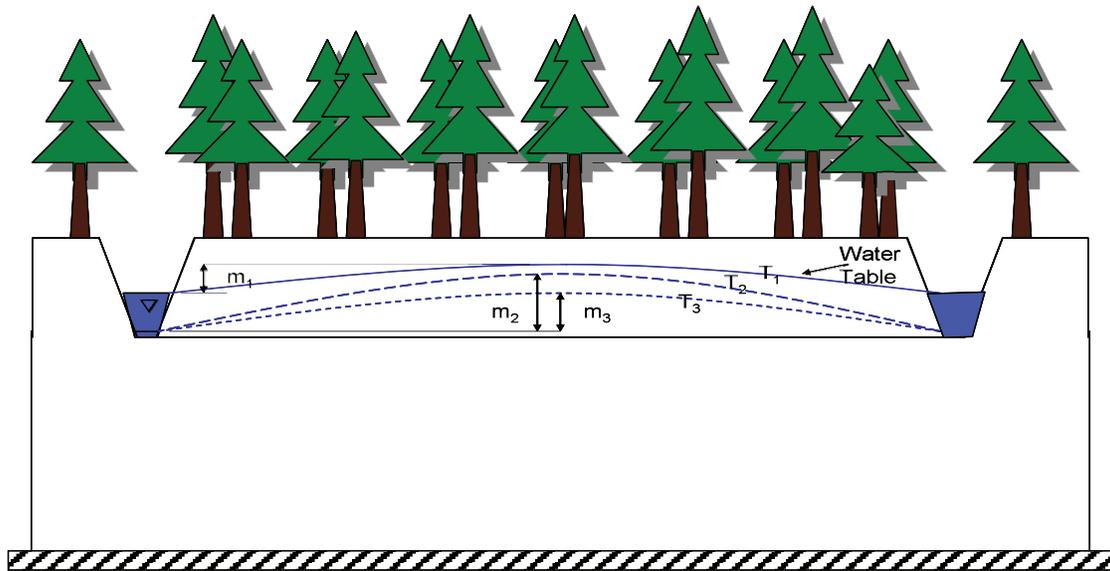


Figure 1—Water table profile following rain events as the water table recedes during a drainage event.

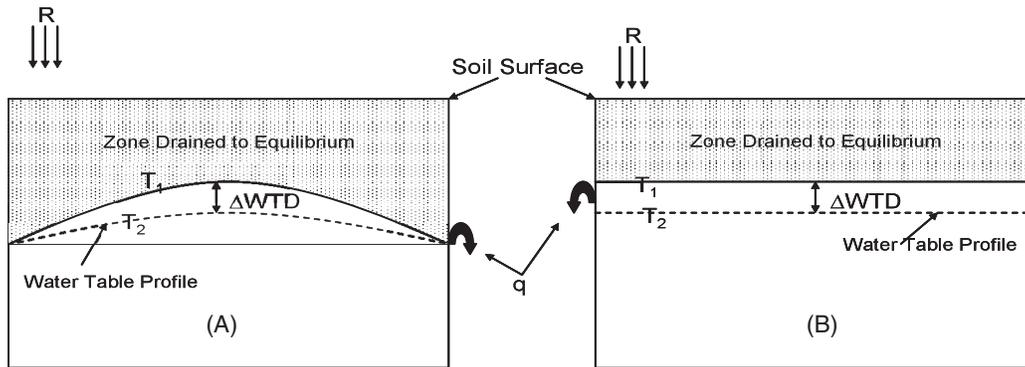


Figure 2—Diagram of theoretical elliptical water table profile during drainage events (A) and water table profile represented in the mass balance equations (B).

from mass balance relationships (fig. 2B) (McCarthy and Skaggs 1991). The elliptical water table profile was verified by observations from the watersheds in this investigation based on water table measurements in the lateral ditch, 1 m from the lateral ditch, 3 m from the lateral ditch, and 50 m from the lateral ditch (midpoint measurement).

Saturated Hydraulic Conductivity

K_{sat} was determined by first defining the relationship between drainage flux and height of the water table above the drain, $q(m)$, using procedures presented by Skaggs and others (2008). The $q(m)$ relationships for the unthinned and thinned conditions are plotted along with the main drainage curve (MDC) as defined by Skaggs and others (2008) (fig. 3). The MDC represents the $q(m)$ relationship for the profile in this investigation in the absence of rainfall based on solutions to the Boussinesq equation (Youngs 1999). Once the $q(m)$ relationship was defined, water table and drainage record

from the field experiment were used to calculate field-effective K_{sat} (K_e) using the following expression based on the drainage equation derived by Hooghoudt (1940):

$$K_e = \sqrt{\frac{qL^2}{4m(2d_e + m)}} \quad (4)$$

where

q = flux (cm/hour)

d_e = equivalent depth of the impermeable layer below the depth of the parallel drains (cm) (for ditches, d_e is the equivalent depth below the water surface in the ditches)

L = distance between parallel drains (cm)

K_e = effective lateral hydraulic conductivity in the soil profile (cm/hour)

m = height of the water table above the water in the parallel drains at the point midway between the drains (cm)

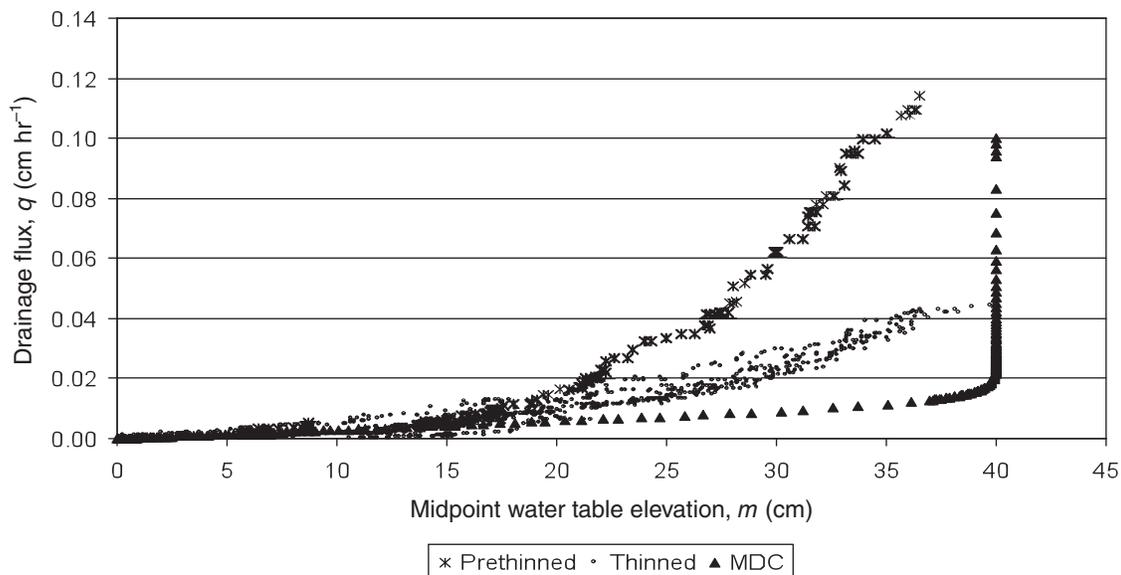


Figure 3—Relationship between observed drainage flux, q , and water table elevation above the ditch water level, m , during the study period for the prethinned and thinned condition. The main drainage curve (MDC) is presented as predicted by solutions to the Boussinesq equation.

These calculations assume that ET is negligible and the existence of steady state conditions. This method of using field measurements to calculate field effective K_{sat} relationships on agricultural lands has been presented as valid for similar field scale drainage systems during periods of low ET (Skaggs 1976). These methods, however, can result in an overestimation of hydraulic conductivity relationships due to ET losses (Skaggs 1976). In this analysis, minimizing the effect of ET on field-effective values required concentrating calculations during fall and winter periods and/or during rainfall events.

RESULTS AND DISCUSSION

The relationships between V_d and change in WTD for WS2 and WS5 over the 3-year study period can be seen in figure 4. V_d relationships for WS2 and WS5 were developed over a relatively narrow range of WTDs (45 to 85 cm). The f from the soil surface to a depth of 45 cm was assumed linear, i.e., assumed to have the same porosity as the 45- to 85-cm range that the relationships characterize. The V_d relationships developed for the WS2 and WS5 prethinned watersheds were not significantly different at the 0.05 level of significance based on t-tests ($P = 0.23$). Data from these prethinned conditions were combined to represent the unthinned condition for further analysis. V_d relationships developed for the watersheds based on field experiment data were statistically similar at the 0.05 level of significance based on t-tests between the unthinned condition and unthinned soil core data previously reported ($P = 0.080$). The V_d values from the field experiment and from soil cores were similar for the thinned condition based on statistical tests ($P = 0.353$).

The V_d for WS2 and WS5 based on relationships developed here give f of 0.14, 0.15, and 0.14 for WS2, the unthinned

condition (WS2 and prethinned WS5 data combined) and the thinned WS5, respectively (fig. 4). Grace and others (2007) reported f values based on soil cores of 0.21 and 0.15 for WS2 WTD < and >60 cm (average of 0.18), respectively. WS5 f values based on soil cores were 0.15 and 0.10 for WTDs < and >60 cm (average of 0.13), respectively. Both methods used to develop V_d relationships have limitations. The V_d relationships developed from soil cores, as discussed previously, can misrepresent the site due to spatial variability of the soil medium. However, determinations of V_d relationships by this using observed drainage and water table response relationships are also limited by the drainage system characteristics. That is, V_d due to changes in WTD can only be determined when the water table elevation is above the ditch depth (in this case 85 cm belowground surface elevation). The water table for both WS2 and WS5 ranged between 45 and 85 cm below average ground surface elevation during drainage events, limiting the developed relationships to this range.

Field-effective values for K_{sat} were also determined for WS2 and WS5 based on the collected hydrology record (precipitation, WTD, ditch stage, and flow rate). The WTD vs. field-effective hydraulic conductivity relationships were presented graphically for the thinned and unthinned condition over the study period (fig. 5). Based on the field-effective K_{sat} values, the K_{sat} values of the surface layer for the unthinned and thinned condition were determined assuming the conductivity values obtained from soil cores in the deeper layers. The conductivity above the range of flow measurements (zero to 40 cm for the unthinned condition and zero to 30 cm for the thinned condition) was assumed similar to values in the adjacent layer (40 to 50 cm for the unthinned condition and 30 to 40 for the thinned condition). These

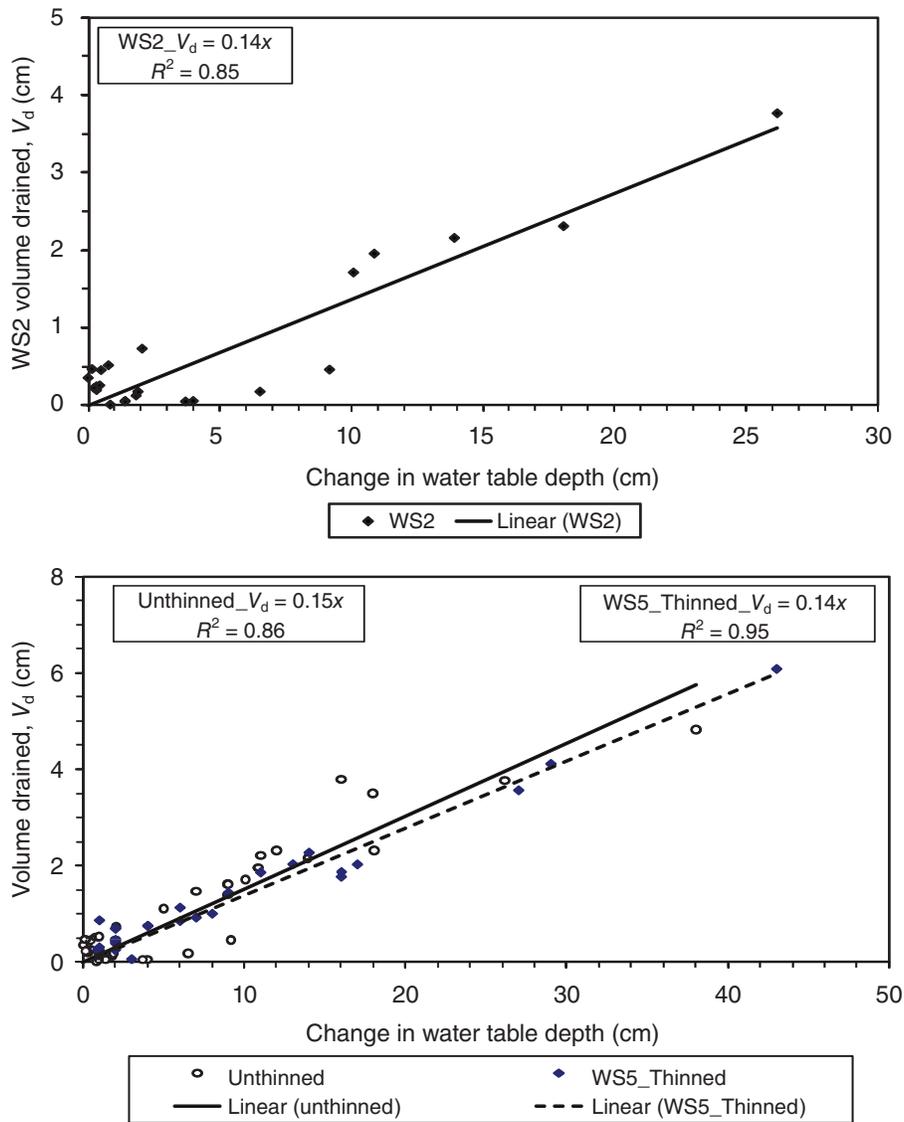


Figure 4—Drainable porosity relationship for WS2 and WS5 watersheds over the 3-year study period (2000–02) based on field-effective V_d computed from measured water table drawdown relationship.

assumptions are supported by the fact that: (1) the flow range is concentrated in the top 40 to 80 cm of the soil profile as presented in figure 5 and (2) previous work (Grace and others 2007) found no differences in cores taken at the 5- to 15-cm and 30- to 45-cm depths.

The mean K_{sat} of the surface layer is estimated at 140 and 90 cm/hour based on the field measurements for the unthinned and thinned condition, respectively. These values are greater than values reported based on soil cores ($P = 0.002$) but not different from values based on the auger-hole method ($P = 0.578$) which had mean conductivities of 100 and 80 cm/hour for unthinned condition, respectively (Grace and others 2007). Similarly, mean K_{sat} value for the thinned condition based on field experiment data was greater than

values reported based on soil cores ($K_{sat} = 32$ cm/hour; $P < 0.0001$) and the auger-hole method ($K_{sat} = 17$ cm/hour; $P = 0.005$). The K_{sat} values determined from these field measurements are also greater than values reported for similar soils in the Tidewater region which had values similar to those determined from soil cores (Broadhead and Skaggs 1989). The upper limit of K_{sat} values determined from soil cores by the constant-head method and the auger-hole method was 500 and 170 cm/hour for these watersheds, respectively. These values are similar to the upper limit for field-effective K_{sat} for the unthinned and thinned watershed was 540 and 210 cm/hour, respectively.

The differences between the field-effective K_{sat} values and those obtained by the other two methods used may

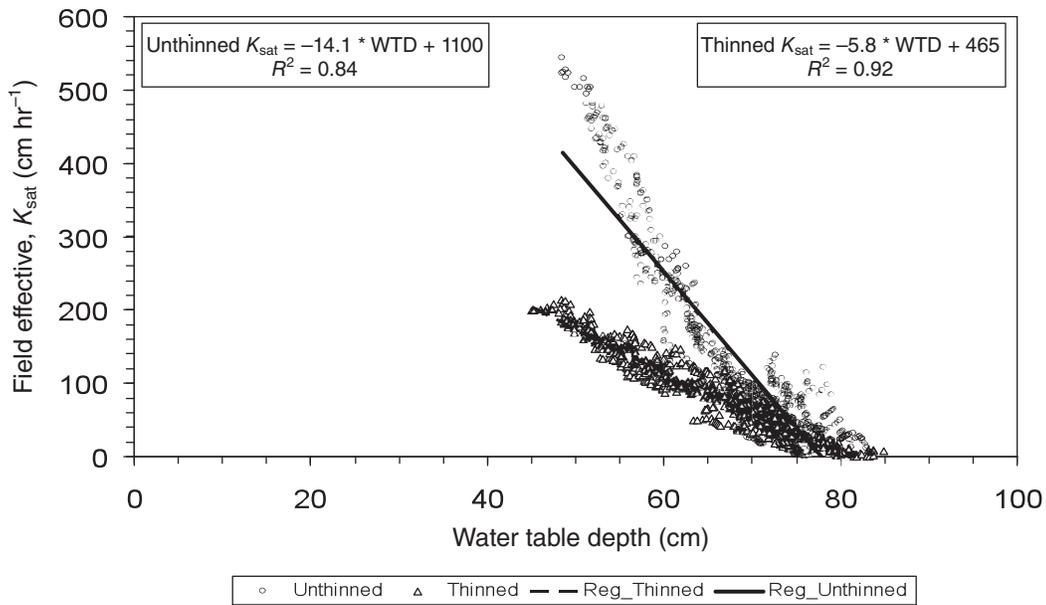


Figure 5—Relationship of observed water table depth and computed field-effective K_{sat} for the unthinned condition and for the thinned condition. Field-effective K_{sat} computed from water table and outflow measurements.

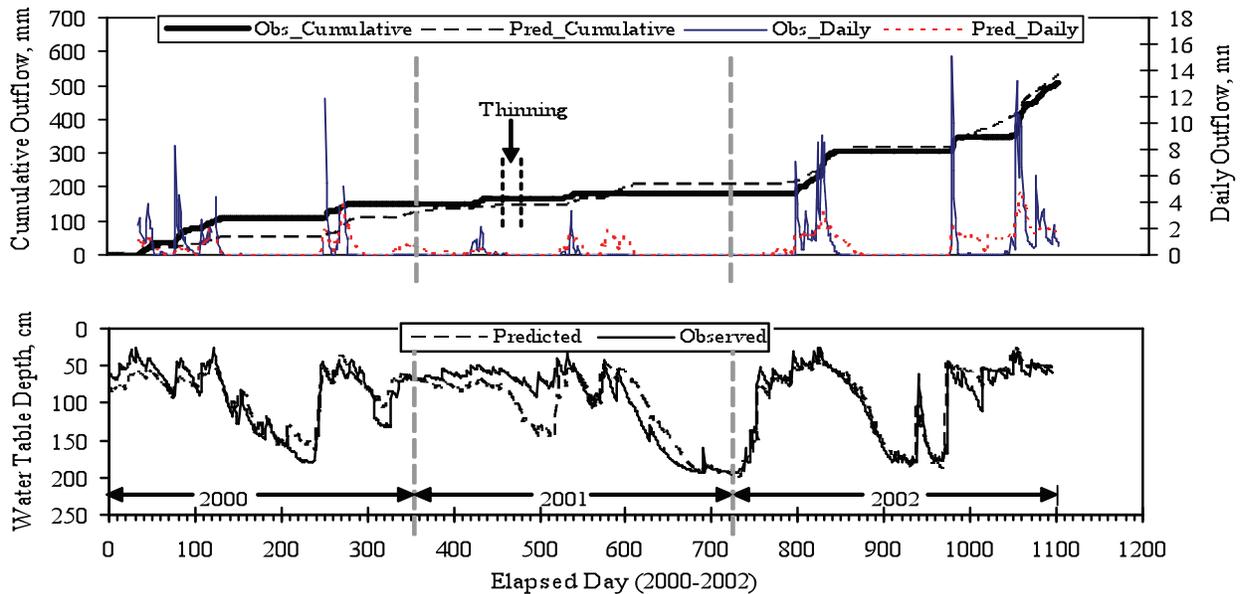


Figure 6—Observed and predicted WS5 cumulative outflow, daily outflow, and daily water table depth during the study period. Predictions based on field-effective V_d and K_{sat} relationships.

be a result of heterogeneity of soils discussed earlier or overestimations in the field-effective results. These factors likely contributed to the observed differences in methods; however, the values determined from the auger-hole and constant-head methods are consistent (within 20 percent) ($P = 0.150$). The field-effective values may be overestimated

due to the influence of ET or deep seepage which was assumed negligible in determining field-effective K_{sat} values from field measurement as discussed earlier. Skaggs (1976) presented vertical losses, ET , and deep seepage as components that can cause significant overestimation errors in determinations from these field-based measures. ET losses

in the determinations made here were assumed negligible but may have been greater than estimated during the periods of record. The errors created by *ET* losses would likely result in the higher K_{sat} values seen in these calculations.

The field-effective values reported here and values previously reported based on soil cores and auger-hole tests were used in predictions of the hydrology from the poorly drained watersheds in this investigation. DRAINMOD predictions based on field-effective and soil core soil input files were compared statistically (table 1) and graphically (figs. 6 and 7).

Cumulative outflow was overpredicted using soil inputs from both methods; however, predictions using values based on soil cores and auger-hole determinations were closer to the observed outflow. A deeper water table was also predicted using values from both methods. The absolute average daily difference (AADD) in outflow was similar for the predictions at 0.45 and 0.46 mm. Based on the results of the predictions, the field-effective soil property inputs resulted in more efficient predictions of outflow with a ME of 0.45 compared to the values representing soil cores which had a ME of 0.42. Both these predictions only resulted in fair agreement between

Table 1—Predictions and statistics for outflow and water table depth components based on values determined based on soil cores and field-effective values

Parameter	Observed	Predicted with core values	Predicted with field effective values
Precipitation, mm	3294	3294	3294
Cumulative outflow, mm	508	527	531
Daily average WTD, cm	95	100	97
ET, mm	2789	2771	2670

AADD outflow, mm		0.45	0.46
AADD WTD, cm		15	14
Outflow ME ^a		0.42	0.45
WTD ME ^a		0.84	0.82

WTD = water table depth; ET = evapotranspiration; AADD = absolute average daily difference.

^a Nash-Sutcliffe model efficiency coefficient (ME).

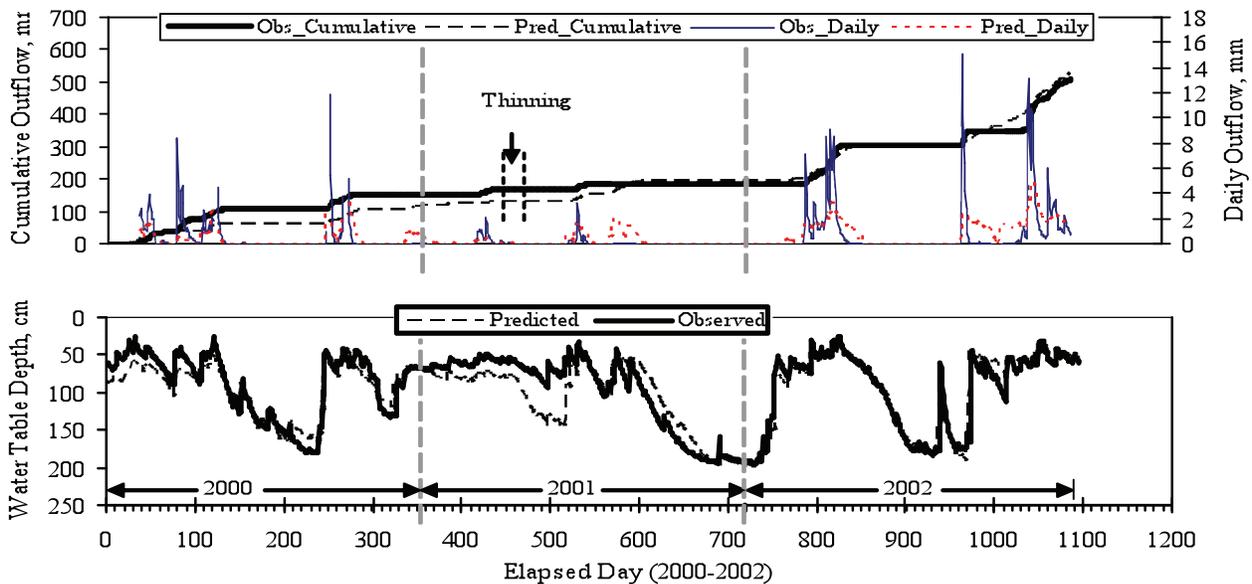


Figure 7—Observed and predicted WS5 cumulative outflow, daily outflow, and daily water table depth during the study period. Predictions based on reported soil core and auger-hole V_d and K_{sat} values.

predicted and observed outflow based on the ME values reported here. Field-effective soil property inputs resulted in a slightly less efficient prediction of WTD (ME = 0.82) in comparison to predictions based on soil property inputs from soil core values (ME = 0.84).

The differences in the predictions are illustrated in the graphical representation of outflow and WTD for the simulation period. Predictions based on field-effective values (fig. 6) show a deeper water table than that of predictions based on soil inputs from soil core values (fig. 7). Field-effective K_{sat} values resulted in a wetter site based on cumulative outflow record (table 1) and more responsive outflow pattern (fig. 6) than found for the soil core input values.

Daily peak outflow rates were in fair agreement to those observed during the study period for predictions based on these field-effective values. However, the deeper water table during most periods following thinning predicted using field-effective values indicate that V_d relationships may have been overestimated in predictions. In contrast, soil inputs based on soil core values resulted in better water table agreement as illustrated in figure 7 and supported by a stronger coefficient of model efficiency (ME = 0.84) (table 1). The predicted outflow hydrograph shows longer duration drainage events with decreased peak outflow rates for predictions based on soil core values. Cumulative outflow predictions based on soil core values did have better agreement during wet periods over the study period than predictions with field-effective soil-property values based on this analysis. These results indicate that true soil-property values for V_d , f , and K_{sat} likely lies somewhere between values obtained from soil cores and auger-hole tests and those obtained in this determination based on outflow and water table record.

CONCLUSIONS

Precipitation, outflow, and water table data were utilized to calculate field-effective soil property inputs for V_d , f , and K_{sat} for artificially drained pine plantation watersheds in this investigation. V_d and subsequent f relationships estimated in this work were similar to those determined based on soil cores collected in the field experiment. The K_{sat} values determined by the constant-head method was less than those presented based on outflow and water table response in the field experiment. Analysis revealed that the field-effective K_{sat} values determined were not different from the values measured using the auger-hole method for the unthinned condition. The field-effective conductivity values determined likely overestimated field conductivities whereas conductivity determined from the constant-head and auger-hole methods likely underestimated the values. The predictions resulting from these alternatives presented in this work appear to support this assumption. The K_{sat} values determined as field-effective values resulted in increased cumulative outflow and a deeper water table for the majority of the study period for both watersheds. The K_{sat} of the surface soil layer lies between the values determined from the small scale tests, constant-head and auger-hole methods, and the field-effective values presented. However, the values are likely closer to the

first than the latter. Due to this large variation in the K_{sat} values from the different methods, K_{sat} was regarded as a critical calibration parameter in modeling efforts for these and similar watersheds (Grace and Skaggs 2006).

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