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Saturated Hydraulic Conductivity and Its Impact on Simulated Runoff for Claypan Soils

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ABSTRACT

Saturated hydraulic conductivity (K_{sat}) is an essential parameter for understanding soil hydrology. This study evaluated the K_{sat} of in situ monoliths and intact cores and compared the results with other studies for Missouri claypan soils. These K_{sat} values were used as runoff-model inputs to assess the impact of K_{sat} variation on simulated runoff. Lateral in situ K_{sat} of the topsoil was determined on 250 by 500 by 230 mm deep monoliths. These values were compared with the K_{sat} of 76 by 76 mm diam. intact cores with and without bentonite to seal macropores. Mean (± SD) lateral in situ K_{sat} was 72 ± 0.7 mm h^{-1} and mean intact core K_{sat} without bentonite was 312 ± 58 mm h^{-1}. The mean intact core K_{sat} without bentonite was significantly larger than the lateral in situ K_{sat} ($P = 0.03$). The lateral in situ K_{sat} was not different from core K_{sat} with bentonite (71 ± 1.1 mm h^{-1}). The intact core K_{sat} with bentonite differed from previous studies by 10 times. This was attributed to the variations in soil depth to claypan, macropore presence, and methodology. The impact of using an effective hydraulic conductivity (K_{eff}) computed from measured K_{sat} on intact cores without bentonite underestimated the Water Erosion Prediction Project (WEPP) simulated runoff by 28% for a measured runoff event of 40 mm. The core K_{sat} with bentonite was correlated with measured runoff from long-term erosion-runoff plots. A quadratic regression explained 95% of the variability between measured and simulated runoff.

SATURATED HYDRAULIC CONDUCTIVITY is an essential parameter for understanding soil water movement. It is a fundamental input for modeling runoff, drainage, and movement of solutes in soils (Mallants et al., 1997). While K_{sat} is widely studied, questions remain about how sample size and boundary conditions influence its determination.

Reports have found that measurements on small samples (<100-mm diam.) tend to give higher K_{sat} values than do measurements on larger samples (Bagarello and Provenzano, 1996). The values of small samples are also questioned because samples are too small to embody a representative elementary volume (REV) of soil. The REV is a conceptual unit representing the smallest volume of a soil unit (Mallants et al., 1997). Its actual dimensions are ill defined. Bouma (1980) suggests three REV sizes for K_{sat} determinations: 100 cm^3 for sand, 1000 cm^3 for silt, and 10 000 cm^3 for clay soils. As a sample size increases, variability in K_{sat} values is expected to decrease.

The use of the REV is thought to reduce the sample-size dependence of K_{sat}, and thus facilitate better measurements (Mallants et al., 1997). Samples based on the REV often reflect the natural boundary conditions (Gupta et al., 1993), and diminish disturbance and compaction of soil during sampling (Vepraskas and Williams, 1995).

Soil texture is generally known to affect K_{sat}. Clay soils typically have low K_{sat} values (Bouma, 1980; Jamison and Peters, 1967). This is of interest in the midwest USA because about 4 million ha of claypan soils exist in this region (Jamison et al., 1968). These soils have an argillic horizon 130 to 460 mm deep, with clay contents >450 g kg^{-1} and are very slowly permeable although published data are limited (Jamison and Peters, 1967).

Because of the argillic horizon, claypan soils may perch water and create lateral flow. A study of claypan hydrology suggests that runoff rates may be equal to rainfall under saturated conditions (Saxton and Whitaker, 1970). Furthermore, studies of runoff and rainfall data from the McCredie rainfall-erosion plots near Kingdom City, MO, indicate that lateral flow known as interflow may be a significant component of the total runoff during springtime when precipitation is usually the most intense and the erosion rates are the highest (Minshall and Jamison, 1965; Ghidey and Alberts, 1998). To date, detailed in situ lateral K_{sat} studies have not been conducted for Missouri claypan soils because measurements are costly and time-consuming (Blevins et al., 1996). Lateral K_{sat} measurements are also limited elsewhere (Ahuja and Ross, 1983; Wallach and Zaslavsky, 1991). The need for in situ lateral K_{sat} determination for Missouri claypan soils has been recognized because of the probability of interflow (Jamison et al., 1968; Wilkinson and Blevins, 1999). Information on in situ lateral K_{sat} through the horizons above the claypan is important for determining their ability to conduct water laterally and assessing runoff and erosion.

Many have characterized the vertical K_{sat} for claypan soils (Doll, 1976; Zeng, 1994). However, most of the measurements were made only for the surface horizons (Jamison and Peters, 1967; McGinty, 1989), therefore, studies of K_{sat} variations with depth are few. Because of their hydrologic attributes, claypan soils probably have quite different effective K_{sat} values with depth from other Alfisols. The information on K_{sat} depth distribution would be valuable in explaining the claypan hydrology and for characterization of variability in horizons of low and high permeability required for accurate flow studies.

Because the K_{sat} values may vary by measurement method (Bouma, 1980; Bagarello and Provenzano, 1996;

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Abbreviations: EC, electrical conductivity; K_{eff}, effective hydraulic conductivity; K_{sat}, saturated hydraulic conductivity; REV, representative elementary volume; SAR, Na adsorption ratio; WEPP, Water Erosion Prediction Project.

Mallants et al., 1997), the available K_{sat} data on these soils need to be studied to determine their consistency and uniformity by method. Data from such measurements should be statistically the same to be used for hydrologic prediction and modeling.

Since knowledge of K_{sat} is essential for the use of water flow models, it is useful to evaluate the influence of measured K_{sat} on modeled runoff. One modeling approach for erosion/runoff prediction is the WEPP. This model has been extensively used for runoff prediction since 1995 when it was publicly released by the USDA-ARS. Although K_{sat} is not the only factor that affects runoff, the WEPP model incorporates the estimated values of hydraulic conductivity as an important soil attribute to predict runoff (Flanagan and Nearing, 1995). The WEPP uses K_{eff} values for surface layers, and internally computes K_{sat} values for subsurface soil layers. Studies indicate that runoff predictions are sensitive to the initial K_{eff} values (Ghidey et al., 1999).

The objectives of this study are to: (i) measure lateral in situ K_{sat} of the 0- to 230-mm depth (above the claypan) using 250 mm wide by 500 mm long soil monoliths, (ii) measure the K_{sat} with and without bentonite of 76-mm diam. soil cores taken at 100-mm intervals to a depth of 2 m, (iii) compare the core K_{sat} vs. lateral in situ K_{sat}, (iv) compare previously measured K_{sat} data for Missouri claypan soils with results of this study, and (v) compare measured runoff vs. WEPP predicted runoff using measured K_{eff} as a model input to illustrate the benefit of using measured K_{eff} values.

MATERIALS AND METHODS

Installation of Soil Monoliths for Lateral in situ K_{sat} Measurements

This study was conducted at the Midwest Research Claypan Farm (McCredie) near Kingdom City, MO. A 10 by 30 m area under long-term (>28 yr) continuous fescue (*Festuca arundinacea* Schreb.) and blue grass (*Poa pratensis* L.) was chosen. The soil is a Mexico silt loam (fine, smectitic, mesic, Aeric Vertic Epiaqualf) formed in loess developed over glacial till on a slope of about 3%. The mineralogy of the argillic horizon consists of 38% montmorillonite, 34% quartz, 21% kaolinite, and 7% illite. Selected soil properties are presented in Table 1.

Three in situ monoliths 250 mm wide by 500 mm long by 230 mm deep (the depth to claypan) were constructed. Depth to the claypan was determined by obtaining 20-mm diam. soil samples using a hand probe. These samples were studied in the field for changes in texture and color to determine the depth. Mean (± SD) depth was 230 ± 7 mm ($n > 100$). Each monolith site was wet for 12 h and then allowed to drain 24 h to soften the soil sufficiently while reducing puddling during construction. A trench was dug around each monolith to form a rectangular soil block with intact bottom.

The monolith set-up had three compartments: (i) water supply pit, (ii) soil monolith, and (iii) water collection pit. Two 6.3-mm steel plates 500 by 700 mm were installed vertically along the two sides of the monolith, which allowed a 100-mm of additional length of steel plate at each end. The additional length allowed for construction of a water supply pit and a water collection pit. Two plates 250 by 500 mm were installed vertically at each end of the border to form a rectangular box. The steel plates extended from 150 mm above

Table 1. Soil characteristics and land use of the hydraulic conductivity studies.

Author (s)	Depth	Silt	Clay	Bulk density	Land use
	cm	g kg^{-1}		Mg m^{-3}	
Blanco†	0–10	761 ± 22	196 ± 25	1.27 ± 0.09	Continuous pasture (>58 yr)—blue grass (*Poa pratensis* L.) and orchard grass (*Dactylis glomerata*)
	10–20	767 ± 14	189 ± 23	1.37 ± 0.11	
	20–30	794 ± 16	204 ± 26	1.35 ± 0.10	
	30–40	555 ± 11	442 ± 10	1.24 ± 0.07	
	40–50	563 ± 11	435 ± 23	1.21 ± 0.08	
	50–60	598 ± 16	398 ± 11	1.28 ± 0.06	
	60–70	663 ± 15	334 ± 11	1.38 ± 0.07	
	70–80	672 ± 9	320 ± 9	1.46 ± 0.04	
	80–90	703 ± 8	293 ± 17	1.44 ± 0.05	
	90–100	764 ± 14	229 ± 11	1.49 ± 0.06	
	100–200	760 ± 19	231 ± 18	1.48 ± 0.13	
Jamison and Peters	0–5	780	180	1.40	Continuous (>28 yr)—blue grass and orchard grass with a weak stand of alfalfa (*Medicago sativa*)
	5–11	700	280	1.31	
	11–16	460	500	1.24	
	16–25	480	480	1.23	
Baer and Anderson	0–10	725	245	1.31	
	10–50	443	520	1.30	
	50–90	499	426	1.28	
Doll	0–15	726	230	1.26	Continuous (>40 yr) fescue (*Festuca arundinacea*) and blue grass
	15–20	712	243	1.36	
	20–28	636	320	1.28	
	28–41	495	495	1.24	
McGinty	0–10	770	175	1.24	12-yr plot study under continuous no-till corn
	10–20	765	200	1.33	
	20–30	670	250	1.30	
	30–40	470	500	1.27	
Zeng	0–8	730	245	1.27	Continuous (>100 yr) grass-fescue sod
	8–15	656	330	1.40	
	18–26	539	450	1.42	
	28–36	499	470	1.45	

† Mean ± SD and $n = 9$.

to 350 mm below the soil surface. Silicone caulking was used to waterproof the steel plate seams. A 20-mm discharge hole was made at the lower end of the collection pit. A divider screen was made from a metal screen with geotextile material, which separated the soil monolith from the collection and supply pits. A bentonite-slurry was used to seal the soil–steel plate interfaces. The excavated trench was backfilled with the original native soil.

Measurement of Lateral in situ K_{sat}

Monoliths were slowly wet for 48 h. The electrical conductivity (EC) of the in situ water used was 0.71 dS m^{-1}, and the Na adsorption ratio (SAR) of the in situ water was 2.39. Once the monoliths were satiated, water was added to the supply pit using a Mariotte bottle for maintaining a constant head and measuring the inflow rate. When the water level rose to the soil surface in the collection pit, excess water flowed through the 20-mm discharge hole. Plastic tubing routed the outflow for measurement.

The monolith lateral K_{sat} was measured by applying water from the water supply pit and measuring outflow in the collection pit for 5 h. A difference in hydraulic head of 16 mm was measured along the in situ pedon. A polyethylene tent was used to cover the plot throughout the measurement to minimize water loss from evaporation. Time, inflow and outflow volumes, and hydraulic gradient were recorded to facilitate calculation of the lateral K_{sat}.

The time to steady flow conditions was 48 h. After 12 h of satiation, 18.9% of applied water was moving downward through the soil. Downward movement decreased to 4.8% of total inflow after 24 h. This continued to decrease to 1.5% when the plots were satiated for 48 h. Downward flow through the claypan was obtained by subtracting outflow from the inflow. Measurements were initiated when downward flow was 1.5%.

Laboratory K_{sat}

One hundred eighty soil cores were taken within 10 m of the in situ study sites, to determine the K_{sat} distribution with depth, and to facilitate comparison of lateral in situ K_{sat} with K_{sat} determined on small intact cores. Nine intact 76-mm diam. soil cores were collected every 100 mm with depth to 2 m using a core sampler (Blake and Hartge, 1986). A replicate area near each monolith was used to collect cores in a vertical orientation when the soil was slightly below field capacity. Samples were transported to the laboratory, and slowly wet from the bottom with tap water using a Mariotte bottle having a supply rate of about 3 mm h^{-1}. The EC of the tap water used was 0.68 dS m^{-1}, and the SAR of the tap water used was 2.34. Cores collected above the 200-mm depth were wet for 24 h. Cores collected at or below the claypan, were wet for 7 d. Measurements for samples with higher K_{sat} were determined with a constant head, and those with low K_{sat} were determined with a falling head (Klute and Dirksen, 1986).

Visible macropores (≥1 mm) and interfacial voids located between the soil and the cylinder wall on a set of the cores were plugged using a bentonite-slurry. The reason for using this slurry was to eliminate the free flow of water through these macropores and voids. Elimination of bypass flow in small cores during K_{sat} determinations is a recommended methodology (Smith and Browning, 1946; Klute, 1965; Fadl, 1979). Blocking of macropores may seem at odds with the goal of estimating in situ K_{sat}, which measures flow through the naturally occurring macropores. However, a problem arises when small, 76-mm cores are used for K_{sat} measurements. Macropore continuity in field conditions is intact while this continuity is broken in small cores. These macropores are commonly finite in small cores and are often rapid pathways for bypass flow because of differences in the boundary conditions between in situ and core measurements. The dominant saturated flow in small cores is mainly via these macropores rather than through the soil matrix.

The K_{sat} values with bentonite were compared with those measured without bentonite to assess the effectiveness of the bentonite. A *t*-test was used to examine the hypotheses that the lateral in situ K_{sat} and laboratory K_{sat} determinations of the topsoil were not different by assuming anisotropic conditions (SAS Institute, 1985). This assumption is well supported by studies, which indicate that K_{sat} within the plow layer of silt loam soils is not appreciably influenced by core orientation (Dabney and Selim, 1987).

Comparison of Existing K_{sat} Data for Missouri Claypan Soils

The consistency of available K_{sat} data for the claypan soils was evaluated by comparing previously collected K_{sat} data with the results from this study. Data are based on studies of Jamison and Peters (1967), Doll (1976), McGinty (1989), Zeng (1994), and Baer and Anderson (1995). Soil characteristics and land use of the study sites are in Table 1. For data from the current study, a 95% confidence interval of the mean was calculated using the pooled variance of the K_{sat} with and without bentonite data of each depth separately.

Runoff Prediction Using Existing K_{sat} Data as Input for the WEPP Model

The study of K_{sat} influence on runoff prediction was conducted by using the WEPP Hillslope model (Version 98.4) on a single event basis using the input of K_{eff}. The K_{eff} input values for WEPP runoff prediction were determined using the K_{sat} measured on 76 by 76 mm diam. soil cores. The K_{eff} was calculated as:

$$K_{eff} = L_T/(L_1/K_1 + L_2/K_2 + L_3/K_3) \qquad [1]$$

where L_T is the total thickness of the 0- to 300-mm depth; L_1, L_2, and L_3 are layer thickness values, and K_1, K_2, and K_3 are the K_{sat} values for each of the three depth intervals (0–100, 100–200, and 200–300 mm; Jury et al., 1991).

The K_{eff} was computed for the horizons within the upper 0 to 300 mm because this depth has soil that is much more permeable ($K_{sat} \approx 71$ mm h^{-1}) than the underlying very slowly permeable argillic horizon ($K_{sat} \approx 1.83$ μm h^{-1}). Hence, the topsoil K_{sat} would largely control water flow in saturated conditions. The 0- to 300-mm depth reflects the inherent soil properties of this permeable soil. The best approach for K_{eff} estimation would likely be to evaluate soil properties with depth on a case-by-case basis and allow the soil profile to direct the depth chosen for K_{eff} estimation. However, this approach may be too costly and time-consuming for routine use.

The procedure used to compute K_{eff} is different from that estimated internally by WEPP which predicts K_{eff} based on approximate relationships with soil properties (Zhang et al., 1995). The predicted K_{eff} determined by WEPP is optimized using measured runoff data from a database derived from multiple plots for various soil types. For instance, the K_{eff} for the surface soil of the Mexico claypan soil is 0.34 mm h^{-1} (Nearing et al., 1996). The WEPP estimate of K_{eff} is useful when measured K_{sat} data are not available. Because we had measured K_{sat} from five studies on Missouri claypan soils, we computed K_{eff} for each study to evaluate the effect of K_{sat} variability on predicted runoff.

The computed K_{eff} was used as an input parameter while using other WEPP input parameters as reported by Ghidey and Alberts (1996) for Missouri claypan soils. The only input parameter that was changed in this study was the K_{eff} for the surface 300-mm depth. Below this depth, the WEPP internally predicted K_{eff} values were used for runoff prediction (Zhang et al., 1995). The WEPP model requires four input files containing information on climate, slope, soil, and crop management to estimate runoff (Flanagan and Nearing, 1995). Ghidey and Alberts parameterized the required input files of WEPP Hillslope Model (Ver. 95.7) using measured runoff and soil data from long-term runoff-erosion plots at (McCredie) Kingdom City, MO.

The WEPP predicted runoff was compared with measured runoff data collected from the natural rainfall erosion plots located at the Midwest Research Claypan Farm (Ghidey and Alberts, 1996). The runoff-erosion plots were managed in no-till corn (*Zea mays* L.) for an 11-yr period (1983–1993). Only the 11 largest rainfall events were selected for study when runoff was likely to occur. Data from the no-till corn plots were used because these plots had the most protective crop residue (~95% residue cover), and thus K_{sat} would not be greatly reduced by surface seal from rainfall. Table 2 indicates that prior to the reported dates of largest rainfall event the soil was practically saturated in 1984, 1985, 1988, and 1993, and near saturation in 1983, 1986, 1987, and 1989 through 1992. Based on these data, the use of K_{eff} using measured K_{sat} for runoff prediction was considered appropriate.

The rate of change in predicted runoff as influenced by the K_{eff} change was quantified by performing a sensitivity analysis of WEPP predicted runoff. The sensitivity index for the WEPP results was computed as described by Lane and Nearing (1989):

$$S = [(R_2 - R_1)/R_{12}]/[(K_{eff2} - K_{eff1})/K_{eff12}] \qquad [2]$$

where R_1 is the predicted runoff using measured K_{eff} with bentonite, R_2 is the predicted runoff using K_{eff} selected from the other studies, R_{12} is the average of R_2 and R_1, K_{eff1} is the K_{eff} with bentonite, K_{eff2} is the K_{eff} selected from the other studies, and K_{eff12} is the average of K_{eff2} and K_{eff1}.

RESULTS AND DISCUSSION

Lateral in situ K_{sat}

In situ K_{sat} values were calculated by assuming that the argillic horizons were nearly impermeable when saturated. Mean lateral in situ K_{sat} was 72 ± 0.7 mm h^{-1}. Differences were not significant among sites ($P > 0.5$). About 98.5% of applied water in the upper end of the monolith moved laterally through the soil layer above the restrictive argillic horizons after 48 h of wetting. A small amount (1.5%) was unaccounted for and likely was downward flow through the claypan equivalent to a K_{sat} of ~9 μm h^{-1}. Results suggest that the argillic horizons were a barrier directing the vertical flow horizontally above the claypan as lateral flow. A perched water table is thus likely as these soils are ponded for several hours. These results support earlier findings of Jamison and Peters (1967), and Saxton and Whitaker (1970), who reported the occurrence of lateral flow in these soils.

Table 2. Rainfall and soil characteristics for 11 large rainfall events from 1983 to 1993.

Rain date	Rainfall	Measured runoff	Soil moisture storage†	Saturation degree
	mm	mm	mm	
1 May 1983	120	91	80	0.7
21 Apr. 1984	48	42	116	1.0
6 Jun 1985	83	67	119	1.0
17 May 1986	70	31	83	0.7
14 Apr. 1987	41	15	79	0.7
29 Mar. 1988	21	10	110	1.0
2 Apr. 1989	28	11	90	0.8
7 June 1990	138	114	92	0.8
14 Apr. 1991	36	15	78	0.7
18 Mar. 1992	60	49	86	0.7
7 July 1993	102	72	114	1.0

† Soil moisture storage = (Precipitation − Runoff − Evapotranspiration). Values were computed from November of the preceding year to the specified rain date.

Comparison of K_{sat} Determined on in situ Monoliths and Intact Cores

The K_{sat} values for cores without bentonite were significantly larger than for the monoliths ($P = 0.033$). The mean value was four times more (312 ± 58 mm h^{-1}) than for the monoliths' K_{sat} values (72 ± 0.7 mm h^{-1}). The difference between the K_{sat} of the monoliths and the K_{sat} of intact cores with bentonite (71 ± 1.1 mm h^{-1}) was not significant ($P = 0.50$). Inspection of the cores showed numerous vertically oriented macropores produced by flora and faunal biological activity (biochannels). Water flow through cores without bentonite was largely governed by flow through macropores extending throughout cores, and resulted in K_{sat} values that were unrealistically high. Under field conditions, such macropores would be expected to terminate in the subsoil because of the decrease in porosity with depth, soil swelling, and from clay hydration, and are thus much less conductive when satiated than continuous open-ended macropores in cores. Since the K_{sat} of cores with bentonite is similar to in situ values, the bentonite technique may be used to approximate laboratory K_{sat} to the K_{sat} of in situ soils. Small cores may not reflect the in situ K_{sat} values if continuous macropores that dominate flow in small cores are not eliminated.

The macropore effect on water flow is also a function of the pore orientation. A macropore extending vertically throughout a 76-mm core causes a higher K_{sat} value compared with values under field conditions. In contrast, a laterally oriented macropore in a core conducts less or no water because free water will not enter the pore, thus reducing the K_{sat} value (Hillel, 1998). This study found that cores having macropores visible at the exposed surface that were oriented vertically produced four times larger K_{sat} values compared with in situ measured K_{sat}, whereas K_{sat} values measured with bentonite injected to eliminate this effect were not statistically different from in situ measured K_{sat} values.

The K_{sat} Profiles with Depth of Intact Cores

Profile plots of K_{sat} are shown in Fig. 1. Data show that K_{sat} with bentonite was significantly lower ($P = 0.007$) than K_{sat} without bentonite throughout the pro-

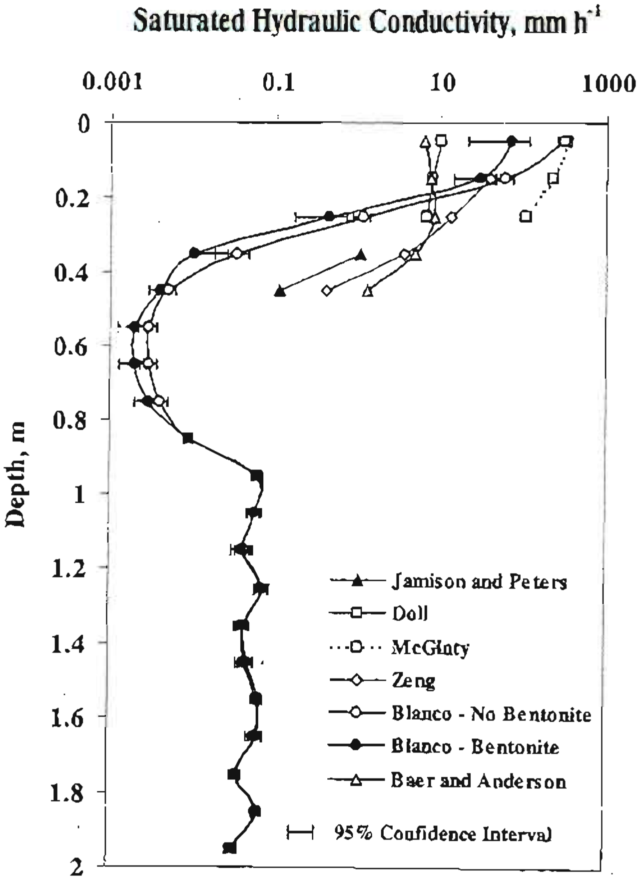

Fig. 1. Comparison of saturated hydraulic conductivity (K_{sat}) data from selected studies for Missouri claypan soils. The error bars represent the 95% confidence interval of the mean K_{sat} value for each depth ($n = 9$).

file. Measurement of K_{sat} on cores without bentonite had higher conductivities even for samples within the claypan with high montmorillonitic clay content. This high clay content is commonly thought to increase swelling and thus close macropores reducing K_{sat} values. However, the measured data suggest this notion is not correct. The mean K_{sat} without bentonite (312 ± 58 mm h^{-1}) is four times greater than K_{sat} with bentonite (71 ± 1.1 mm h^{-1}) for the surface 100 mm of soil. The comparison of K_{sat} of cores with and without bentonite indicates that ~90% of water flow through cores from the upper 100 mm of the soil can be conducted by the macropores. McGinty (1989) also measured the K_{sat} of 76-mm diam. cores without bentonite on claypan soils and found high K_{sat} values for the surface soil (333 mm h^{-1}). This work was done on soil samples collected from no-till sites where some macropores were present and very likely were not closed, and thus conducted water very rapidly.

Differences in the K_{sat} profile (with bentonite) among the three sampling sites across a depth of 2 m were not significantly different ($P = 0.77$). A significant variation in K_{sat} with depth occurred ($P = 0.001$). The lowest conductivities (2.2–1.8 μm h^{-1}) were between the 550- and 750-mm depth, correlating to soil with weakly developed, compact, and firm structure. This layer corresponds to the region immediately below the claypan (the zone of maximum clay accumulation). The K_{sat} measured at the 100-mm depth was about 40 000 times greater than that found at the 600-mm depth (1.8×10^{-3} mm h^{-1}). An increase is noted from the 600- to 950-mm depth likely because of the textural change from silty clay to silty clay loam (Bohnert, 1967).

Comparison of K_{sat} Determinations for Missouri Claypan Soils

Figure 1 shows the K_{sat} measured on selected Missouri claypan soils. The K_{sat} decreases with depth because of changes in soil density, texture, and structure. The K_{sat} values with bentonite were nearly 10 times greater than the K_{sat} values measured by Doll (1976), and Baer and Anderson (1995). The K_{sat} values were nearly five times less than those reported by McGinty (1989) for the upper 200-mm depth. The K_{sat} values reported by Zeng (1994) on 76-mm cores were 1.3 times greater than the K_{sat} with bentonite.

The variation in K_{sat} presented in Fig. 1 is mainly attributable to (i) the variations in depth to the claypan among the studies, (ii) the presence of conductive macropores, and (iii) the method of K_{sat} determination. First, the depth to claypan varies between 130 and 370 mm with an average of 250 mm (Jamison and Peters, 1967). Samples taken by previous investigators from different sites at the same depth may also have differed in clay content and bulk density, altering K_{sat} values (Table 1). The low K_{sat} values found by Baer and Anderson (1995) for example, may be explained because their samples were collected from severely eroded soil that had exposed the claypan. Secondly, claypan soils often have abundant macropores (Jordan et al., 1997). Small cores may overestimate K_{sat} values particularly for surface depths with abundant macropores. This is shown in Fig. 1 where the K_{sat} without bentonite is about four times higher than that the K_{sat} with bentonite. The K_{sat} values by McGinty (1989) are higher than the K_{sat} values with bentonite because his measurements were made without bentonite, and had large macroporosity (about 3–5% porosity in the size range of 1- to 2-mm diam.). Thirdly, the K_{sat} variation may be due to different methods and different aspects of measurement (with vs. without macropores). For example, Jamison and Peters (1967) determined the K_{sat} with the double tube method, Doll (1976) used the crust method, and the core K_{sat} in this study was measured with and without bentonite.

Influence of K_{sat} on Modeled Runoff Prediction

Process-based hydrologic models require input of K_{sat}. However, model users often have limited access to measured data and thus use published or estimated values. Studies of claypan soils indicate that K_{sat} values may vary by 100 times due in part to spatial and temporal variability (Fig. 1). This variability in input K_{sat} has the undesirable effect of producing variable and inaccurate model predictions.

The impact of K_{sat} variability on runoff was evaluated by performing the WEPP runoff prediction using measured K_{sat} from selected studies for the Missouri claypan

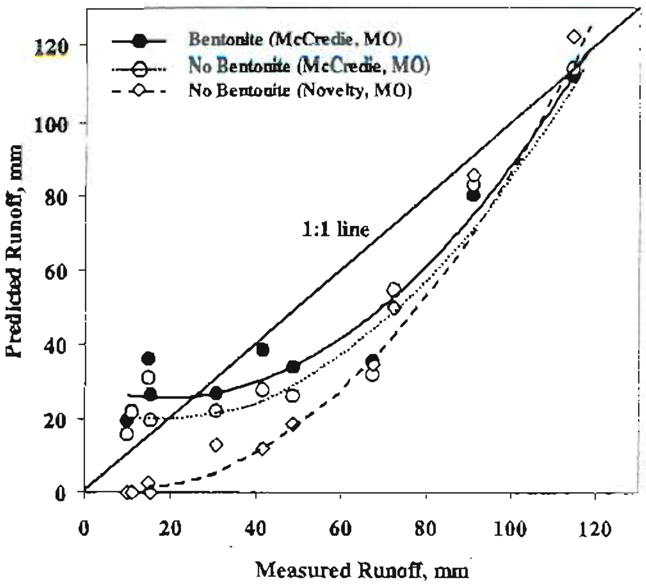

Fig. 2. Comparison of Water Erosion Prediction Project (WEPP) predicted and measured runoff using effective hydraulic conductivity (K_{eff}) with bentonite = 1.3 mm h^{-1} (McCredie, MO), K_{eff} without bentonite = 3.4 mm h^{-1} (McCredie, MO), and K_{eff} without bentonite = 183.6 mm h^{-1} (Novelty, MO) as input values.

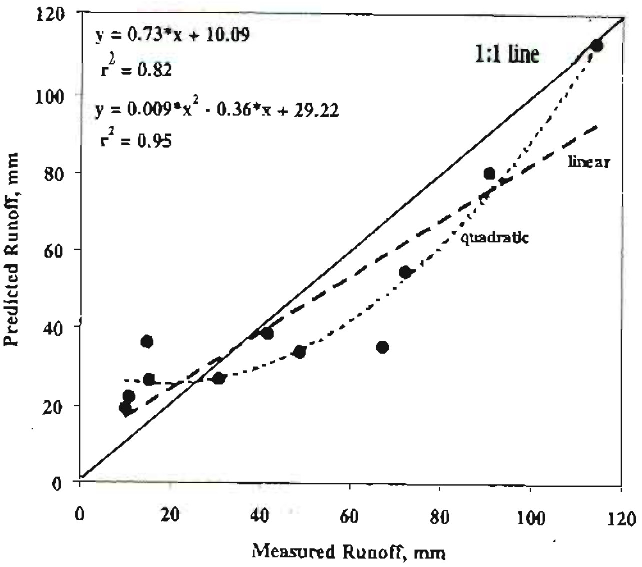

Fig. 3. Relationships between Water Erosion Prediction Project (WEPP) predicted runoff and measured runoff, using effective hydraulic conductivity (K_{eff}) as input computed from saturated hydraulic conductivity (K_{sat}) with bentonite determined on small 76-mm soil cores.

soils. The K_{eff} values for the surface 300-mm depth are: Blanco (with bentonite) = 1.3 mm h^{-1}, Doll = 2.7 mm h^{-1}, Blanco (without bentonite) = 3.4 mm h^{-1}, Baer and Anderson = 5.4 mm h^{-1}, Zeng = 8.2 mm h^{-1}, and McGinty = 183 mm h^{-1}. Prediction results show runoff to vary greatly in response to changes in K_{eff} input. The K_{eff} of the other studies is significantly higher than the K_{eff} with bentonite and underestimated the observed runoff. As expected, higher K_{eff} values produce lower predicted runoff. Figure 2 compares the measured runoff with the predicted runoff using the K_{eff} with and without bentonite (McCredie, MO), and the highest K_{eff} (Novelty, MO) reported by McGinty. The effect on WEPP predicted runoff of using an K_{eff} without bentonite measured at 40-mm runoff was 29 mm versus about 39 mm when using an K_{eff} with bentonite. This indicates that the use of K_{eff} without bentonite underestimated the runoff by 28% at a measured runoff of 40 mm. Use of K_{eff} value calculated from cores with bentonite most closely correlated with the observed runoff (Fig. 2). This is attributed to the fact that K_{sat} measured with bentonite excluded macropore flow through continuous macropores in small cores and thus better reflected the in situ conditions where the water flow in macropores is reduced when the soil is saturated.

Figure 3 shows the relationship between WEPP predicted using K_{eff} with bentonite as input versus measured runoff. It was expected that a linear relationship would be found but there was a significant quadratic relationship (r^2 = 0.95). The quadratic behavior is probably due to (i) spatial and temporal variability of K_{eff}, (ii) dependence of K_{eff} on rainfall amount and intensity, (iii) variable satiated initial conditions, and (iv) effect of the underlying argillic horizons on runoff. Three points in the WEPP predicted runoff emerge in Fig. 3. The WEPP model (i) overpredicted the runoff in the low range, (ii) underpredicted runoff in the medium range, and (iii) performed well in the high range of measured runoff. These results highlight that selection of K_{sat} has a great impact on runoff prediction. Previously collected K_{sat} data cited above all underpredicted runoff when compared with measured values.

This highlights the need for researchers to use caution when using K_{sat} data as model input without field validation. Model users need to consider both the variability of K_{sat} data associated with a specific soil location and understand how the method of determination may influence its value. The K_{sat} data determined on small soil cores with bentonite predicted runoff satisfactorily, indicating that the use of bentonite to plug macropores is advisable. The core K_{sat} values with bentonite were not significantly different from in situ K_{sat} values because the bypass flow through the visible pores (>1 mm diam.) in the small cores was eliminated. The K_{eff} values without bentonite were 160% higher than K_{eff} values with bentonite. The use of bentonite was useful to approximate the core K_{sat} to in situ K_{sat}.

The sensitivity index for the WEPP results reflects the change in runoff with respect to change in K_{eff}. It was the greatest (0.25) for the highest K_{eff} reported by McGinty indicating that for a 100% increase in K_{eff}, runoff would be increased by 25%. The sensitivity values of other studies were: 0.10 for Zeng, 0.08 for Baer and Anderson, 0.07 for Blanco (without bentonite), 0.05 for Doll, and 0.04 for Blanco (with bentonite). This last sensitivity value was obtained using in situ K_{sat} values for comparison. Predicted runoff was sensitive to changes in K_{eff}, indicating that K_{sat} is a critical parameter for obtaining accurate runoff estimates (Fig. 2). Indeed, Flanagan and Nearing (1991) stated that hydraulic conductivity is one of the most sensitive soil input parameters in predicting runoff. Consequently, model users should be cautious in using estimated K_{sat} without proper evaluation of its accuracy.

As suggested by Kutilec and Nielsen (1994), use of a pedotop-scale model will likely improve K_{sat} estimation for use as model input by accounting for some of the spatial variability in K_{sat} (the pedotop-scale consists of a surface area overlying similar soil REV units typically totaling from 100 to 1000 m^2 in size). Laboratory K_{sat} of small cores should only be regarded as a rapid approximation of field conditions rather than a representative measure of the pedotop K_{sat}. Careful consideration of measurement method, presence of biochannels, natural variations in soil depth, and use of pedotop scaling should be pursued to improve the K_{sat} estimation.

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