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Green-Ampt Infiltration Parameters in Riparian Buffers

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Abstract. Riparian buffers can improve surface water quality by filtering contaminants from runoff before they enter streams. Infiltration is an important process in riparian buffers. Computer models are often used to assess the performance of riparian buffers. Accurate prediction of infiltration by these models is dependent upon accurate estimates of infiltration parameters. Of particular interest here are Green-Ampt infiltration parameters, satiated hydraulic conductivity (K_o) and wetting front suction (h_f). The objectives of this research were to (i) modify the Smith sorptivity procedure so that it can be used to estimate Green-Ampt infiltration parameters, (ii) Determine the relative closeness of K_o estimated by the inverse sorptivity and inverse Green-Ampt procedures and h_f estimated by Rawls and Brakensiek (1985) to the laboratory-determined standards and (iii) Compare K_o estimates of the inverse sorptivity and inverse Green-Ampt procedures to those estimated by pedotransfer functions. This project was conducted at six sites in Nebraska, at which soil type and land use varied. The results of this study suggest that the inverse Green-Ampt procedure can be used to provide K_o estimates, even in the presence of macropores. Generally, pedotransfer function predictions did not estimate K_o well. Finally, h_f as predicted by pedotransfer function was lower than laboratory-determined h_f. These predicted infiltration parameters were used in the Green-Ampt infiltration equation to illustrate their effect on cumulative infiltration. Cumulative infiltration based on the inverse Green-Ampt procedure parameters resulted in the closest match to cumulative infiltration prediction from laboratory-based infiltration parameters at five of the six sites.

Keywords. *buffers, Green-Ampt, infiltration, infiltration parameters, macropores*

Introduction

Riparian buffers, perennial vegetation between agricultural and urban areas and streams, can improve water quality by filtering contaminants from the runoff water (Dosskey et al., 2001). Infiltration is an important process in buffers because it lowers the sediment transport capacity of overland runoff, which results in sediment deposition (Munoz-Carpena, 1993). Infiltration also removes a portion of the soluble contaminants from the overland runoff (Bingham et al., 1980).

Computer models are often used to assess the performance of riparian buffers. The Vegetative Filter Strip Model (Munoz-Carpena et al., 1999) and the Riparian Ecosystems Management Model (Lowrance et al., 2000 and Inamdar et al., 1999) use the Green-Ampt equation (Green and Ampt, 1911 and Mein and Larson, 1973) for infiltration prediction. Obviously it is important to have good estimates of the parameters for the Green-Ampt equation when using these models. These parameters must be representative of the conditions in a buffer, which, due to the perennial vegetation, can include the effect of macropores (Bharati et al., 2002) on soil hydraulic properties.

The key parameters for the Green-Ampt equation are the satiated or field saturated hydraulic conductivity (K_o) and the wetting front suction (h_f). K_o can either be estimated using pedotransfer functions (PTFs) or through measurement with laboratory or field techniques. Wetting front suction can also be estimated by PTFs or inferred from another measured soil property, the hydraulic conductivity function (Neuman, 1976). PTFs circumvent direct measurement of soil hydraulic properties by using more easily measured soil physical properties such as particle size and bulk density (Elsenbeer, 2001). Rawls and Brakensiek (1985), Rawls et al. (1998), and Schaap et al. (2001) presented several PTF approaches . Laboratory and field techniques for determining soil hydraulic properties are given by Klute (1986), Klute and Dirksen (1986), Topp et al. (1992), and Dane and Topp (2002). Of interest here, is the use and modification of a relatively simple technique for measuring soil sorptivity developed by Smith (1999). When applied in conjunction with PTF estimates of h_f, the technique potentially could be used to estimate Green-Ampt equation parameters.

Sorptivity is a function of saturated hydraulic conductivity (K_s), initial and saturated water contents (θ_i and θ_s, respectively), and h_f as presented in the following equation (Youngs, 1964)

$$S^2 = 2 \cdot h_f \cdot K_s \cdot (\theta_s - \theta_i) \tag{1}$$

where S is sorptivity (cm/s$^{1/2}$). At early times of infiltration from an instantly ponded surface, cumulative infiltration (I) reduces to

$$I = St^{1/2} \tag{2}$$

where t is the time of infiltration (s). With Smith's technique sorptivity measurements take only a few minutes.

To run the test, a known volume of water (equivalent to 1-2 cm of depth) is added to an infiltration ring. The elapsed time to infiltrate the known volume is recorded. Since the test is short-term the soil water flow is retained within the ring and thus is one-dimensional vertical.

Research Hypothesis and Objectives

Because of the importance of infiltration in buffers it is imperative to have good estimates of infiltration parameters as inputs to the buffer models. Further, methods that are relatively inexpensive, time efficient, and accurate are necessary to implement these models. Our interest in this research is the estimation of Green-Ampt infiltration parameters in areas with perennial vegetation, especially where needed for modeling the hydrology of riparian buffers. It is likely that under these conditions, macropores may be present in the soil profile. One hypothesis is that the Smith (1999) sorptivity procedure can be modified to estimate Green-Ampt infiltration parameters for sites that have long-term perennial vegetation. A second hypothesis is that the two modified procedures, called the inverse sorptivity and inverse Green-Ampt procedures, will provide better estimates of the Green-Ampt infiltration parameters than do the Rawls and Brakensiek (1985), Rawls et al. (1998), and ROSETTA (Schaap et al., 2001) PTF approaches.

The objectives of the research were to:

- Modify the Smith sorptivity procedure so that it can be used to estimate Green-Ampt infiltration parameters.
- Compare K_o estimated by the inverse sorptivity and inverse Green-Ampt procedures and h_f estimated by Rawls and Brakensiek (1985) to values obtained by standard laboratory methods.
- Compare K_o estimates of the inverse sorptivity and inverse Green-Ampt procedures to those estimated by PTFs.

Materials and Methods

We conducted the field experiments starting in the fall of 2000 and completed them in the fall 2003. Data collection sites were in central and southeastern Nebraska (Table 1). The sites were selected because of their variation in soil type and land use.

Table 1. Summary of sorptivity test sites.

Site	Location	Soil series	Surface soil texture	Vegetation	Land use at site	Year sampled
Clear Creek 1	Polk County: S of Platte River near Silver Creek, NE	Hord	silt loam	warm season grass mixture*	grass filter planted in 1999	2000
Clear Creek 2	Polk County: S of Platte River near Silver Creek, NE	Alda and Cozad	clay loam/ silty clay loam	reed-canary grass	grass filter, 30-yr old	2001
Gudmundsen Ranch	Hooker County: NW of Mullen, NE	Valentine	sand	Sand Hills Prairie	rangeland	2002
Otoe County 1	Otoe County: NE of Burr, NE	unnamed sand spot	sandy loam	smooth brome grass	Conservation Reserve Program (smooth brome since 1958)	2002
Otoe County 2	Otoe County: NE of Burr, NE	Pawnee	clay loam	smooth brome grass	Conservation Reserve Program (13 yrs)	2002
Rogers Farm	Lancaster County: East of Lincoln, NE	Judson and Kennebec	silt loam	warm season grass mixture*	grass filter, planted in 1998	2001
				deciduous forest	native riparian forest	

* mixture included big bluestem, Indian grass, and switchgrass

Field Infiltration and Soil Sample Collection

At each of the six sites the modified Smith (1999) sorptivity procedure was conducted, soil samples were taken for initial moisture content, and undisturbed samples were collected for lab analysis of the water retention curve, satiated hydraulic conductivity, particle size analysis, and bulk density. We collected 24 samples from each site.

Rings of inside diameter 14.88 cm and length of 15 cm were driven vertically into the ground so that approximately 10 cm of the ring extended into the soil. To minimize disturbance of the soil surface when water was added to the ring, a porous protective covering (geofabric or coffee filter) was placed on the soil surface. Next, 174 mL of water was poured into the ring, a volume equaling a 1 cm depth distributed across the area of the ring. If it seemed that 1 cm would infiltrate too rapidly for precise measurement of elapsed time, another 1 cm was added. After water application, the protective covering was removed. Recorded measurements included cumulative infiltrated depth of water, the time when approximately half of the ground surface was exposed (no longer inundated with water), and water temperature. Soil samples were collected just outside of the sorptivity ring in a cylinder with inside diameter of 5.4 cm and length 3 cm. These samples were used to determine initial water content and bulk density.

After the sorptivity tests had been conducted, the rings were covered and the soil was allowed to drain for a couple of days. Undisturbed soil samples were collected from inside the sorptivity ring and contained in a ring with an inside diameter of 8.25 cm and a length of 7.5 cm.

The intent of Smith's procedure is estimation of sorptivity. The modified procedures, inverse sorptivity and inverse Green-Ampt procedures, go one step further and use the collected data to estimate K_o and h_f.

Sorptivity was calculated using a rearrangement of Equation (2). The sorptivity values were corrected to a standard temperature of 20°C. K_o is estimated by rearrangement of equation (1), the inverse sorptivity procedure. h_f was estimated from porosity, percent clay, and percent sand using Table 1 in Rawls and Brakensiek (1985). Initial water content was based on field collected samples, and satiated water content was taken as 0.9 times the porosity. In the Rawls and Brakensiek Equation (1985) porosity was equal to 90% of the maximum theoretical porosity for the measured bulk density.

K_o is estimated by the inverse Green-Ampt procedure using the Green-Ampt infiltration equation (Clothier and Scotter, 2002).

$$K_o = \frac{1}{t} \cdot \left[I - \Delta\theta \cdot h_f \cdot \ln\left(1 + \frac{I}{\Delta\theta \cdot h_f}\right)\right] \qquad (3)$$

where $\Delta\theta$ is $\theta_o - \theta_i$ and θ_o is the satiated water content.

The inverse solutions, sorptivity and Green-Ampt, treat the media as one domain, even with presumed macropore flow. Mohanty et al. (1997) also followed this approach.

Five other estimates of K_o were determined using Rawls and Brakensiek (1985), Rawls et al. (1998), ROSETTA (Schaap et al., 2001), Rawls and Brakensiek (1985) with rangeland correction factor, and Rawls et al. (1998) with rangeland correction factor.

Laboratory and PTF Analysis

Laboratory tests were performed on the soil samples in the Biological Systems Engineering Soil and Water Properties Laboratory. Soil bulk density, soil water retention, and K_o were measured. The multi-step outflow method (ASTM, 1968) was used to measure retention at capillary pressures of 1 kPa, 4 kPa, 10 kPa, and 33 kPa. Additionally, retention was measured at 60 kPa for Clear Creek 2 and Rogers Farm samples. In order to complete the retention curve, estimates of water content at capillary pressure heads of 60 kPa, 100 kPa, 200 kPa, 400 kPa, 700 kPa, and 1000 kPa were calculated from Rawls et al. (1982). Complete saturation was not preferred; instead the goal was field imitated conditions, or satiation.

Satiated conductivities were determined using the falling head method (Amoozegar and Dirksen, 1986; ASTM, 1990). Four to five pore volumes of water were allowed to flow through the cores before conducting a test. During this test, 7 cm of water, or the approximate length of the soil core, flowed through the soil (ASTM, 1990). The water temperature was also recorded and used to correct hydraulic conductivity measurements to 20°C.

Thermocouple psychrometry was used to find the water content at a capillary pressure head of 1500 kPa, or approximately wilting point.

Laboratory tests were not performed on all soil cores from each site because of biological activity from earthworms and loose soil structure, in which the sample did not maintain its structure within the soil cylinder for testing.

Soil samples were sent to a private laboratory for analysis of percent sand, silt, and clay and organic matter. These data were utilized in PTF estimates of K_s. Three PTF estimates were included. Rawls and Brakensiek (1985), Rawls et al. (1998), and ROSETTA (Schaap et al., 2001). K_s was calculated from Rawls and Brakensiek (1985) Table 1.

Another equation from Rawls et al. (1998),

$$K_s = C\Phi_e^{3-\lambda} \tag{4}$$

where *C,* empirically derived constant, 1930; Φ_e, effective porosity (porosity minus water content at –33 kPa); and λ*,* Brooks and Corey pore size distribution, which is also found in Rawls and Brakensiek (1985) Table 1. The water content at –33 kPa needed in Equation (4) was estimated from Rawls et al. (1982). ROSETTA was the third PTF that was used. Soil textural information, percent sand and clay, and bulk density were used for prediction of the K_s by ROSETTA.

Rangeland Correction Factor

Rawls et al. (1989) developed a procedure for predicting infiltration of rangeland soils and correction factors that account for macroporosity. The adjusted conductivity, KE, is given by the equation

$$KE = (CF)\left[\left(\frac{BC}{CAN}\right)(CRC) + A\left(1-\left(\frac{BC}{CAN}\right)\right)\right](K) \tag{5}$$

where *CF*, canopy factor; *BC* , bare area under canopy (%); *CAN*, canopy area (%); *CRC,* crust factor; *A*, macroporosity factor; and *K*, hydraulic conductivity of the soil (cm/hr). The factor A, the macroporosity adjustment, is shown below:

$$A = EXP(2.82 - 0.099 \cdot SA + 1.94 \cdot BD) \tag{6}$$

where SA is % sand and BD is bulk density. The Rawls and Brakensiek (1985) and Rawls et al. (1998) K_o estimates were adjusted by estimating factors included in Equation (5).

A comparison of texturally-estimated and laboratory-measured wetting front suction was made. The texturally-estimated wetting front suction was estimated using Rawls and Brakensiek (1985). The laboratory-measured wetting front suction was determined based on the soil water retention curve as measured in the laboratory. The water retention functions were modeled with the Brooks and Corey equation (Brooks and Corey, 1966). Using the parameters from the Brooks and Corey (1966) equation the wetting front suction was estimated using the following equation from Rawls et al. (1982):

$$h_f = \frac{h_{ce}}{2}\left(\frac{2+3\lambda}{1+3\lambda}\right). \tag{7}$$

where h_{ce} is the capillary entry pressure head (cm).

Tension Infiltrometer Measurements

Tension infiltrometer tests were conducted in October, 2003, at the Rogers Farm to confirm the presence of macropores. A total of 12 tests were conducted, six in the grass filter and six in the forest. The tension infiltrometers have an ~8 cm diameter base covered with nylon mesh and a 42 cm tall water reservoir, which is connected to the bubbling tower.

The infiltration of the water was measured by recording the rate of drop of water in the reservoir. Measurements were taken starting with the highest tension, 10 cm. Water level readings were taken until a quasi-steady state infiltration rate was reached. The methods of Watson and Luxmoore (1986), Reynolds and Elrick (1991), and Dunn and Phillips (1991) were used to quantify macroporosity. The number of macropores per unit area and percent total conductivity were calculated.

Results and Discussion

The range of field conditions and soil textures tested in this study are summarized (Table 2).

Table 2. Summary of field conditions and soil information means for each site.

	Field experiment conditions		Soil textural information					
	θ_i (cm^3/cm^3)	**Water temperature (°C)**	**% sand**	**% silt**	**% clay**	**texture**	**% organic matter**	**bulk density (g/cm^3)**
Clear Creek 1	0.18	4-9	30	48	22	silt loam	2.3	1.4
Clear Creek 2	0.20	36	43	30	27	clay loam/ silty clay loam	3.4	1.2
Gudmundsen	0.0080	24	94	3	3	sand	0.73	1.4
Otoe County 1	0.10	36	68	17	15	sandy loam	1.6	1.5
Otoe County 2	0.11	43	34	37	29	clay loam	2.8	1.3
Rogers Farm	0.18	36	21	56	23	silt loam	4.5	1.1

The K_o data for each method are compared to laboratory K_o for two sites in Figures 1 and 2 and for all sites in Table 3.

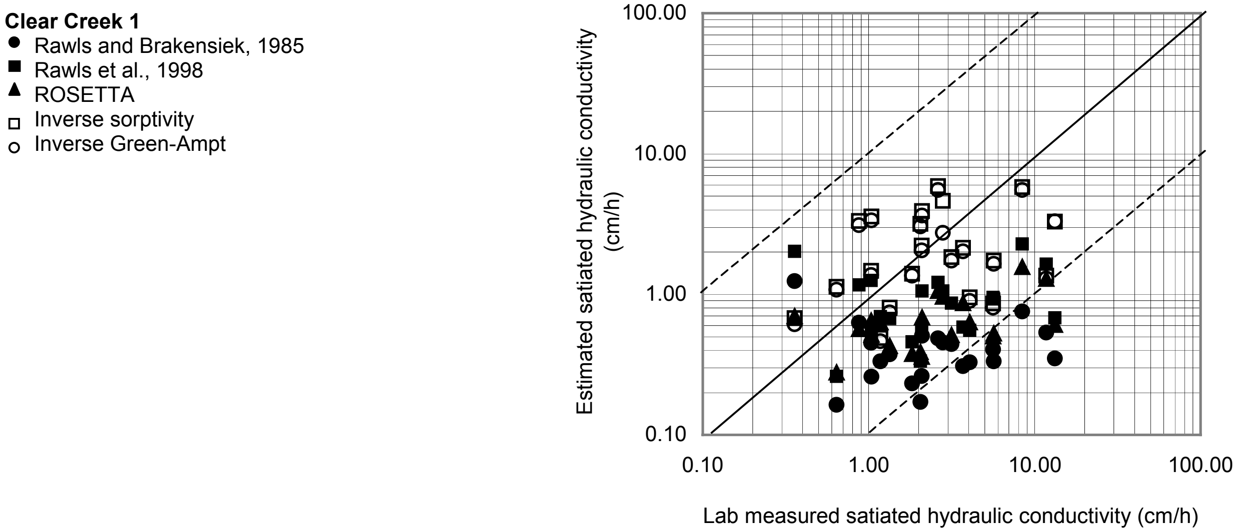

Figure 1. Comparison of laboratory-measured K_o values at Clear Creek 1 to each of four other estimates: Rawls and Brakensiek (1985), Rawls et al. (1998), ROSETTA, inverse sorptivity procedure, and inverse Green-Ampt procedure.

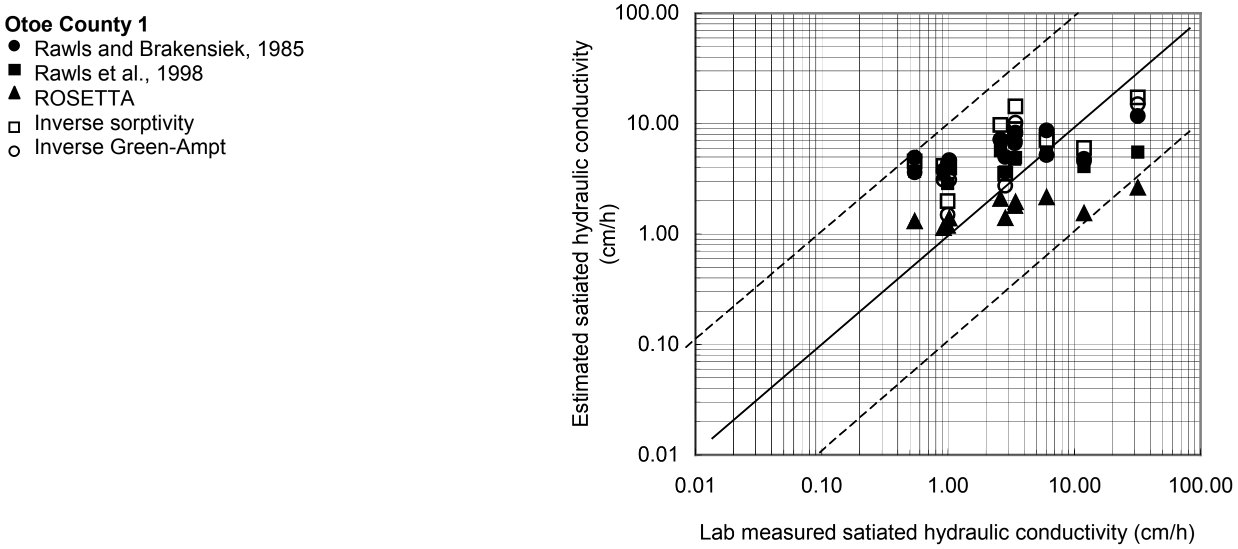

Figure 2. Comparison of laboratory-measured K_o values at Otoe County 1 to each of four other estimates: Rawls and Brakensiek (1985), Rawls et al. (1998), ROSETTA, inverse sorptivity procedure, and inverse Green-Ampt procedure.

Table 3. Summary of mean K_o values for each site and method. Also included are values, mean ± 1 standard deviation.

		Geometric Mean K_o (cm/h) (± 1 standard deviation)					
Location	**No. of points at each location**	**Lab**	**Rawls and Brakensiek, 1985**	**Rawls et al., 1998**	**ROSETTA**	**Inverse sorptivity**	**Inverse Green-Ampt**
Clear Creek 1	21	2.4 (0.93-6.1)	0.38 (0.24-0.61)	0.81 (0.47-1.4)	0.60 (0.39-0.92)	1.9 (0.93-3.9)	1.8 (0.87-3.5)
Clear Creek 2	8	13 (0.95-170)	2.7 (0.94-7.7)	2.9 (1.3-6.2)	1.6 (0.79-3.4)	60 (19.5-190)	49 (16-150)
Gudmundsen Ranch	12	11 (7.3-17)	46 (39-54)	16 (14-18)	29 (25-33)	20 (12-32)	13 (8.2-21)
Otoe County 1	11	2.9 (0.85-9.6)	6.0 (4.2-8.6)	4.3 (3.4-5.3)	1.6 (1.2-2.1)	6.2 (3.2-11.8)	4.7 (2.4-9.1)
Otoe County 2	10	8.4 (3.4-21)	0.6 (0.39-0.93)	1.3 (0.96-1.9)	0.70 (0.58-0.83)	2.7 (1.4-4.9)	2.4 (1.3-4.4)
Rogers Farm	16	21 (7.6-61)	0.73 (0.47-1.2)	1.8 (1.0-3.2)	2.1 (1.3-3.3)	27 (8.3-86)	24 (7.4-76)
Total:	84						
Weighted geometric mean:		5.7	1.4	2.0	1.7	8.5	7.2
Ratio of method mean to lab mean:		-	0.25	0.35	0.30	1.5	1.3

* *mean ± 1 std. dev.* = $10^{\left(\log_{10}\bar{y} \pm s_y\right)}$

$\bar{y}$ = geometric mean K_o (cm/h)

s_y = standard deviation of the $\log_{10}$-tranformed K_o

Satiated hydraulic conductivities as estimated from inverse sorptivity and inverse Green-Ampt procedures, are in better agreement with the laboratory-measured data than the PTF methods. For example, across all the sites the percent difference from the laboratory-measured was 50% and 26% for inverse sorptivity and inverse Green-Ampt, respectively. There is high variability, sometimes orders of magnitude, in measurements of K_o, even at the same location and soil type as shown in Figures 1 and 2. The estimated values of conductivity from the two field methods fall relatively uniformly across the 1:1 comparison line for Clear Creek 1 and Otoe County 1. Most of the K_o predictions fall within the order of magnitude lines. Similar results were found for the other three sites. K_o estimates resulting from PTFs are generally lower than that of laboratory-measured. Rawls et al. (1998) appears to have performed the best of PTF methods.

A two-way analysis of variance (ANOVA) was conducted on conductivity data that was pooled from all sites. The two experimental factors varied were: site and method of K_o prediction. The two-way ANOVA was conducted using log-transformed values of K_o because conductivity is commonly log-normally distributed (Watson and Luxmoore, 1986).

The P values for site and method were < 0.001 indicating that there is a difference among sites and also among methods. A statistical comparison was made between the standard, lab-measured, K_o and other estimates of K_o (Table 4). The data suggests that that both the inverse sorptivity and inverse Green-Ampt procedures are the best alternatives to laboratory-measured data under varying soil and vegetative conditions. However, the inverse sorptivity procedure was in violation of the scaled infiltration depth criteria (Smith, 1999), $I/h_f\Delta\theta$, <0.1, at five of the six data collection sites. The Rawls et al. (1998) PTF may be an alternative method for predicting K_o if field testing is not possible. However, on average, it predicted K_o 70% lower than measured in the laboratory.

Table 4. Summary of statistical results from two-way ANOVA conducted using pooled log K_o.

	Site						
Method vs. laboratory-measured	**Clear Creek 1**	**Clear Creek 2**	**Gudmundsen Ranch**	**Otoe County 1**	**Otoe County 2**	**Rogers Farm**	**Fraction not different***
Green-Ampt	no	yes	no	no	yes	no	4/6
Inverse sorptivity	no	yes	no	no	yes	no	4/6
Rawls and Brakensiek, 1985	yes	yes	yes	no	yes	yes	1/6
Rawls et al., 1998	yes	yes	no	no	yes	yes	2/6
ROSETTA	yes	yes	yes	no	yes	yes	1/6
passed normality:	x	x			x		
passed equal variance:		x				x	

yes = significant difference between lab measured and estimated K_o

no = no significant difference between lab measured and estimated K_o

*Fraction not different means the proportion of sites where the methods did not differ statistically (P<0.01) from lab measured

A comparison was also made between the laboratory-measured K_o and the rangeland adjusted factor values for Rawls and Brakensiek (1985) and Rawls et al. (1998) (Table 5). Based on these results, the rangeland adjustment factor applied to Rawls and Brakensiek (1985) and Rawls et al. (1998) brings the estimated K_s closer to the laboratory-measured value in most cases. The geometric mean for all sites shows that the adjustment to Rawls and Brakensiek (1985) is only slightly closer to laboratory-measured value than Rawls et al. (1998).

Prior to adjustment, Rawls and Brakensiek (1985) under predicted K_s on average by 75 percent, while after adjustment; on average it over predicted K_s by 72 percent. However, use with Rawls et al. (1998) K_o estimates was questionable because it was developed later than the rangeland adjustment factor.

Table 5. Summary of rangeland adjustment factors and estimated K_s.

	Clear Creek 1	Clear Creek 2	Gudmundsen Ranch	Otoe County 1	Otoe County 2	Rogers Farm
Rawls and Brakensiek, 1985, K_s (cm/h)	0.38	11	46	6.0	0.60	0.75
Rawls et al., 1998, K_s (cm/h)	0.81	4.3	16	4.3	1.3	1.4
Adjusted Rawls and Brakensiek, 1985, K_s (cm/h)	9.7	53	32	4.9	6.5	26
Adjusted Rawls et al., 1998, K_s (cm/h)	21	21	11	4	14	49
Laboratory-measured K_o (cm/h)	2.4	35	11	2.9	8.4	29

Brooks and Corey parameters from water retention data were determined using non-linear regression. In most instances, estimated values of h_f were lower than laboratory determined h_f values and on average were 52% lower (Table 6). This affects the results of K_o as calculated by the inverse sorptivity and inverse Green-Ampt procedures. If estimated values of h_f are lower than actual (laboratory determined) h_f values, K_o estimates will tend to be too high. This held true for the K_o values for inverse sorptivity and inverse Green-Ampt in this study.

Table 6. Geometric mean values for both laboratory determined and estimated h_f at each site. Also included are values, geometric mean ± one standard deviation.

		Geometric Mean (mean ± 1 standard deviation)	
Location	**No. of points at each location**	**Laboratory determined h_f**	**Rawls and Brakensiek, 1985, h_f**
Clear Creek 1	21	46 (34-63)	37 (31-45)
Clear Creek 2	8	60 (36-98)	15 (9.8-23)
Gudmundsen	12	13 (9.9-17)	4.7 (4.4-5.0)
Otoe County 1	11	35 (28-44)	8.8 (7.8-10)
Otoe County 2	10	44 (35-54)	27 (23-33)
Rogers Farm	16	62 (45-83)	30.95 (27-36)
Total:	84		
Weighted geometric mean:		42	20

Statistical analysis was performed to detect significant differences between laboratory determined and estimated h_f. Also like K_o, h_f is usually log-normally distributed (Brakensiek et al., 1981). Therefore, the data for all sites was pooled and a one-way ANOVA conducted on the log-transformed values of h_f. According to the pooled results, there were significant differences ($P<0.001$) between the laboratory-determined and estimated values.

Tension Infiltrometer

Tension infiltrometer tests can be used to estimate macroporosity (Dunn and Phillips, 1991; Reynolds and Elrick, 1991; and Watson and Luxmoore, 1986). An objective of this research was to develop a method based on field collected data that would estimate Green-Ampt infiltration parameters, K_o and h_f, even in the presence of macropores. Therefore, it was important to confirm that macropore flow occurred at least at one site where data were collected. The number of macropores per unit area and the percent total conductivity flowing through macropores are used as indicators of macropore flow. Watson and Luxmoore (1986) found that most of the ponded water flux was conducted through pores >0.1 cm diameter, which corresponds to 3 cm tension and are considered macropores.

Pores in the 0-3 cm tension range contributed significantly to the percent of total conductivity (Table 7). When the media is saturated, approximately 46% of the flow in the grass filter area and 40% of the flow in the forested area, occurs through pores associated with this tension interval. In work by Watson and Luxmoore (1986) and in work done by Clothier and White (1981), as reported in Watson and Luxmoore (1986), 48% and 73 % respectively, of saturated flow occurred in the 0-3 cm tension range at a site that they considered to have macroporosity.

Table 7. Macroporosity parameters estimated from tension infiltrometer data.

Grass filter area

Tension, cm water	No. of samples	Pore radius, cm	Number of pores per m^2	Percent of conductivity
0-3	6	>0.05	286	46
3-6	6	0.025-0.05	1300	11
6-10	6	0.015-0.025	2400	2

Riparian forest area

Tension, cm water	No. of samples	Pore radius, cm	Number of pores per m^2	Percent of conductivity
0-3	6	>0.05	347	40
3-6	6	0.025-0.05	4525	15
6-10	6	0.015-0.025	2.73×10^4	23

Based on these results and the criteria observed in the literature, macroporosity is present at the Rogers Farm site.

Implications of Improved K_o Estimation on Riparian Buffer Models

To quantify the effect of the estimates of K_o and h_f on infiltration, we used the Green-Ampt equation (Green and Ampt, 1911) to compute cumulative infiltration on hourly intervals up to six hours. We did this for four parameter estimation methods, the laboratory, inverse Green-Ampt, Rawls and Brakensiek (1988), and ROSETTA. In order pool the results from all six field sites, the cumulative infiltration at one-hour intervals was normalized relative to the cumulative six-hour infiltration at each site. This results in a normalized infiltration of unity at six-hours at all sites.

The normalized infiltration (cumulative) curves for each method are shown in Figure 3. The results illustrate that the closest prediction to the laboratory-based prediction is the inverse Green-Ampt procedure with the six-hour infiltration being 15 percent high on the average. The mean ROSETTA based prediction was approximately 50 percent low and the mean Rawls and Brakensiek (1998) prediction was about 70 percent low.

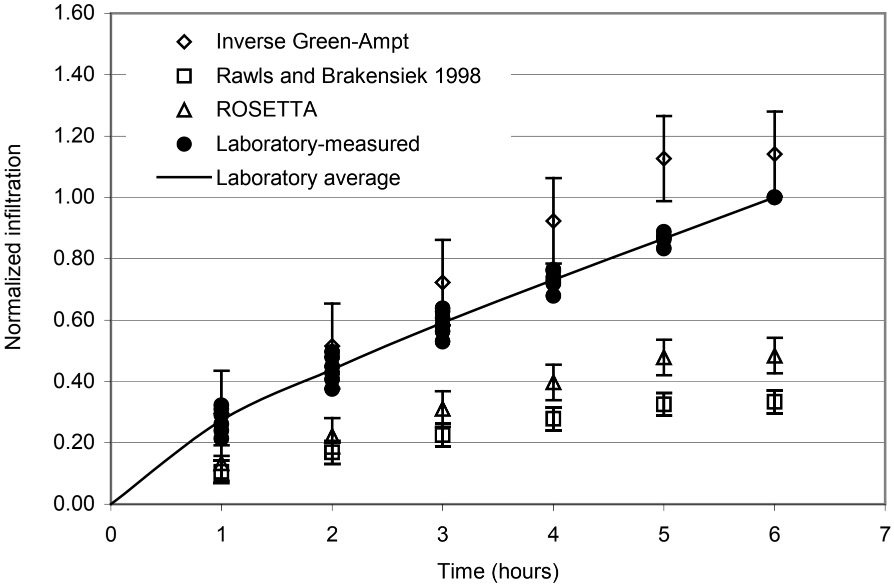

Figure 3. Normalized infiltration (cumulative) for four of the parameter estimation methods based on data from all six field sites. Bars indicate ± standard error from the mean.

Conclusion

Relatively good estimates of infiltration parameters are needed to predict infiltration in vegetative filter and riparian buffer models such as VFSMOD and REMM. In this study, Green-Ampt infiltration parameters for sites that had perennial vegetation, were estimated by several procedures. Procedures to estimate K_o included two field infiltration methods; the inverse sorptivity and inverse Green-Ampt, and four PTF methods.

Two modifications were made on the Smith (1999) procedure, resulting in two procedures for predicting Green-Ampt parameters: the inverse sorptivity and inverse Green-Ampt procedures. Estimates resulting from the inverse Green-Ampt procedure were relatively good. K_o was also predicted using PTFs. These estimates were compared to laboratory-measured, inverse sorptivity, and inverse Green-Ampt estimates. In general, the PTFs underestimated K_o.

Comparisons were also made between laboratory determined and Rawls and Brakensiek (1985) estimated values of h_f.

Since vegetative filters and riparian buffers contain perennial vegetation, it is likely that the soils in these areas have good structure and contain some macropores. Tension infiltrometer tests were conducted at the Rogers Farm site to confirm the presence of macropores. Conclusions based on the results of this study are:

- The inverse sorptivity and inverse Green-Ampt procedures resulted in relatively good estimates of K_o, even in the presence of macropores.
- In general, PTF predictions did not predict K_o well, with the exception of Rawls et al. (1998), which gave relatively good K_o predictions overall, but was statistically significantly different than the laboratory standard at four of the six sites.
- The Rawls and Brakensiek (1985) PTF estimate of h_f was statistically significantly lower than laboratory-based h_f.

- Infiltration that was predicted using parameters from the inverse Green-Ampt procedure were the closest match to the infiltration prediction from laboratory-based parameters.

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