TRANSIENT SOIL SURFACE SEALING AND INFILTRATION MODEL FOR BARE SOIL UNDER DROPLET IMPACT

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ABSTRACT. *The marked reduction in infiltration rate caused by formation of a soil surface seal due to water droplet impact on bare soil is a well known phenomenon but is rarely considered in infiltration models, especially under center-pivot irrigation. Water application rates under center-pivot irrigation commonly exceed the infiltration rate, especially near the end of the system lateral. This can lead to off-site runoff and erosion, but more importantly results in field-scale non-uniform water infiltration that can substantially reduce water use efficiency of these irrigation systems. The objective of this study was to develop a sealing soil infiltration model that considers transient soil seal formation on a 30 min or less time scale and can potentially be applied to center-pivot sprinkler irrigation systems. A sealing soil infiltration model was developed using an explicit finite difference solution scheme with a transient soil seal formation model, which is unique from other studies in that it explicitly uses droplet specific power as the driving factor for formation of a soil surface seal. The form of the transient seal formation model is also unique in that it is expressed as a rational function of specific power rather than an exponential decay function of droplet kinetic energy. The model was applied to published runoff data from two rainfall simulation studies with varying droplet kinetic energies and application rates on three soils. The sealing soil infiltration model represented the measured infiltration rates very well for all rainfall simulator tests. The transient soil seal formation model uses three parameters, one of which is an empirical parameter representing the susceptibility of the soil to aggregate breakdown that was constant for a given soil. A second model parameter, final saturated hydraulic conductivity of the surface seal, was well correlated to droplet specific power for a given soil. Application of the model to center-pivot irrigation will require the development of a model for estimating droplet specific power and application rate profiles from center-pivot sprinklers for a range of sprinkler designs, flow rates, operating pressures, spacings, and heights.*

Keywords. *Droplet impact, Infiltration, Kinetic energy, Rainfall, Runoff, Soil surface sealing, Specific power, Sprinkler irrigation.*

The marked reduction in water infiltration rate of bare soils caused by raindrop impact has been recognized for over a century and has been extensively documented and studied over the past 70 years. The decrease in water infiltration rate of soils under droplet impact was first investigated by Duley (1940), Borst and Woodburn (1942), and Ellison (1945). McIntyre (1958) was the first to measure saturated hydraulic conductivity of soil surface seals created by raindrop impact. He found that the saturated hydraulic conductivity of the formed seals was a function of the soil, applied water depth, and application rate. Seal saturated hydraulic conductivity was found to be two to three orders of magnitude less than for the underlying soil. Moldenhauer and Long (1964) found that infiltration rate was a function of soil properties, kinetic energy of the water drops, and application intensity. They found that time for runoff to begin was a function of cumulative kinetic energy applied to the soil. Morin and Benyamini (1977) studied the effect of droplet impact on infiltration rate of a bare soil and found that for a constant kinetic energy per unit volume of water applied, infiltration rate could be reliably modeled using an exponential decay function similar to the Horton (1941) infiltration equation, with the exponential decay expressed as a function of cumulative depth of water applied. Studies of Edwards (1967), Mannering (1967), Sharma (1980), Baumhardt (1985), Mahamad (1985), Thompson and James (1985), and Betzalel et al. (1995) have demonstrated the influence that droplet kinetic energy and water application rate have on infiltration rate into bare soils.

Studies documenting the significant effect that water droplet impact has on the infiltration rate of bare soils led to the development of empirical models representing the transient nature of the saturated hydraulic conductivity of soil surface seals during a rainfall event. In general, these models expressed hydraulic resistance or saturated conductivity of the seal layer as an exponential decay function of time or applied droplet kinetic energy (Farrell and Larsen,

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1972; van Doren and Allmaras, 1978; Linden, 1979; Moore et al., 1981; Brakensiek and Rawls, 1983; Bosch and Onstad, 1988; Baumhardt et al., 1990). The models all include three or more parameters that need to be estimated from simulated rainfall infiltration experiments. These parameters have not been related to bulk soil properties to expand the models to other soils in general, with the exception of Brakensiek and Rawls (1983), who developed a crust factor to account for crusted soil infiltration with the Green and Ampt (1911) infiltration model. Assouline and Mualem (1997) proposed a physically based model for soil surface seal formation that accounted for the effects of raindrops on detachment of soil particles and aggregate destruction. Changes in seal hydraulic properties were modeled in terms of changes in the soil bulk density resulting from raindrop impact. The modeling approach resulted in several parameters that need to be calibrated for a particular soil. Augeard et al. (2007) used an inverse solutions approach to calibrate the model parameters from simulated rainfall infiltration experiments and x-ray bulk density measurements.

Numerous studies on modeling water infiltration into soil have been conducted over the past 40 years, resulting in two main physically based approaches to modeling infiltration. Studies concentrating on the dynamics of the infiltration process are generally based on numerical approximations to the Richards equation, and those concentrating on determining the volume of infiltration for an event use the Mein and Larsen (1973) interpretation of the Green and Ampt (1911) infiltration equation, designated hereon as GAML. Numerical solution of the Richards equation has been used by Moore (1981a), Baumhardt et al. (1990), Ruan et al. (2001), and Assouline and Mualem (2001) to investigate soil water content and matrix potential throughout the soil profile under soil sealing conditions. Various adaptations of the GAML equation have been used by Moore and Larson (1980), Moore (1981b), Ahuja (1983), Brakensiek and Rawls (1983), Rawls et al. (1990), and Alberts et al. (1993) to model infiltration under soil sealing conditions. Despite 30 years of research on incorporating soil surface sealing due to raindrop impact into infiltration modeling, few infiltration models incorporate transient soil surface sealing in estimating infiltration and runoff.

Nearly all of the research related to soil surface sealing has focused on rainfall conditions, but the same processes occur under sprinkler irrigation (von Bernuth and Gilley, 1985; Ben-Hur et al., 1995; Silva, 2006). Transient soil surface seal formation is especially important because the irrigation event may only last 20 to 30 min. Soil surface seal formation in combination with high water application rates under center-pivot sprinkler irrigation exacerbates the potential runoff and erosion hazard. Runoff under center-pivot sprinkler irrigation is a well recognized problem (Undersander et al., 1985; DeBoer et al., 1992; Hasheminia, 1994; Ben-Hur et al., 1995; Silva, 2006) but is normally unseen because runoff often infiltrates before exiting the field boundary, as only a small fraction of the field is irrigated (saturated) at a given time and/or runoff collects in low spots within the field.

The operational characteristics of center-pivot sprinklers such as wetted diameter, application rate pattern shape, and drop size distribution have been studied (e.g., Kincaid et al., 1996; Faci et al., 2001; DeBoer, 2001; Sourell et al., 2003; Playan et al., 2004; Kincaid, 2005). However, studies evaluating the effect that the operating characteristics of a particular sprinkler have on infiltration, runoff, and erosion of specific soil types are limited (Undersander et al., 1985; DeBoer et al., 1992; Silva, 2006; King and Bjorneberg, 2011). Area-weighted kinetic energy per unit volume of common sprinklers has been modeled by Kincaid (1996). King and Bjorneberg (2010) found that area-weighted kinetic energy does not represent the actual kinetic energy applied to the soil by irrigation sprinklers. They developed a methodology to calculate actual kinetic energy applied under center-pivot sprinkler irrigation. With the wide range in operating characteristics of center-pivot sprinklers currently available, the potential to select sprinklers that minimize runoff and erosion exist (King and Bjorneberg, 2011). However, data or models relating sprinkler operating characteristics to runoff and erosion for specific soil types are limited. Models relating potential runoff to sprinkler peak application rate have been developed by Dillion et al. (1972), Slack (1980), Gilley (1984), DeBoer et al. (1988), Allen (1990), Wilmes et al. (1993), and Martin et al. (2010). Based on the work of Gilley (1984), von Bernuth and Gilley (1985) developed a model for center-pivot sprinkler irrigation runoff that included infiltration rate reduction due to water drop impact on bare soil. The models currently available for estimating runoff under center-pivot irrigation do not account for the effect of soil surface sealing on infiltration. Thus, such runoff estimations are of limited value under actual field conditions of arid regions where sprinkler irrigation on bare soil is generally required for crop germination and establishment.

The objective of this study was to develop a soil infiltration model that incorporates transient reduction in soil surface seal hydraulic conductivity as affected by soil characteristics, droplet kinetic energy, and application intensity and that can potentially be used under center-pivot sprinkler irrigation.

Model Development

Soil and Infiltration Data

Data used to develop and evaluate the sealing soil infiltration model were obtained from Mahamad (1985) and Baumhardt (1985). Mahamad (1985) measured runoff from two *in situ* soils under simulated rainfall over a range of application rates and droplet kinetic energies per unit volume. The two soils were Vienna loam with 43% sand, 34% silt, and 23% clay and Lowry silt loam with 12% sand, 70% silt, and 18% clay. Plot areas were 2.1 × 3.0 m on freshly tilled soil smoothed by hand to a 2% slope with large clods removed to provide a visually uniform soil surface. Runoff plot area was 1.0 × 1.0 m within the prepared plot area. Resulting bulk density of the top 0.2 m of the soil profile was 1.05 Mg m^{-3}. Application rates ranged from 43 to 155 mm h^{-1}, and droplet energies ranged from 7.2 to 24.4 J m^{-2} mm^{-1}. Droplet energy of 0 J m^{-2} mm^{-1} was obtained by protecting the soil surface using screen material

Table 1. Soil hydraulic parameters used in the sealing soil infiltration model to predict infiltration under simulated rainfall for the three soils evaluated in this study.

Model Parameter	Soil: Vienna Loam	Lowry Silt Loam	Atwood Silty Clay Loam
Porosity	0.51	0.54	0.48
Residual moisture content (% volume)	1.3	1.1	0.1
Satiated moisture content (% volume)	41.0	43.3	39.7
Initial soil water potential (mm)	-2200	-3700	-1800000
Water entry head (mm)	-124	-373	-300
Brooks-Corey exponent (λ)	0.28	0.36	0.158
Satiated hydraulic conductivity[a] (mm h^{-1})	110.0	24.5	6.0

[a] Equal to K_i in equation 3 for a protected soil surface.

suspended directly above the soil surface. Rainfall simulation duration ranged from 60 to 90 min.

Baumhardt (1985) measured runoff from laboratory soil columns measuring 0.3 m tall and 0.35 m in diameter over a range of application rates and droplet kinetic energies per unit volume. The soil was an Atwood silty clay loam with 12% sand, 60% silt, and 28% clay. The soil was air-dried, sieved, and packed into the soil column to a density of 1.4 Mg m^{-3}. The columns were placed on a ramp with a 9% slope during rainfall simulation. The rainfall simulator produced droplets with kinetic energies of 20.0 and 27.5 J m^{-2} mm^{-1} with a range of application rates from 20 to 90 mm h^{-1}. Rainfall simulation duration ranged from 60 to 120 min.

Soil water retention characteristics of the soils used in this study were estimated based on soil texture using the pedotransfer functions of Saxton and Rawls (2006). The Brooks and Corey (1964) relationships were used to model soil hydraulic properties as a function of soil water potential. Parameters for the Brooks and Corey (1964) soil water relationships were estimated by fitting them to values of soil water potential versus soil water content estimated by the Saxton and Rawls (2006) pedotransfer functions. Satiated water content was taken as 80% of pedotransfer function predicted porosity. Other infiltration studies have estimated satiated water content as 62% to 92% of saturated water content (Mein and Larson, 1973; Slack, 1980; Moore, 1981a; Römkens et al., 1986; Eisenhauer et al., 1992). Water entry pressure head for soil wetting was taken as one-third the air entry pressure estimated by the Saxton and Rawls (2006) pedotransfer function. Satiated hydraulic conductivity was determined by fitting the infiltration model absent soil surface sealing to infiltration data with the surface protected from droplet impact. Values used to characterize soil water retention properties of the soils are given in table 1.

INFILTRATION MODEL

Infiltration was modeled using a one-dimensional, fully implicit, finite-difference numerical solution to the Richards equation (Rathfelder and Abriola, 1994; Shahraiyni and Ashtiani, 2009). The Thomas algorithm (Thomas, 1949) was used to solve the tridiagonal matrix of simultaneous equations. The model was written in Microsoft Visual Basic. Soil profile depth increments were 1 mm, and the time increments were 0.01 min for the first 3 min of infiltration and then 0.1 min thereafter. The convergence criterion for each time step was less than 0.1 mm of head change between subsequent iterations for any node in the soil profile. The developing soil surface seal hydraulic properties were assumed to be uniform over a 5 mm depth below the soil surface (Moore and Larson, 1980; Moore, 1981a; Moore et al., 1981; Ahuja, 1983; Baumhardt et al., 1990; Ruan et al., 2001, Assouline, 2004). The soil profile was assumed to be infinitely uniform below the surface seal with constant hydraulic properties equivalent to the soil surface layer prior to infiltration.

SOIL SURFACE SEALING MODEL

Specific power or *SP* (W m^{-2}), also termed kinetic energy flux density (Thompson and James, 1985), can be calculated for a rainfall simulator with constant application rate and drop kinetic energy as:

$$SP = \frac{KE_d \cdot R}{3600} \tag{1}$$

where KE_d is droplet kinetic energy per unit volume (J m^{-2} mm^{-1}), and R is application rate (mm h^{-1}). Cumulative kinetic energy applied to a soil surface can then be calculated as *SP* multiplied by time in seconds.

Transient soil surface seal development has traditionally been modeled using an exponential decay function of cumulative kinetic energy (Farrell and Larsen, 1972; van Doren and Allmaras, 1978; Linden, 1979; Moore et al., 1981; Brakensiek and Rawls, 1983; Bosch and Onstad, 1988; Baumhardt et al., 1990) of the general form:

$$K(t) = K_f + \left(K_i - K_f\right) \cdot e^{-c \cdot E} \tag{2}$$

where K is hydraulic conductivity (mm h^{-1}), K_f is final saturated hydraulic conductivity (mm h^{-1}) of the soil surface seal after an extended period of droplet impact absent the effect of seal erosion, K_i is initial satiated hydraulic conductivity of the surface soil (mm h^{-1}), c is an empirical parameter that represents soil structural stability (m^2 J^{-1}), and E is some representation of cumulative droplet energy (J m^{-2}). The empirical parameter c is required in the model to incorporate inherent differences between soils concerning susceptibility to surface seal formation due to soil texture, salinity, organic matter, cropping history, and tillage history (Bosch, 1986).

Equation 2 was incorporated into the infiltration model by calculating a reduced hydraulic conductivity for the surface seal (top 5 mm) at each time step by representing E as *SP* multiplied by time in seconds. Application of the infiltration model to the Vienna loam data set of Mahamad (1985) using the exponential decay function (eq. 2) tended to underpredict the infiltration rate under low levels of *SP* (i.e., low rainfall intensity and/or low droplet kinetic energy). Based on this observation, other mathematical forms of a transient soil surface seal development model were considered. The ideal mathematical functional form would be similar to equation 2 in that it is a decreasing function of cumulative droplet kinetic energy with a diminishing rate of decrease over time and has the capability of incorporating the same three parameters: initial satiated hydraulic conductivity, seal final saturated hydraulic conductivity, and an empirical parameter representing the resistance of aggregate breakdown to applied droplet kinetic energy. Possible mathematical functional forms include inverse first-order polynomial, exponential linear combination, three-parameter hyperbolic decay, three-parameter power, two-parameter rational, and two-parameter logarithm, along with some other less common mathematical forms. Evaluation of the performance of each mathematical form was beyond the scope of this article and was not undertaken. Based solely on simplicity, the two-parameter rational mathematical form was evaluated first. The resulting infiltration model was found to consistently overestimate infiltration, indicating that the transient soil sealing model was not sensitive enough to cumulative droplet kinetic energy. In an attempt to overcome this issue, cumulative droplet kinetic energy was raised to a power. By trial-and-error application of the infiltration model to the Vienna loam data set of Mahamad (1985), a power of 1.2 was found to work well and provide excellent results. Mathematical forms that were not evaluated may provide equivalent or marginally improved results. The resulting transient soil surface sealing model was:

$$K(t) = K_f + \frac{(K_i - K_f)}{1 + S_f (SP \cdot t)^{1.2}} \tag{3}$$

where S_f is a dimensionless empirical soil factor that represents resistance to surface seal formation, consistent with the use of c in equation 2, and t is time in seconds. Consequently, this empirical transient soil surface seal model was used in this study.

Model Fit Criteria

Infiltration model goodness of fit was quantified by examining the sum of squared difference between model-predicted values and data relative to the sum of squared difference between data and mean data values, which is termed model efficiency (*ME*). Model efficiency (Nash and Sutcliffe, 1970; Bjorneberg et al., 1999) is defined as:

$$ME = 1 - \frac{\sum (y_i - y_{pred})^2}{\sum (y_i - y_{avg})^2} \tag{4}$$

where y_i is the ith data value, y_{pred} is the model-predicted value for y_i, and y_{avg} is the mean of the data values. Model efficiency was used to optimize model parameters and quantify goodness of fit. Model efficiency is similar to the correlation coefficient associated with linear regression in that its value ranges from $-\infty$ to 1. A value of 1 means the model is a perfect fit to the data, but a negative *ME* value signifies that the data mean is a better estimate of the data than the model. Use of *ME* alone can be misleading as it does not take into account other factors that enter into determining model goodness of fit. For example, with infiltration models, a reliable estimate of time to ponding is important but is not quantified by using *ME* alone. Model parameters were determined based on maximizing *ME* but adjusted when there was considerable variability in the data to provide an improved estimate of mean time to ponding with little quantitative decrease in the value of *ME*.

Model Calibration

The three parameters used in modeling transient seal development (eq. 3) were determined by fitting the infiltration model to the data for the three soils over the range of *SP* values found in the data sets. The value for satiated hydraulic conductivity for each soil was determined by trial-and-error fitting of the infiltration model to maximize *ME* when the soil surface was protected from droplet impact. The value obtained for satiated hydraulic conductivity was held constant for all subsequent model simulations under transient soil seal development due to varying kinetic energy levels and application intensities (*SP*) for each soil. The values for K_f and S_f were then determined jointly for each soil by trial-and-error fitting of the two parameters to maximize *ME* for each specific power.

Results

The Vienna loam soil did not produce runoff under protected soil surface conditions when simulated rainfall was applied at 155 mm h^{-1} for 90 min. The minimum value of hydraulic conductivity used in the infiltration model that did not result in predicted runoff for a 90 min rainfall event was taken as the satiated hydraulic conductivity of the Vienna loam soil (table 1). Simulated rainfall for the other two soils did result in runoff when the soil surface was protected from droplet impact. The infiltration model without surface sealing provided good fit to the infiltration data based on the values of *ME* obtained in each case (fig. 1). The numerical value of *ME* for the Atwood soil is about half that for the Lowry soil. This is due to scatter in the infiltration data rather than poor model fit to the infiltration data. For the Atwood soil infiltration data (fig. 1), the infiltration model provides an improved fit to the data compared to the mean, but the improvement is relatively small,

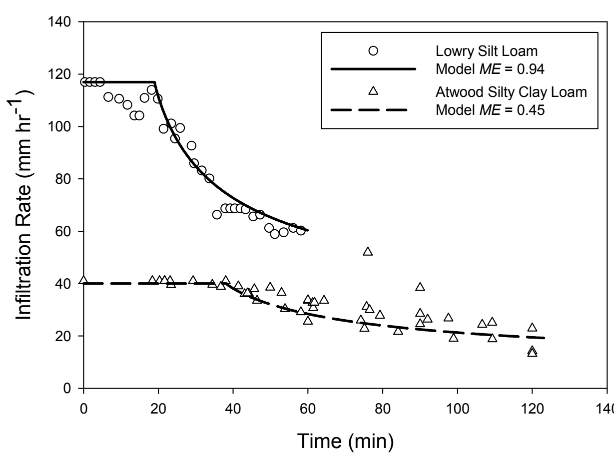

Figure 1. Infiltration model fit to runoff data from protected soil surfaced conditions used to determine satiated hydraulic conductivity of the soil listed in table 1.

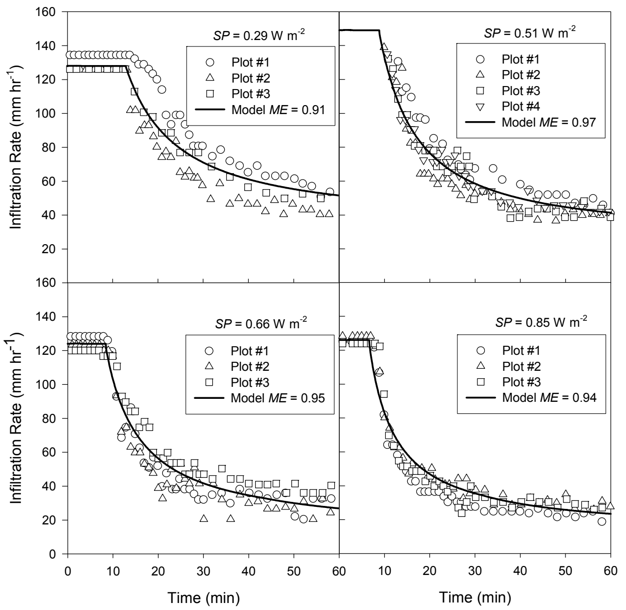

Figure 2. Infiltration model fit to runoff from *in situ* Vienna loam soil reported by Mahamad (1985) under four levels of specific power (*SP*) applied by simulated rainfall.

hence the lower value of *ME* compared to the Lowry soil. The corresponding values for satiated hydraulic conductivity determined from the infiltration model fit to the data for protected soil surface shown in figure 1 are listed in table 1.

The sealing soil infiltration model provided an excellent fit to the Vienna loam infiltration data of Mahamad (1985) over a range of *SP* values. The results at four levels of *SP* are shown in figure 2. The value for S_f (eq. 3) was held constant at 0.03, and the value of K_f (eq. 3) ranged from 0.03 to 0.05 mm h^{-1}. The sealing soil infiltration model also provided an excellent fit to the Lowry silt loam infiltration data of Mahamad (1985) for the two levels of *SP* reported (fig. 3). The value for S_f was held constant at 0.07, and the value of K_f was 0.08 mm h^{-1} for an *SP* of 0.45 W m^{-2} and 0.05 mm h^{-1} for an *SP* of 0.76 W m^{-2}.

The sealing soil infiltration model provided a good fit to the laboratory infiltration data of Baumhardt (1985) for an Atwood silty clay loam soil at four levels of *SP* (fig. 4). The value for S_f (eq. 3) was held constant at 0.02, and the value of K_f (eq. 3) ranged from 0.005 to 0.04 mm h^{-1}. The fit of the model was slightly reduced at higher levels of *SP* due to an apparent increase in final infiltration rates with an increase in *SP*. Assouline and Ben-Hur (2006) found that final infiltration rate and soil loss increased with rainfall intensity (*SP*) and became more prominent with slope steepness, consistent with the results of several other studies (Assouline and Ben-Hur, 2006). This phenomenon is absent in the data of Mahamad (1985) (figs. 2 and 3) but present in the data of Baumhardt (1985). This is likely due to the fact that Baumhardt (1985) used a 9% slope, whereas Mahamed (1985) used a 2% slope. The increase in final infiltration rate (seal conductivity) with increasing rainfall intensity in Baumhardt's data can be due to a thinner and less compacted seal layer resulting from higher erosion of the soil surface and a lower normal component of drop impact force (Assouline and Ben-Hur, 2006). Another possibility is that as the slope steepens, more fine particles that are susceptible to being washed in and clogging pores below the surface are instead transported away by overland flow, thus reducing the probability of pore clogging within the seal layer and consequently affecting the thickness of

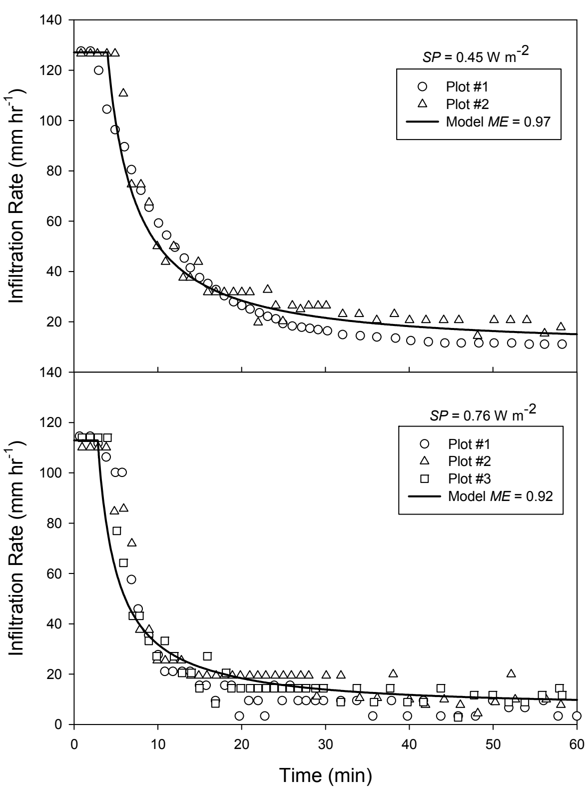

Figure 3. Infiltration model fit to runoff from *in situ* Lowry silt loam soil reported by Mahamad (1985) under two levels of specific power (*SP*) applied by simulated rainfall.

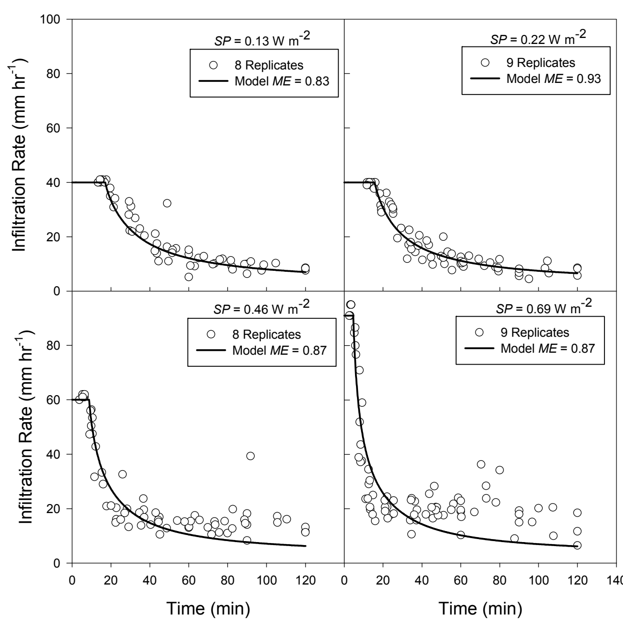

Figure 4. Infiltration model fit to runoff from soil columns of Atwood silty clay loam soil reported by Baumhardt (1985) under four levels of specific power (*SP*) applied by simulated rainfall.

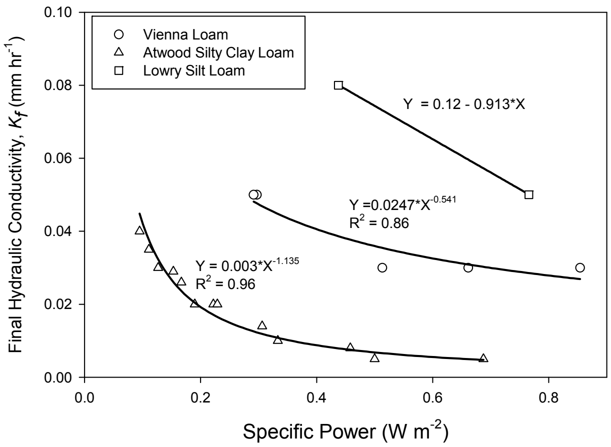

Figure 5. Relationships found between final hydraulic conductivity of surface seal (K_f) and specific power (*SP*) for Vienna loam and Lowry silt loam soils reported by Mahamad (1985) and for Atwood silty clay loam soil reported by Baumhardt (1985).

the layer and the final infiltration rate (Assouline and Ben-Hur, 2006). The surface seal model used in this study (eq. 3) does not account for erosion of the seal layer, potentially the cause for the reduced fit to the infiltration data of Baumhardt (1985) at higher *SP* values.

The value for S_f (eq. 3) ranged from 0.02 to 0.07 but was constant for each soil, irrespective of *SP*. However, the value of K_f (eq. 3) ranged from 0.005 to 0.08 mm h^{-1}, depending on the soil and *SP* (fig. 5). For all three soils, final infiltration rate (K_f) decreased with increasing *SP*. This can be due to a thicker soil surface seal and an increase in surface seal density with greater *SP* applied to the soil surface. The finite difference model used a constant 5 mm soil surface seal thickness. Thus, any change in surface seal thickness is modeled as a change in final hydraulic conductivity. For the Atwood silty clay loam and the Vienna loam soils, a power relationship between K_f and *SP* provided a good fit to the data (fig. 5). It may be possible to develop a relationship between K_f, *SP*, and soil texture, but more infiltration data are needed to determine if such a relationship exists. The effect of *SP* on K_f is consistent with the results of Shainberg and Singer (1988), who found that final infiltration rate decreased with increasing droplet fall height for an application rate of 40 mm h^{-1}.

MODEL SENSITIVITY

The transient surface seal formation model (eq. 3) uses three parameters to simulate soil surface seal formation. The influence of each parameter on infiltration rate is depicted in figure 6. Initial satiated hydraulic conductivity (K_i) has a large effect on time to ponding and less effect on final infiltration rate (60 min infiltration), both of which are directly related to K_i. A 53% reduction in K_i results in a 58% reduction in time to ponding and a 30% reduction in final infiltration rate for soil hydraulic characteristics similar to those of the Vienna loam used in this study. Final saturated hydraulic conductivity of the surface seal (K_f) affects the final infiltration rate of the soil the most and time to ponding to a small degree (fig. 6b). A 57% reduction in K_f results in a 32% reduction in final infiltration rate

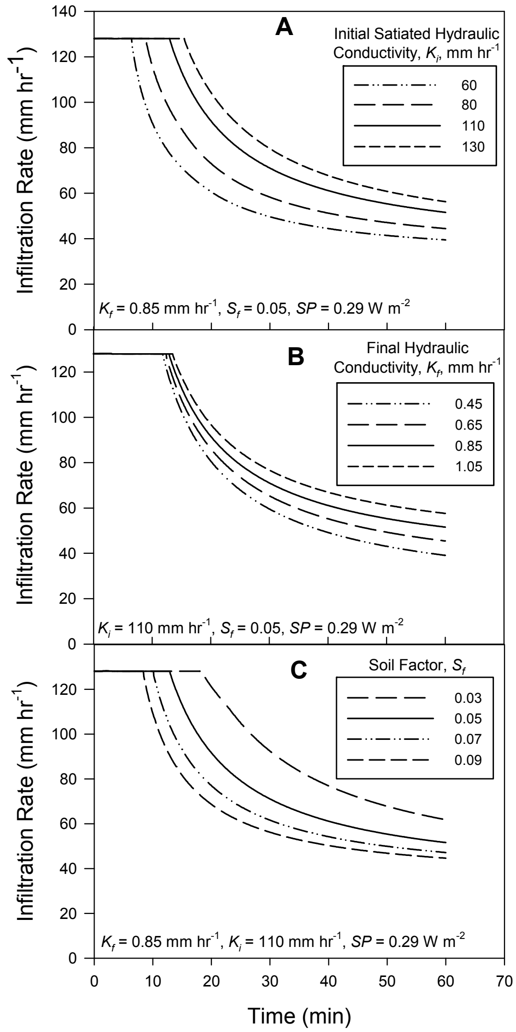

Figure 6. Sensitivity of infiltration model to (a) initial satiated hydraulic conductivity(K_i), (b) final hydraulic conductivity (K_f), and (c) soil factor (S_f) for a specific power (*SP*) of 0.29 W m^{-2}.

(60 min infiltration rate) and a 12% reduction in time to ponding for soil hydraulic characteristics similar to those of the Vienna loam. Simulated infiltration rate is least sensitive to the soil factor (S_f) parameter in equation 3. A threefold decrease in S_f only results in a 54% decrease in time to ponding and a 28% decrease in final infiltration rate. The relative insensitivity of infiltration rate to S_f may partially explain why this parameter was constant with *SP* and only varied by soil type in this study.

DISCUSSION

The transient soil seal formation model used in this study (eq. 3) is unique from other studies in that it explicitly uses *SP* as the driving factor for formation of a soil surface seal. The form of the model is also unique in that it is expressed as a rational function of *SP* rather than an exponential decay function of cumulative droplet kinetic energy. The advantage of using *SP* is that application rate as well as droplet kinetic energy are implicitly incorporated into soil surface seal formation. The utility of using *SP* as the driving factor is demonstrated by application and performance of the model across multiple soil types and rainfall simulation studies with varying droplet kinetic energies and application rates (figs. 2 through 4).

The transient soil seal formation model uses three parameters to model bare soil surface seal formation under droplet impact. The applicability of the model is limited to the extent to which the three model parameters can be predetermined. Of the three parameters, initial satiated hydraulic conductivity (K_i) is likely the most difficult to estimate and has a large influence on predicted time of ponding and final infiltration rate (fig. 6). Pedotransfer functions are largely constructed from measured saturated hydraulic conductivity of subzone or consolidated tillage layer soil samples in the laboratory. The satiated hydraulic conductivity of recently tilled soil is likely substantially different from the saturated hydraulic conductivity of a consolidated soil sample. For example, the pedotransfer function of Saxton and Rawls (2006) estimates a saturated hydraulic conductivity for the Vienna loam soil of Mahamad (1985) as 25 mm h^{-1}, but the infiltration model fit to infiltration data under protected soil surface conditions requires that a satiated hydraulic conductivity of 110 mm h^{-1} be used. However, the pedotransfer function provided close estimates for initial satiated hydraulic conductivity of the Lowery silt loam and Atwood silty clay loam soils used in the infiltration model.

Final saturated hydraulic conductivity (K_f) of the surface seal maybe easier to predict than initial satiated hydraulic conductivity, partially because it appears to be less variable (fig. 5). Sharma (1980) measured final conductivity of 12 Minnesota agricultural soils with soil textures ranging from loam to silty clay loam after 30 min of simulated rainfall at 53 mm h^{-1} application rate. Final saturated hydraulic conductivity of the surface seals ranged from 0.5 to 2.8 mm h^{-1} despite initial saturated hydraulic conductivities ranging from 11 to 829 mm h^{-1}. Ben-Hur et al. (1985) found that final infiltration rate was related to soil clay content. Soils with approximately 20% clay content were the most sensitive to crust formation. With increasing clay percentage, soil structure was more stable and the formation of a crust was diminished. For soils with lower clay content (<20%), a limited amount of clay was available to disperse and fill surface soil pores. As a result, crust development was less of a factor. The soils used in this study all had clay contents approximating 20% and exhibited a high susceptibility to soil seal formation. It may be possible to predict final saturated hydraulic conductivity based on *SP* applied, soil clay content, and initial satiated hydraulic conductivity, but that is beyond the scope of this study.

The soil factor (S_f) used to model transient soil surface sealing maybe the most difficult to predetermine as it is an empirical model parameter. The soil factor has a substantial effect on time to ponding and final infiltration rate for precipitation event durations less than 2 h. Fortunately, it appears to be related only to soil characteristics and not rainfall characteristics. It may be possible to correlate the parameter with soil physical properties, but additional infiltration data across a range of soil textures are needed. The soil factor (S_f) and final saturated hydraulic conductivity (K_f) are likely highly correlated since both are related to the susceptibility of soil aggregate breakdown, which may make it difficult to predict them independently.

The sealing soil infiltration model has potential applicability to center-pivot sprinkler irrigation. The model will be useful for center-pivot sprinkler design selection when model parameters can be determined based on site-specific soil conditions. With center-pivot sprinkler irrigation, *SP* is a function of sprinkler design, flow rate, spacing, operating pressure, mounting height, and will also be a function of distance perpendicular to the center-pivot lateral, which means it will vary in time as the center-pivot sprinkler system passes over a field location. The time-variable nature of *SP* will depend on center-pivot speed and radial location from the pivot point. The *SP* application profiles for four common center-pivot sprinklers were calculated by King and Bjorneberg (2010) for a single sprinkler flow rate, spacing, and height using measured sprinkler drop size and radial application rate distribution measured in the laboratory. Models for estimating *SP* application profiles for any sprinkler design, height, spacing, flow rate, and pressure will need to be developed, as it is not feasible to make laboratory measurements of drop size and velocity for all combinations. The effect that time-variant *SP* under center-pivot sprinkler irrigation has on model parameters S_f and K_f, if any, will also need to be evaluated. Additionally, the effect that surface residue and canopy cover have on *SP* reaching the soil surface needs to determined and incorporated into the model.

SUMMARY

A sealing soil infiltration model was developed using an explicit finite difference solution scheme with a transient soil seal formation model, which is unique from other studies in that it explicitly uses specific power as the driving factor for formation of a soil surface seal. The transient seal formation model is also unique in that it is expressed as a rational function of specific power rather than an exponential decay function of cumulative droplet kinetic energy, water applied, or time. The advantage of using specific power is that application rate as well as droplet kinetic energy are implicitly incorporated into soil surface seal formation. The utility of using specific power as the driving factor was demonstrated by application and performance of the sealing soil infiltration model across multiple soil types and rainfall simulation studies with varying droplet kinetic energies and application rates.

The transient soil seal formation model uses three parameters: initial satiated hydraulic conductivity of the soil, final saturated hydraulic conductivity of the soil surface seal, and an empirical soil factor that represents the susceptibility of the soil to aggregate breakdown under droplet impact. Final saturated hydraulic conductivity of the soil surface seal was found to be well correlated with specific power for a specific soil. The soil factor was found to depend on soil only for the tests used in this study with bare soil. Predetermined estimation of the three model parameters is difficult but could potentially be achieved by the development of correlations with soil physical parameters.

Application of the model to center-pivot sprinkler irrigation will require the development of models relating specific power to sprinkler design, flow rate, operating pressure, height, and center-pivot lateral location and travel speed.

References

Ahuja, L. R. 1983. Modeling infiltration into crusted soils by the Green-Ampt approach. *SSSA J.* 47(3): 412-418.

Alberts, E. E., M. A. Nearing, M. A. Weltz, L. M. Risse, F. B. Pierson, X. C. Zhang, J. M. Laflen, and J. R. Simanton. 1993. Chapter 7: Soil component. In *Technical Documentation: USDA Water Erosion Prediction Project (WEPP)*, 7.1-7.47. D. C. Flanagan and M. A. Nearing, eds. NSERL Report No. 10. West Lafayette, Ind.: National Soil Erosion Research Laboratory.

Allen, R. G. 1990. Applicator selection along center pivots using soil infiltration parameters. In *Visions of the Future*, 549-555. St. Joseph, Mich.: ASAE.

Assouline, S. 2004. Rainfall-induced soil surface sealing: A critical review of observations, conceptual models, and solutions. *Vadose Zone J.* 3(2): 570-591.

Assouline, S., and M. Ben-Hur. 2006. Effects of rainfall intensity and slope gradient on the dynamics of interrill erosion during soil surface sealing. *Catena* 66(3): 211-220.

Assouline, S., and Y. Mualem. 1997. Modeling the dynamics of seal formation and its effect on infiltration as related to soil and rainfall characteristics. *Water Resources Res.* 33(7): 1527-1536.

Assouline, S., and Y. Mualem. 2001. Soil seal formation and its effect on infiltration: Uniform versus nonuniform seal approximations. *Water Resources Res.* 37(2): 297-305.

Augeard, B., S. Assouline, A. Fonty, C. Kao, and M. Vauclin. 2007. Estimating hydraulic properties of rainfall-induced soil surface seals from infiltration experiments and x-ray bulk density measurements. *J. Hydrol.* 341(1-2): 12-26.

Baumhardt, R. L. 1985. The effect of rainstorm characteristics on soil sealing and infiltration. Unpublished PhD diss. Mississippi State, Miss.: Mississippi State University.

Baumhardt, R. L., M. J. M. Romkens, D. F. Whisler, and Y.-J. Parlange. 1990. Modeling infiltration into a sealing soil. *Water Resources Res.* 26(10): 2497-2505.

Ben-Hur, M., I. Shainberg, D. Bakker, and R. Keren. 1985. Effect of soil texture and $CaCO_3$ content on water infiltration in crusted soil as related to water salinity. *Irrig. Sci.* 6(4): 281-294.

Ben-Hur, M., Z. Plaut, G. J. Levy, M. Agassi, and I. Shainberg. 1995. Surface runoff, uniformity of water distribution, and yield of peanut irrigated with a moving sprinkler system. *Agron. J.* 87(4): 609-613.

Betzalel, I., J. Morin, Y. Benyamini, M. Agassi, and I. Shainberg. 1995. Water drop energy and soil seal properties. *Soil Sci.* 159(1): 13-22.

Bjorneberg, D. L., T. J. Trout, R. E. Sojka, and J. K. Aase. 1999. Evaluating WEPP-predicted infiltration, runoff, and soil erosion for furrow irrigation. *Trans. ASAE* 42(6): 1733-1741.

Borst, H. L., and R. Woodburn. 1942. The effect of mulching and methods of cultivation on runoff and erosion from Muskingum silt loam. *Agric. Eng.* 23(1): 19-22.

Bosch, D. D. 1986. The effects of rainfall on the hydraulic conductivity of soil surfaces. Unpublished MS thesis. St. Paul, Minn.: University of Minnesota.

Bosch, D. D., and C. A. Onstad. 1988. Surface seal hydraulic conductivity as affect by rainfall. *Trans. ASAE* 31(4): 1120-1127.

Brakensiek, D. L., and W. J. Rawls. 1983. Agricultural management effects on soil water processes: Part II. Green and Ampt parameters for crusting soils. *Trans. ASAE* 26(6) 1753-1757.

Brooks, R. H., and A. T. Corey. 1964. Hydraulic properties of porous media. Hydrology Paper No. 3. Ft. Collins, Colo.: Colorado State University.

DeBoer, D. W. 2001. Sprinkler application pattern shape and surface runoff. *Trans. ASAE* 44(5): 1217-1220.

DeBoer, D. W., A. Moshref-Javadi, and S. T. Chu. 1988. Application of the Green-Ampt infiltration equation to sprinkler irrigation management. *Applied Agric. Res.* 3(3): 128-132.

DeBoer, D. W., D. L. Beck, and A. R. Bender. 1992. A field evaluation of low, medium, and high pressure sprinklers. *Trans. ASAE* 35(4):1 185-1189.

Dillion, R. C., E. A. Hiler, and G. Vittetoe. 1972. Center-pivot sprinkler design based on intake characteristics. *Trans. ASAE* 15(5): 996-1001.

Duley, F. L. 1940. Surface factors affecting the rate of intake of water by soils. *SSSA Proc.* 4(C): 60-64.

Edwards, W. M. 1967. Infiltration of water into soils as influenced by surface conditions. Unpublished PhD diss. Ames, Iowa: Iowa State University.

Eisenhauer, D. E., D. F. Heermann, and A. Klute. 1992. Surface sealing effects on infiltration with surface irrigation. *Trans. ASAE* 35(6): 1799-1807.

Ellison, W. D. 1945. Some effects of raindrops and flow on soil erosion and infiltration. *Trans. American Geophys. Union* 26(3): 415-429.

Faci, J. M., R. Salvador, E. Playan, and H. Sourell. 2001. A comparison of fixed and rotating spray plate sprinklers. *J. Irrig. Drain. Eng. ASCE* 127(4): 224-233.

Farrell, D. A., and W. E. Larson. 1972. Dynamics of the soil-water system during rainstorm. *Soil Sci.* 113(2): 88-95.

Gilley, J. R. 1984. Suitability of reduced-pressure center pivots. *J. Irrig. Drain. Eng. ASCE* 110(1): 21-34.

Green, W. H., and G. A. Ampt. 1911. Studies on soil physics: I. The flow of air and water through soils. *J. Agric. Sci.* 4(1): 1-24.

Hasheminia, S. M. 1994. Controlling runoff under low-pressure center-pivot irrigation systems. *Irrig. and Drain. Systems* 8(1): 25-34.

Horton, R. E. 1941. An approach toward a physical interpretation of infiltration capacity. *SSSA Proc.* 5(C): 399-417.

Kincaid, D. C. 1996. Spraydrop kinetic energy from irrigation sprinklers. *Trans. ASAE* 39(3): 847-853.

Kincaid, D. C. 2005. Application rates from center-pivot irrigation with current sprinkler types. *Applied Eng. in Agric.* 21(4): 605-610.

Kincaid, D. C., K. H. Solomon, and J. C. Oliphant. 1996. Drop size characteristics for irrigation sprinklers. *Trans. ASAE* 39(3): 839-845.

King, B. A., and D. L. Bjorneberg. 2010. Characterizing droplet kinetic energy applied by moving spray-plate center-pivot irrigation sprinklers. *Trans. ASABE* 53(1): 137-145.

King, B. A., and D. L Bjorneberg. 2011. Evaluation of potential runoff and erosion of four center-pivot irrigation sprinklers. *Applied Eng. in Agric.* 27(1): 75-85.

Linden, D. R. 1979. A model to predict soil water storage as affected by tillage practices. Unpublished PhD diss. St. Paul, Minn.: University of Minnesota.

Mahamad, D. A. 1985. Seal development and infiltration as affected by rainfall kinetic energy. Unpublished PhD diss. Brookings, S.D.: South Dakota State University.

Mannering, J. V. 1967. The relationship of some physical and chemical properties of soils to surface sealing. Unpublished PhD diss. West Lafayette, Ind.: Purdue University.

Martin, D. L., W. L. Kranz, A. L. Thompson, and H. Liang. 2010. Selecting sprinkler packages for center pivots. In *Proc. 5th Natl. Decennial Irrigation Conf.* St. Joseph, Mich.: ASABE.

McIntyre, D. S. 1958. Permeability measurements of soil crusts formed by raindrop impact. *Soil Sci.* 85(4): 185-189.

Mein, R. G., and C. L. Larson. 1973. Modeling infiltration during a steady rain. *Water Resources Res.* 9(2): 384-394.
Moldenhauer, W. C., and D. C. Long. 1964. Influence of rainfall energy on soil loss and infiltration rates: I. Effect over a range of texture. *SSSA Proc.* 28(6): 813-817.
Moore, I. D. 1981a. Effect of surface sealing on infiltration. *Trans. ASAE* 24(6): 1546-1552, 1561.
Moore, I. D. 1981b. Infiltration equations modified for surface effects. *J. Irrig. Drain. Div. ASCE* 107(IR1): 71-86.
Moore, I. D. and C. L. Larson. 1980. An infiltration-runoff model for cultivated soils. *Trans. ASAE* 23(6): 1460-1467.
Moore, I. D., C. L. Larson, D. C. Slack. B. N. Wilson, F. Idike, and M. C. Hirschi. 1981. Modeling infiltration: A measureable parameter approach. *J. Agric. Eng. Res.* 26(1): 21-32.
Morin, J., and Y. Benyamini. 1977. Rainfall infiltration into bare soils. *Water Resources Res.* 13(5): 813-817.
Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part 1. A discussion of principles. *J. Hydrol.* 10(1): 282-290.
Playan, E., S. Garrido, J. M. Faci, and A. Galan. 2004. Characterizing pivot sprinkler using an experimental irrigation machine. *Agric. Water Mgmt.* 70(3): 177-193.
Rathfelder, K., and L. M. Abriola. 1994. Mass conservative numerical solutions of the head-based Richards equation. *Water Resources Res.* 30(9): 2579-2586.
Rawls, W. J., D. L. Brakensiek, J. R. Simanton, and K. D. Kohl. 1990. Development of a crust factor for a Green-Ampt model. *Trans. ASAE* 33(4): 1224-1228.
Römkens, M. J. M., R. L. Baumhardt, M. B. Parlange, F. D. Whisler, J.-Y. Parlange, and S. N. Prasad. 1986. Rain-induced surface seals: Their effect on ponding and infiltration. *Annales Geophysicae* 4(2): 417-424.
Ruan, H., L. R. Ahuja, T. R. Green, and J. G. Benjamin. 2001. Residue cover and surface-sealing effects on infiltration: Numerical simulations for field applications. *SSSA J.* 65(3): 853-861.
Saxton, K. E., and W. J. Rawls. 2006. Soil water characteristics estimates by texture and organic matter for hydrologic solutions. *SSSA J.* 70(5): 1569-1578.
Shainberg, I., and M. J. Singer. 1988. Drop impact energy-soil exchangeable sodium percentage interactions in seal formation. *SSSA J.* 52(5): 1449-1452.
Shahraiyni, H. T., and B. A. Ashtiani. 2009. Comparison of finite difference schemes for water flow in unsaturated soils. *Intl. J. Aerospace and Mech. Eng.* 3(1): 1-5.
Sharma, P. P. 1980. Hydraulic gradients and vertical infiltration through rain-formed quasi-seals on a range of Minnesota soils. Unpublished MS thesis. St. Paul, Minn.: University of Minnesota.
Silva, L. L. 2006. The effect of spray head sprinklers with different deflector plates on irrigation uniformity, runoff, and sediment yield in a Mediterranean soil. *Agric. Water Mgmt.* 85(3): 243-252.
Slack, D. C. 1980. Modeling infiltration under moving sprinkler irrigation systems. *Trans. ASAE* 23(3): 596-600.
Sourell, H., J. M. Faci, and E. Playan. 2003. Performance of rotating spray plate sprinklers in indoor experiments. *J. Irrig. Drain. Eng. ASCE* 129(5): 376-380.
Thomas, L. H. 1949. Problems in linear difference equations over a network. New York, N.Y.: Columbia University, Watson Scientific Computing Laboratory.
Thompson, A. L., and L. G. James. 1985. Water droplet impact and its effect on infiltration. *Trans. ASAE* 28(5): 1506-1510, 1520.
Undersander, D. J., T. H. Marek, and R. N. Clark. 1985. Effect of nozzle type on runoff and yield of corn and sorghum under center-pivot sprinkler systems. *Irrig. Sci*. 6(1): 107-116.
van Doren, D. M., and R. R. Allmaras. 1978. Effect of residue management practices on the soil physical environment, microclimate, and plant growth. In *Crop Residue Management Systems*, 49-83. Madison, Wisc.: ASA.
von Bernuth, R. D., and J. R. Gilley. 1985. Evaluation of center-pivot application packages considering droplet-induced infiltration reduction. *Trans. ASAE* 28(6): 1940-1946.
Wilmes, G. J., D. L. Martin, and R. J. Supalla. 1993. Decision support system for design of center pivots. *Trans. ASAE* 37(1): 165-175.