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SEAL DEVELOPMENT AND INFILTRATION AS
AFFECTED BY RAINFALL KINETIC ENERGY

BY
DEAH ABED MAHAMAD

A dissertation submitted
in partial fulfillment of the requirements for the
degree of Doctor of Philosophy
Major in Agronomy
South Dakota State University
December, 1985
SEAL DEVELOPMENT AND INFILTRATION AS AFFECTED BY RAINFALL KINETIC ENERGY

This dissertation is approved as a creditable and independent investigation by a candidate for the degree, Doctor of Philosophy, and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this dissertation does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Robert A. Kohl
Thesis Advisor

Maurice L. Horton
Head, Plant Science Department
This dissertation is dedicated to the memory of

MY FATHER

in appreciation of his support throughout my lifetime
ACKNOWLEDGEMENTS

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INTRODUCTION

The infiltration of water into soil has been studied for more than 50 years. Much of the effort has concentrated on obtaining infiltration rate measurements for different soils and on developing equations which describe the resulting data. A portion of the infiltration literature has dealt with the large affect that the development of a surface seal has had on the resulting infiltration measurement of a soil. This surface seal may be more significant in determining the infiltration characteristics of a soil than any other single or perhaps combination of factors.

Surface seal development has been linked to both rainfall energy and intensity as well as soil aggregate stability. However, quantitative relationships between these parameters have not been reported in the literature. Therefore, this study was established to investigate the relationship between rainfall kinetic energy and infiltration into a bare soil surface and to study the development of a surface seal during the application of the rainfall with different intensities.

The objectives of this study were:

1) To describe the effects of rainfall kinetic energy level on infiltration.

2) To determine the effects of rainfall energy on the time to runoff and time to infiltrate 50 mm of water.

3) To measure the effect of rainfall intensities on the rate of seal development and the final infiltration rate.

4) To investigate the effect of stopping periods on the infiltration rate.
5) To analyze the field data by a theoretical approach using a modified Green-Ampt model and to determine the rainfall sealing energy.
REVIEW OF LITERATURE

Infiltration as influenced by a surface seal development

The effects of raindrop impact on the infiltration process was studied by Duley (1939) and by Ellison (1947). They showed that the raindrops destroy the surface aggregates and a surface seal is gradually formed with a much lower hydraulic conductivity than the original soil surface. Duley (1939) reported that surface sealing has a greater effect on infiltration than other soil properties such as soil texture, soil moisture, etc. He presented a comparison between a covered and bare soil surface. He also demonstrated that the infiltration rate returned to its original value after removing the surface seal and covering the surface with burlap as shown, in Figure 1. Ellison (1947) indicated in his study that both raindrop impact and soil properties had a significant effect on the infiltration rate of a bare soil. He also mentioned that to increase the infiltration capacity of a bare soil one must achieve either a reduction of raindrop impact or a change in soil structural properties.

McIntyre (1958a) carried out studies to determine the mechanisms of surface seal formation. His results produced the following conclusions:

1) Wet soil aggregates are broken by raindrop impact.
2) Surface pores are clogged by washed in particles and pore volume is reduced.
3) The soil surface is compacted by raindrop impact, producing the seal layer.
Figure 1. Effect of sprinkling a sandy loam soil on intake of water when soil is protected as compared with rate when soil is bare (after Duley, 1939).
4) Suspended particles of clay or silt may be deposited on the surface after the rainfall has stopped.

McIntyre (1958a) noticed two distinct layers within the surface seal:

1) A skin seal (upper layer) approximately 0.1 mm thick, formed by compaction due to drop impact.
2) A lower, "washed-in" layer formed by fine particles clogging the pores and reducing the porosity.

McIntyre (1958b) stated that the rapid variation in splash rate indicates that the following process takes place at the soil surface.

A) Initially rapid wetting of the surface decreases cohesion and increases soil splash.
B) After formation of the surface seal has taken place, soil splash is reduced because of the accumulation of water on the surface.
C) The permeability of the soil surface then increases due to the removal of the skin seal (0.1 mm) by turbulence of the ponded water.

Ellison and Slater (1945) studied the factors affecting surface sealing and infiltration and indicated that the duration of rainfall, the soil carried by the raindrop splash, soil aggregation and clay content were the major factors affecting the infiltration rate.

Morin and Benyamini (1977) reported that the accumulation of raindrop impact with time causes an increase in the sealed area until the seal completely covers the exposed surface. It was the seal formation on a bare soil that was the major factor affecting the reduction of the infiltration rate.
Other researchers reported that surface seal formation was influenced by texture (Mannering, 1967); aggregate stability (Allison, 1956); organic matter (Ahmad and Roblin, 1971); tillage practices, crop history, and rainfall intensity (Sharma, 1980).

Moore (1981a) indicated that the effect of surface sealing on time to surface ponding is an order of magnitude greater than the effect of initial water content. Edwards (1967) showed that soil surface seal has greater effect on the hydraulic conductivity than on the soil water content of the soil profile.

Effect of rainfall kinetic energy on infiltration

Wischmeier and Smith (1958) studied the effects of rainfall kinetic energy and its interaction with other variables on soil loss. The results were represented by a multiple regression equation which related a combined function of rainfall kinetic energy and intensity to soil loss. Since runoff is inversely related to infiltration these same factors could be significant in reducing infiltration.

Moldenhauer and Long (1964) indicated that a sharp decrease in infiltration rate occurred immediately after runoff started. Equilibrium rate was reached shortly after runoff began. They reported that the final infiltration rate was constant for all the soils they tested except fine sand. They also noticed that a certain amount of energy was required to form a seal and initiate runoff. Thus, infiltratability decreases faster with a high application rate than with a lower one. Moldenhauer and Kemper (1969) applied different artificial rainfall kinetic energies to various clod sizes. As the kinetic
energy increases the infiltration rate after runoff was decreased. They mentioned in their study that the amount of kinetic energy required to initiate runoff is a function of clod size in the tilled soil. The smaller the clods the less energy is required to break down the clods and the less washed-in particles will be required to reduce the pores to their final volume.

Burwell and Larson (1969) found that the amount of energy needed to establish runoff was higher on the rough, porous surface (plowed treatment) than the other tillage treatments they studied.

Falayi and Bouma (1975) studied the effect of different soil management treatments on seal formation as exposed to artificial rainfall and compared the results to that of natural rainfall. They found that the conductivity of the seal formed under short-time, high-kinetic energy, artificial rainfall was similar to the seal formed under natural rainfall, the later characterized by intermittent low kinetic energy rainfall for a four-month period.

In a study using soil columns, Thompson and James (1983) found that the amount of water which would infiltrate prior to surface ponding for a given application rate increased as the kinetic energy per unit area decreased for all application rates tested.

Ragab (1983) reported that his laboratory study on the influence of sprinkler intensity and kinetic energy on soil surface sealing showed that the soil surface should approach a certain structural condition to form surface sealing. He indicated that the volume of pores in the sealed surface decreases as the impact energy increases.
Eigle and Moore (1983) indicated that soil surface sealing affects the time to surface ponding in a laboratory study using disturbed soil columns. They developed a regression equation to describe this relationship using kinetic energy as the causal agent for surface sealing. Their equation is:

\[ tp = a - b \cdot KE \]  

where \( tp \) is the time to ponding, \( KE \) is the kinetic energy \((J/m^2\cdot mm)\), and \( a, b \) are the regression constants. Three levels of kinetic energy were used in the study: zero energy (protected surface); 17.9 Joules/m\(^2\)·mm and 24.5 Joules/m\(^2\)·mm. The intensities were kept constant as much as possible between 65-98 mm/hr. Their studies also included the effect of rainfall kinetic energy on soil bulk density and particle size distribution. Bulk density was affected by raindrop energy after aggregate break down was completed. Eigle and Moore (1983) showed that two factors control the time to surface ponding; soil surface sealing and the physical properties of the soil.

Hudson (1981) reported that most of the study of kinetic energy came from its relationship with soil erosion. A certain amount of rainfall energy caused the erosion process to start.

Kinnell (1981) and Hudson (1965) studied the relationship between rainfall kinetic energy and rainfall intensity. The theoretical equation as written by Kinnell (1981) is:

\[ ER_a = B(1-Ke^{-hp}) \]  

where \( ER_a \) is kinetic energy per unit depth of rainfall, \( p \) is rainfall intensity, \( B, K \) and \( h \) are empirical constants, and \( e \) is the exponential function. This equation has been developed from McGregor and Mutchler.
Hudson's (1965) equation is:

\[ ER_a = c(b - a p^{-1}) \]  

(3)

where \( ER_a \) is in J/m².mm, \( c \), \( b \) and \( a \) are empirical constants and \( P \) is rainfall intensity in mm/hr.

Wischmeier and Smith (1958) derived the following form to describe the relationship of \( p \) and \( ER_a \):

\[ ER_a = a + b \log_{10} p \]  

(4)

where \( a \) and \( b \) are empirical constants. This equation is used to describe the \( p-ER_a \) relationship and to calculate the \( R \) factor in the universal soil loss equation in the United States.

Kinnell (1981) reported that equations 3 and 4 were not adequate to account for the \( i-ER_a \) relationship. He attributed the failure of these two equations to the circumstances under which they were derived. For example, Equation 3 was derived from the relationship between the rate of expenditure of rainfall kinetic energy (\( ERR \)) in units of energy/area.time and \( p \) (rainfall intensity), which biased toward the variation of \( ER_a \) in units energy/area.depth at high rainfall intensities. Equation 4 was derived from drop-size data obtained by Laws and Parsons (1943) which were obtained under low rainfall intensity (2.5-50.8 mm/hr). For this reason equation 4 was inadequate at high rainfall intensity for describing the \( p-ER_a \) relationship.

**Soil surface response to rainfall**

A soil seal is a thin dense surface layer of well oriented clay particles as defined by many researchers. It is a few millimeters
thick (0.1 - 5 mm) (Onofiook and Singer, 1984). The seal has a great
effect on surface infiltration, runoff and erosion.

Cary and Evans (1974) as mentioned by Parker (1984) reported
that decreasing organic matter content, high exchangeable sodium per-
centage and increasing silt content increase soil surface suscep-
tibility to sealing as a result of weakening aggregate stability.
Miller and Gifford (1974) came to similar conclusions.

Robinson and Page (1950) indicated that slaking of aggregates
can be caused by the development of high air pressure within the aggre-
gates due to the capillary forces of water entering the aggregates on
entrapped air. They also studied the effect of organic matter, clay
mineral type, aggregate size, and effect of wetting on slaking.
Organic matter associated with clay particles was the most effective
factor for maintaining aggregate stability.

Edwards (1967) reported that the hydraulic conductivity and
porosity of the soil surface was reduced while bulk density increased as
the time of exposure to rainfall increased. He studied various prop-
erties of soil surfaces after exposure to different rainfall treatments.

Lyles et al. (1969) studied the effect of rainfall intensity,
wind velocity, and soil properties on clod disintegration using simu-
lated rainfall in a laboratory tunnel-rain tower facility. They
concluded that clod size, the time of exposure, rainfall intensity and
wind speed were the most effective factors on clod disintegration.

Dexter et al. (1983) investigated the effect of rainfall on
macrostructure; the results showed that increasing rainfall intensity
caused isolation of the void space by welding the aggregates to each
other at their contact points and decreased soil macroporosity and void space. They used multiple regression equations to describe the relationship of soil macrostructure parameter such as (mean aggregate size, mean void size and mean macroporosity) and cumulative rainfall after tillage and depth in the tilled soil layer.

Cruse and Larson (1977) reported that water from raindrops acts both as an energy source causing particle detachment, and as a wetting source. They studied the relationship of soil detachment by a single raindrop impact and the shearing strength. They indicated that as the soil matric potential decreased the shear stress required for soil failure increased.

The amount of energy required to break down aggregates and cause soil loss was investigated by Wustamidin, et al. (1983). Their study showed that there were no differences in amount of energy required to break down aggregates for different size of aggregates of the same soil. But they noticed large differences in the amount of energy required to break down aggregates for different soils. Their results were different from McCalla (1944) results. McCalla found that the amount of energy required to break down large aggregates was less than that required to break down small aggregates.

Francis and Cruse (1983) measured aggregate breakdown as indicated by soil splash as a function of metric potential. Raising soil water potential from -1.5 KPa to zero caused a three-fold increase in soil splash illustrating the effect of surface tension on aggregate stability.
THEORY OF INFILTRATION MODELS

The early analyses developed to describe the infiltration of water into soil were based on the assumption of a uniform soil profile without a surface seal. Theoretical equations were derived to describe the rate of water flow into the soil profile. Recently, the parameters of a soil seal were added to describe infiltration into tilled soils.

Darcy's law is the fundamental equation used to develop the infiltration models. Darcy's law was originally developed to describe saturated soil water movement. It was later extended to describe water movement in unsaturated porous media.

Darcy's equation is:

\[ V = -K(\theta) \frac{d\psi}{dz} \]  

where \( V \) is the flux of water, \( K(\theta) \) is the unsaturated hydraulic conductivity of the soil as a function of water content, and \( \frac{d\psi}{dz} \) is the hydraulic gradient.

The Green-Ampt equation (1911) has been used and modified by scientists to describe the infiltration rate through layered and sealed soil profiles. The Green-Ampt equation can be written as:

\[ i = K(1+ \frac{\Delta \theta \psi_m}{I}) \]  

where \( i \) is the infiltration rate, \( K \) is the hydraulic conductivity of the soil, \( \Delta \theta \) is the soil water content difference before and after application, \( I \) is the amount of water infiltrated into the soil, and \( \psi_m \) is the soil water potential at the wetting front. The integrated form of Green-Ampt equation can be written as:

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\[ I - \Delta \theta \ln (1 + \frac{I}{\Delta \theta}) = Kt \]  

(6)

where \( t \) is the time from the beginning of rainfall. The Green-Ampt equation as derived was based upon several assumptions including a constant rainfall rate at the surface, a negligible depth of water on the soil surface, a uniform and homogenous soil profile and water content, a constant water potential at the wetting front, and an abrupt wetting front.

Richards (1931) equation can be obtained by combining Darcy's law with the continuity equation to describe the water flow through the soil profile. The equation is:

\[ \frac{\partial \theta}{\partial t} = - \frac{\partial}{\partial z} (K(\theta) \frac{\partial \psi}{\partial z}) - \frac{\partial K(\theta)}{\partial z} \]  

(7)

where \( \theta \) is the volumetric water content, \( t \) is time, \( z \) is the distance below the soil surface, \( K(\theta) \) is the unsaturated hydraulic conductivity, and \( \psi \) is the capillary pressure or water potential. This equation is a non-linear partial differential equation and describe vertical soil-water movement in a non-homogenous unsaturated soil in an unsteady state.

Mein and Larson (1971, 1973) developed a two-stage model to describe the infiltration process through a homogeneous soil with a uniform initial water content and under a constant rainfall condition. A parameter called ponding time \( (t_p) \) was used to separate the two stages. The first stage described the infiltration up to the ponding time. During this stage the rainfall rate is less than the infiltration capacity rate. At the ponding time, the rainfall rate equals the infiltration capacity rate \( (i = P) \), where \( i \) is the infiltration rate, \( P \)
is the rainfall rate. The infiltration equation up to the time of ponding is described by:

\[ I_p = \frac{\Delta \theta \psi_m}{\left( \frac{P}{K} \right) - 1} \]  

(8)

where \( I_p \) is the amount of water infiltrated at the time of ponding and \( K \) is the effective hydraulic conductivity.

For the second stage of infiltration Mein and Larson (1971, 1973) used a modified Green-Ampt equation to describe infiltration after surface ponding. The infiltration rate equation is the same as the original Green-Ampt equation and is:

\[ i = K \left( \frac{\Delta \theta \psi_m}{I} \right) \]  

(9)

However the integrated form of the equation is different and can be written as (Mein and Larson, 1971, 1973):

\[ I - \Delta \theta \psi_m \ln \left( 1 + \frac{I}{\Delta \theta \psi_m} \right) = K(t - t_p + t_s) \]  

(10)

where \( t_p \) is the time to surface ponding and can be calculated as:

\[ t_p = \frac{I_p}{I} \]  

(11)

and \( t_s \) is the time calculated from the original Green-Ampt equation when the infiltration volume equals \( I_p \) and it can be written as:

\[ t_s = \frac{1}{K} \left[ I_p - \Delta \theta \psi_m \ln \left( 1 + \frac{I_p}{\Delta \theta \psi_m} \right) \right] \]  

(12)

Equation (10) is similar to the Green-Ampt equation (eq. 6), but uses an adjusted time variable. This equation is called the Green-Ampt-Mein and Larson equation (GAML).

Morel-Seytoux and Khanji (1974) reported that the assumption of an abrupt wetting front for the Green-Ampt equation, separating the
saturated from the unsaturated area, could lead to a large error (10-70%) in the resulting calculation. They modified the Green-Ampt equation to account for viscous resistance caused by air movement through the soil. They introduced a viscous correction factor ($\beta$) to adjust the hydraulic conductivity in the Green-Ampt equation for the effects of air movement. The viscous correction factor is a function of the initial water content. The Morel-Seytoux and Khanji (1974) equation is:

$$i = \frac{K}{\beta} \left( \frac{H + \Psi_m + Z}{Z} \right)$$

where $i$ is the infiltration rate, $K$ is the saturated hydraulic conductivity, $\beta$ is the viscous correction factor, $H$ is the depth of ponded water above the surface, $\Psi_m$ is the capillary pressure or water potential at the wetting front, and $Z$ is the vertical distance below the soil surface.

**Infiltration Models for a Sealed Surface**

Steady and transient infiltration into unsaturated sealed surfaces were studied by Hillel (1964) and Hillel and Gardner (1969, 1970). They used Darcy's law for unsaturated porous media in their studies and assumed that the flow was equal through the seal and subseal layers because of the continuity ($V_c = V_u$ where $V_c$ is the flux through the seal layer). They assumed that the total hydraulic gradient is constant across the sealed layer if the soil is saturated and homogeneous. They indicated that the hydraulic properties of both layers, the seal and subseal, are shown to affect the process of infiltration through both layers. Hillel and Gardner (1970) applied
Green-Ampt assumptions to examine the infiltration into uniform and sealed soils which were initially dry. They designated three stages: a finite stage in which infiltration depends only on the seal layer which they called the "initial stage"; an intermediate stage in which the cumulative infiltration increased as the square root of time; and a final stage in which the infiltration rate was reduced to a final steady-state. They assumed a constant water content and water potential at the interface between the seal and the subseal.

Morin and Benyamini (1977) used a different approach to describe the infiltration process through the sealed soil from those described by Hillel (1964), and Hillel and Gardner (1969, 1970). They developed an empirical Horton type equation. The equation as written by Morin and Benyamini (1977) in terms of the number of median sized drops hitting the soil surface is:

\[ i = f_i + (i_0 - f_i) \exp(-n \cdot a \cdot t) \]  

and in terms of rainfall intensity:

\[ i = f_i + (i_0 - f_i) \exp(-\gamma \cdot P \cdot t) \]  

where \( i \) is the infiltration rate as a function of time, \( f_i \) is the final infiltration rate, \( \exp \) is the natural exponential operator, \( n \) is the number of median sized drops striking a unit area of surface, \( a \) is the area sealed by a median sized drop impact, \( P \) is the rainfall intensity, \( \gamma = \frac{a}{V_m} \), \( V_m \) is the volume of a median drop, and \( t \) is the time of exposure. The equations above were used with a constant rainfall intensity. The application of the equation to a sealed soil surface is illustrated in Figure 2 for different drying periods and shows the
Figure 2. Infiltration rate as a function of accumulated rain depth for bare and mulched Hamra soil (after Morin and Benyamini, 1977).
infiltration rate as a function of rainfall depth. This type of exponential decay function was also used by Moore (1979) and Moore et al. (1980) to describe the transient hydraulic conductivity of a surface seal. Also, similar equations were used by Van Doren and Allmaras (1978) and Linden (1979). In this study similar types of equations (14 and 15) were used to calculate the transient seal conductivity.

Ahuja (1973) used the Green-Ampt equation in a theoretical study of the vertical flow of water into a homogeneous soil through a sealed surface with constant non-zero hydraulic resistance. He reported that the water content at the interface between the seal and subseal increased all the time, more rapidly in the beginning and slowly later, until the flow reached a steady state. Ahuja (1974) extended the Green-Ampt approach of Hillel and Gardner (1970) to the process of infiltration through a seal after the initial stage. He reported that the model fit well for small seal resistances but involved increasing error with increasing seal resistance.

Chu and Engman reported that the traditional Green-Ampt equation was insufficient to describe infiltration and runoff in two field experiments. The modified Green-Ampt equation by Chu and Engman (1982), which depends on a two-phase infiltration process, was found to be more adequate than the traditional equation. Brakensiek and Rawls (1983) modified the Green-Ampt equation for field data with a sealed surface where the parameters of the equation were predicted from the physical properties of the soil; namely soil texture, surface cover, and roughness of the surface. The infiltration rate was predicted for the seal and subseal layers and compared to field data. The measured
and predicted data are shown in Figure 3. The Green-Ampt model for a two-layer profile as written by Brakensiek and Rawls (1983) is:

\[
\text{MA} \cdot \frac{dL}{dt} = \frac{K}{2} \frac{(L + \psi_m)}{L}
\]

where \( \text{MA} \) is the soil water storage of the tilled layer, \( dL \) is the wetting front advance rate, \( K \) the effective hydraulic conductivity, \( L \) is the wetting front depth including the seal thickness and the tilled layer and \( \psi_m \) is the negative pressure at the wetting front. The composite hydraulic conductivity for the two layers can be written as:

\[
K = \frac{L}{\frac{Z_c}{K_c} + \frac{L - Z_c}{K_a}}
\]

where \( K \) is the composite hydraulic conductivity, \( Z_c \) is the seal thickness, \( L \) is the tilled layer and seal thickness, and \( K_c \) and \( K_a \) are the seal conductivity and tilled layer conductivity, respectively. The seal hydraulic conductivity as written by Brakensiek and Rawls (1983) is:

\[
K_c = K_f + (K_o - K_f) \exp(-CE_s)
\]

where \( K_c \) is the transient seal saturated hydraulic conductivity, \( K_o \) is the initial seal conductivity, \( K_f \) is the final seal conductivity, \( C \) is a constant and \( E_s \) is the rainfall sealing energy at the soil surface. This equation can be applied to describe transient seal conductivity under a variable rainfall rate.

Linden (1979) described the rainfall sealing energy as follows:

\[
E_s = B(1 - RR/4) \text{EOA}
\]

where \( B \) is the friction of soil surface exposed, \( RR \) is the surface random roughness, and \( \text{EOA} \) is the rainfall energy. The constant \( C \) can
Figure 3. Infiltration rate as a function of time (after Brakensiek and Rawls, 1983).
be written as:

\[ C = -\ln\left(\frac{K_f}{K_0 - K_f}\right) \frac{1}{EOP} \]  \hspace{1cm} (20)

where EOP is the accumulative rainfall energy to reduce Kc to 2 Kf when B = 1 and RR = 0. The substitution of equations (19 and 20) into equation (18), Linden (1979), leads to:

\[ K_c = K_f + (K_0 - K_f) \exp[-\ln\left(\frac{K_f}{K_0 - K_f}\right) \cdot B \left(1 - \frac{RR}{4}\right) EOA] \]  \hspace{1cm} (21)

or

\[ K_c = K_f + (K_0 - K_f) \exp[-D \cdot B \left(1 - \frac{RR}{4}\right) EOA] \]  \hspace{1cm} (22)

where

\[ D = -\ln\left(\frac{K_f}{K_0 - K_f}\right) \]  \hspace{1cm} (23)

The accumulative rainfall energy (EOA) was described by Wischmeier and Smith (1978) as:

\[ EOA = \left[0.02062 + 0.00379 \cdot \ln(P)\right] \cdot P \cdot t \]  \hspace{1cm} (24)

where P is the rainfall intensity (cm/hr) and t is the time required for the sealing energy to reach EOP.

The two layer Green-Ampt equation of Brakensiek and Rawls (1983) was modified by Chu (1984) to include the subsoil layer also. The model included the interface between the subseal (tilled layer) and the subsoil, and the ponding of water above the subsoil. The soil profiles assumed to include three layers: the surface seal, the tilled layer and the subsoil (Moore and Larson, 1980). Each layer was described by its specific thickness, hydraulic conductivity, capillary tension and storage parameter as discussed in detail by Chu (1984). The first two layers were described by Brakensiek and Rawls (1983). The infiltration
capacity rate which describes the three layer Green-Ampt infiltration model as written by Chu (1984) is:

$$\frac{Mb \cdot d(Lb)}{dt} = \frac{1}{2} \frac{Zc + Za + Lb + hb}{Zc + Za + Lb}$$

(25)

where $Mb$ is the soil storage of the subsoil layer, $d(Lb)$ is the infiltration capacity rate (cm/hr), $Zc$, $Za$ and $Lb$ are the seal thickness (cm), the tilled layer depth (cm) and the wetting front depth within the subsoil (cm), respectively, $hb$ is the effective soil water pressure in the subsoil (cm) and $Kc$, $Ka$ and $Kb$ are the hydraulic conductivities of the seal, tilled and the subsoil (cm/hr), respectively. The amount of water infiltrated ($I$) when there is no water pondage on the interface is:

$$I = MD_1 \cdot Zc + MD_2 \cdot Za + MD_3 \cdot Lb$$

(26)

where $MD_1$, $MD_2$ and $MD_3$ are the soil storage of the seal, tilled and subsoil layers, respectively.

The final hydraulic conductivity of the seal layer ($Kf$) was calculated as follows:

$$Kf = \frac{Zc \cdot Sc \cdot Ko}{PFc + Zc}$$

(27)

where $Zc$ is the seal thickness (cm), $Sc$ is the correction factor in Linden's formula (1979), $Ko$ is the initial seal conductivity and $PFc$ is the water potential (cm) at the seal and subseal interface. In summary, two soil sealing parameters were used to describe the transient seal hydraulic conductivity. They are the soil water potential beneath the seal ($PFc$) and the energy parameter $EOP$.

Preliminary tests of equations 16 and 25 by comparing field data...
with simulated results indicated that the layered Green-Ampt model by Brakensiek and Rawls (1983) and the modified layered Green-Ampt equation by Chu (1984) were not adequate to describe the infiltration rate in Vienna loam and Lowry silt loam. The primary difficulty is that the effective soil conductivity is represented by the harmonic mean of the seal conductivity, the tilled soil conductivity and the subsoil conductivity. Because the thickness of the seal is thin, its relative effect on the harmonic mean is negligible. Observation in practice indicated that the seal layer is the controlling factor in the infiltration process. Therefore the model was modified by the concept described by Childs (1969), who stated "when the saturated conductivity of the upper layer is less than that of the lower layer, the infiltration capacity is quite unaffected by the presence of the lower layer, and is, in fact, simply the infiltration capacity of the upper layer by itself." As a result, the hydraulic conductivity of the tilled layer (Ka), and the conductivity of the subsoil layer (Kb) in equation (25) became equal to the conductivity of the seal layer (Kc). The equation (25) is then rewritten as:

\[
\frac{d(Lb)}{dt} = \frac{1}{2} \frac{Zc + Za + Lb + hb}{Zc + Za + \frac{Lb}{Kc}} + \frac{Lb}{\min(Kc, Kb)}
\]

(28)

where all the terms were defined previously. The operator (min) refers to the smaller value of the two quantities included in the parentheses. When Kb is less than Kc the conductivity of the subsoil is equal to Kb, and when Kb is greater than Kc, the hydraulic conductivity of the subsoil is equal to Kc. Equation (28) was used to describe the infiltration rate in both soils and compared to field data.
**MATERIALS AND METHODS**

**Infiltrometer**

A rain simulator was used to produce different intensities and kinetic energies. The Purdue infiltrometer developed by Bertrand and Parr (1960) and described in detail by Bertrand and Parr (1961) was used in this study, though slightly modified by Dr. Shu-Tung Chu, Agriculture Engineering Department, SDSU. The infiltrometer was supplied with all the equipment for runoff accumulation and measurement, (pressure tank, pumps, water reservoir, etc.), as shown in Figure 4. The main modification was the replacement of the stationary nozzle mount with an oscillating mechanism. Flat spray nozzles were then used in place of the full cone nozzles and a horizontal arm was attached to the oscillating mechanism to accommodate multiple nozzles. This arrangement accomplished numerous features. Varying nozzle sizes changed the kinetic energy at a given intensity. Varying the number of nozzles changes rainfall intensity except for the single nozzle arrangement. The oscillating mechanism also provided for a more uniform distribution of water to the 2.1 meter by 3.0 meter area containing the one square meter plot.

Runoff was measured by pumping the runoff water from the plot collection basin with a peristaltic pump into a pan suspended from a 50 Kg scale. A stop watch was used to determine when to take readings at one minute intervals.

Soil water contents were determined by sampling before and after water application.
Figure 4. The infiltrometer with all equipment such as (water reservoir, pressure tank, pumps, runoff pan, scale, etc.).
Types of Nozzles

Spraying System Company VeeJet Nozzles were used to supply artificial rainfall with different intensities and kinetic energies. The nozzles used are listed in Table 1.

Table 1. Type of nozzle, nozzle number, discharge, diameter and kinetic energy rate (KE) used in the study.

<table>
<thead>
<tr>
<th>Type of Nozzle</th>
<th>Nozzle No.</th>
<th>Discharge (L/S) at 6 psi</th>
<th>Diameter (mm)</th>
<th>KE J/m²·mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>S S Co VeeJet</td>
<td>H 1/8 U 8010</td>
<td>0.025</td>
<td>1.98</td>
<td>7.2</td>
</tr>
<tr>
<td>S S Co VeeJet</td>
<td>H 1/8 U 8020</td>
<td>0.049</td>
<td>2.78</td>
<td>8.2</td>
</tr>
<tr>
<td>S S Co VeeJet</td>
<td>H 1/8 U 8030</td>
<td>0.079</td>
<td>3.57</td>
<td>12.4</td>
</tr>
<tr>
<td>S S Co VeeJet</td>
<td>H 1/4 U 8070</td>
<td>0.170</td>
<td>5.16</td>
<td>19.4</td>
</tr>
<tr>
<td>S S Co VeeJet</td>
<td>H 1/2 U 80150</td>
<td>0.365</td>
<td>7.54</td>
<td>24.4</td>
</tr>
</tbody>
</table>

The rainfall intensities, spatial distributions of the nozzle arrangements, and drop size distribution measurements were made in the laboratory before moving the infiltrometer to the field. Nozzle arrangements were adjusted at this time to provide uniform spatial distribution of water to the application surface.

Field Plot Preparation

The field experiments were conducted on Vienna loam (Mixed Udic Haploboroll) and Lowry silt loam (Typic Haplustoll) soils. Areas were mechanically tilled to a depth of 0.15 - 0.20 m. Individual plot areas of 2.1 by 3.0 m were graded to a 2% slope with a garden rake. Large clods were removed to provide a uniform soil surface. The test plots
were isolated within this area by a 1.0 meter square frame. A plot ready for exposure to rainfall is shown in Figure 5.

**Field Treatments:**

The combination treatments of rainfall kinetic energies and intensities are presented in Table 2 for Vienna loam. Six levels of rainfall energy were used. The zero level of energy was obtained by protecting the soil surface with cheesecloth. Two covers were used on Vienna loam, a screen which was located about 10-15 cm above the surface and another cover which was located directly on the surface. Three rainfall intensities were applied with the kinetic energy levels of 0, 7.2, 12.4 J/m$^2$.mm while one rainfall intensity was used for the remaining kinetic energy level in Vienna loam. One rainfall intensity was applied with three levels of kinetic energy (low, 12.4 and 24.4 J/m$^2$.mm) to Lowry silt loam as shown in table 3. The low energy level was obtained by covering the surface with a screen which was located about 10-15 cm above the soil surface. No direct cover on the soil surface was used. The treatments on both soils (Table 2, 3) were initiated on dry-bare surfaces for the first run and then on wet-bare surfaces for the second run (17-24 hours after the first run). With the covered treatments, the first run started with a dry-covered surface and the second with a wet-covered surface (17-24 hours after the first run).
Figure 5. A field unit before the rainfall application on a bare soil surface.
Table 2. Kinetic energy rate and rainfall intensities for different treatments on Vienna loam soil.

<table>
<thead>
<tr>
<th>Kinetic energy rate, J/m²·mm</th>
<th>Rainfall Intensities (mm/hr)*</th>
<th>Soil surface Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.4</td>
<td>123.7 125.4</td>
<td>Dry-bare Wet-bare</td>
</tr>
<tr>
<td>19.4</td>
<td>123.0 115.0</td>
<td>Dry-bare Wet-bare</td>
</tr>
<tr>
<td>12.4</td>
<td>149.0 151.9 101.6 101.7 53.6</td>
<td>Dry-bare Wet-bare</td>
</tr>
<tr>
<td>8.2</td>
<td>128.0 128.0</td>
<td>Dry-bare Wet-bare</td>
</tr>
<tr>
<td>7.2</td>
<td>148.5 148.5 79.3 79.8 43.5</td>
<td>Dry-bare Wet-bare</td>
</tr>
<tr>
<td>0</td>
<td>155.4 155.2 100.6 101.8 53.8 54.1</td>
<td>Dry-covered Wet-covered</td>
</tr>
</tbody>
</table>

*Rainfall intensity values are the mean of 4, 3, 4, 3, 2 and 1 plots for the energy levels of 24.4, 19.4, 12.4, 8.2, 7.2 and 0 J/m²·mm, respectively.
Table 3. Kinetic energy rate and rainfall intensities for different treatments on Lowry silt loam.

<table>
<thead>
<tr>
<th>Kinetic energy rate (J/m².mm)</th>
<th>Rainfall intensity* (mm/hr)</th>
<th>Soil surface treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.4</td>
<td>112.2</td>
<td>Dry-bare</td>
</tr>
<tr>
<td></td>
<td>113.8</td>
<td>Wet-bare</td>
</tr>
<tr>
<td>12.4</td>
<td>129.3</td>
<td>Dry-bare</td>
</tr>
<tr>
<td></td>
<td>125.0</td>
<td>Wet-bare</td>
</tr>
<tr>
<td>0</td>
<td>113.7</td>
<td>Dry-covered</td>
</tr>
<tr>
<td></td>
<td>116.8</td>
<td>Wet-covered</td>
</tr>
</tbody>
</table>

*Rainfall intensity values are the mean of three plots.
Soil water contents

Soil samples were collected before and after water applications. The soil samples were oven dried at 110° C for water content determination. Soil water was measured for several reasons:

1) To determine the water distribution before and after rainfall applications.
2) For use as a soil water difference (MD) in the Green-Ampt infiltration model.
3) And to determine the water content of the surface aggregates before the rainfall application.

Soil aggregates stability

Aggregate stability for the surface soil of Vienna loam and Lowry silt loam was determined in the laboratory by the method described by Kemper and Koch (1966). Stability was measured on initially dry and initially wet soil aggregates. Samples from the surface and subsurface were tested. The samples were sieved to obtain the 1-2 mm aggregates. Four grams of the aggregates were loaded onto a sieving screen and carefully placed into a wetting chamber before testing. The soil water content of the wetted aggregates ranged between 20-40%. The screens with the soil aggregates were placed into aluminum cans and sieved for five minutes. They were then transferred to other aluminum cans for dispersion of the remaining aggregates. A sonifier was used for dispersion with the sand remaining on the screen. The aluminum cans and screens were oven dried at 110° C. After weighing the oven dry material, the aggregate stability was calculated.
as follows:

\[
\text{Agg.
}\text{stab. } \% = \frac{(\text{Wt. of stab. agg. + sand}) - (\text{Wt. of sand})}{(\text{Wt. of sample}) - (\text{Wt. of sand})} \times 100
\]  

(29)

where the stable aggregates are the remaining aggregates on the sieve after five minutes of sieving in water.

**Drop size distribution**

The drop size distributions of the different nozzles were measured in the laboratory by the flour method used by Laws and Parsons (1943) and verified by Kohl (1974). Trays were filled with sifted flour and exposed to the rainfall drops 2.4 meters below the nozzles. The trays were 1.5 cm deep and 21 cm in diameter. After exposing the flour to the raindrops, a thin layer of flour was added to insure that all pellets were covered. The pellets were oven dried at 110° C for 4-6 hours. The pellets along the edges were eliminated by sampling the center 20 cm diameter of the trays. The pellets were separated from the flour by shaking on a 50 mesh sieve. Pellets were then separated by using a set of 16 sieves, U. S. series 5-50 mesh size as mentioned by Kohl (1974), and Kohl and DeBoer (1983). The flour pellets on each sieve were weighted. The mass ratio (Rm), the mass of water droplet to dry flour pellet mass (Pm), as determined by Meyer (1958) and verified by Kohl (1974) was used. The equation was:

\[
R_m = 1.05 \ P_m^{0.61}
\]  

(30)

where the mass is in mg.

**Kinetic energy**

The kinetic energy is equal to \(1/2 \ mV^2\), where kinetic energy is
in joules, the raindrop mass \((m)\) is in Kg and the impact velocity of the raindrop \((V)\) is in meter/sec. The total energy, \(\Sigma KE\) of the distribution was calculated as the sum of the droplets energies:

\[
\Sigma KE = \frac{1}{2} \sum_{i=1}^{n} M_i V_i^2
\]  

where \(n\) is the total number of drop size classes. Droplet velocities were computed using the procedure of Seginer (1965). Table 4 shows the median drop sizes and their corresponding velocities:

<table>
<thead>
<tr>
<th>Sieve #</th>
<th>Mean drop diameter (mm)</th>
<th>Velocity (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4.88</td>
<td>9.00</td>
</tr>
<tr>
<td>6</td>
<td>4.00</td>
<td>8.85</td>
</tr>
<tr>
<td>7</td>
<td>3.32</td>
<td>8.65</td>
</tr>
<tr>
<td>8</td>
<td>2.77</td>
<td>8.27</td>
</tr>
<tr>
<td>10</td>
<td>2.32</td>
<td>7.85</td>
</tr>
<tr>
<td>12</td>
<td>1.96</td>
<td>7.35</td>
</tr>
<tr>
<td>14</td>
<td>1.59</td>
<td>6.60</td>
</tr>
<tr>
<td>16</td>
<td>1.31</td>
<td>5.70</td>
</tr>
<tr>
<td>18</td>
<td>1.12</td>
<td>5.05</td>
</tr>
<tr>
<td>20</td>
<td>0.95</td>
<td>4.05</td>
</tr>
<tr>
<td>25</td>
<td>0.80</td>
<td>3.32</td>
</tr>
<tr>
<td>30</td>
<td>0.67</td>
<td>2.82</td>
</tr>
<tr>
<td>35</td>
<td>0.56</td>
<td>2.46</td>
</tr>
<tr>
<td>40</td>
<td>0.47</td>
<td>2.05</td>
</tr>
<tr>
<td>45</td>
<td>0.39</td>
<td>1.65</td>
</tr>
<tr>
<td>50</td>
<td>0.33</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Table 4. Median drop velocities and drop diameters for the dough balls retained on the sieve sizes used in this study.

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Green-Ampt Input Data:

A program written in Fortran by Dr. S. T. Chu, Agricultural Engineering Department, SDSU, was used to calculate the predicted values of the infiltration rate, cumulative infiltration depth, runoff, wetting front depth and seal conductivity.

The input parameters of the modified Green-Ampt model are divided into groups: first, the constant parameters which do not change with changing kinetic energy levels for all plots within the same soil as listed in Table 5. The average seal thickness was assumed to be 0.5 cm which corresponds to values reported by several researchers (Ahuja, 1974 and 1983, Brakensiek and Rawls, 1983 and Chu, 1984). The tilled layer thickness in both soils is 15 cm including the thickness of the seal. The initial hydraulic conductivity of the seal (K0), the effective hydraulic conductivity of the seal layer (K1) was changing with the time, and the effective conductivity of the tilled layer (K2) was assumed to be equal to the application rate of the covered plots in both soils. The conductivity of the subsoil (K3) was calculated from the no-till plot results (Chu, 1985, personal communication). The water potential, PF1, PF2 and PF3, for the three layers is assumed to be small because of the water movement through the large pores (macropores) (Chu, 1985, personal communication). PFc is the water potential beneath the seal, a controlling factor in the determination of the final seal conductivity (Linden, 1979). However, this factor is difficult to measure in the field. The value of PFc in this study was obtained indirectly by trial and error by matching simu-
Table 5. Infiltration parameters input of Green-Ampt model for Vienna loam and Lowry silt loam.

<table>
<thead>
<tr>
<th>Parameter symbol*</th>
<th>Lowry silt loam</th>
<th>Vienna loam</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD1</td>
<td>0.5</td>
<td>0.5</td>
<td>Depth to seal bottom (cm)</td>
</tr>
<tr>
<td>LD2</td>
<td>15.0</td>
<td>15.0</td>
<td>Depth to tilled boundary (cm)</td>
</tr>
<tr>
<td>LT1</td>
<td>0.5</td>
<td>0.5</td>
<td>Seal thickness (cm)</td>
</tr>
<tr>
<td>LT2</td>
<td>14.5</td>
<td>14.5</td>
<td>Tilled layer thickness (cm)</td>
</tr>
<tr>
<td>K1</td>
<td>---</td>
<td>---</td>
<td>Effective seal conductivity (cm/hr)</td>
</tr>
<tr>
<td>K2</td>
<td>13.5</td>
<td>13.5</td>
<td>Effective tilled conductivity (cm/hr)</td>
</tr>
<tr>
<td>K3</td>
<td>2.0</td>
<td>2.5</td>
<td>Effective subsoil conductivity (cm/hr)</td>
</tr>
<tr>
<td>K0</td>
<td>13.5</td>
<td>13.5</td>
<td>Initial seal conductivity (cm/hr)</td>
</tr>
<tr>
<td>PF1</td>
<td>0.5</td>
<td>0.5</td>
<td>Water potential in seal (cm)</td>
</tr>
<tr>
<td>PF2</td>
<td>0.5</td>
<td>0.5</td>
<td>Water potential in tilled layer (cm)</td>
</tr>
<tr>
<td>PF3</td>
<td>0.8</td>
<td>0.8</td>
<td>Water potential in subsoil (cm)</td>
</tr>
<tr>
<td>PFc</td>
<td>5.0</td>
<td>3.0</td>
<td>Water potential under seal (cm)</td>
</tr>
<tr>
<td>RR</td>
<td>1.0</td>
<td>1.0</td>
<td>Random roughness (cm)</td>
</tr>
<tr>
<td>SS</td>
<td>0.18</td>
<td>0.18</td>
<td>Surface storage capacity (cm)</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
<td>1.0</td>
<td>Bare soil fraction (dimensionless)</td>
</tr>
<tr>
<td>Sc</td>
<td>0.82</td>
<td>0.81</td>
<td>Correction factor (dimensionless)</td>
</tr>
<tr>
<td>INT</td>
<td>0.0</td>
<td>0.0</td>
<td>Interception (cm)</td>
</tr>
</tbody>
</table>

*The parameters, K1, K2 and K3 correspond to the parameters, Ke, Ka and Kb, respectively in equation 13.
lated runoff and final hydraulic conductivities with the measured plot runoff and hydraulic conductivity. The bare soil roughness (RR) is about equal to 1.0 cm. Since all of the soil surface is exposed to the rainfall application, the bare soil friction (B) is 1.0. The correction factor (Sc) has the values of 0.81 and 0.82 for the Vienna loam and Lowry silt loam, respectively (Linden, 1979). Since no plants were present on the plots, the interception (Int) value is zero. The second group of parameters change as the kinetic energy changes and from plot to plot. The total kinetic energy EOP (J/cm^2) is different for each kinetic energy level. The soil water contents are different for the seal, tilled and subsoil layers (MD_1, MD_2, MD_3) both before and after each run.

The main input into the program is the infiltration depth (cm) with respect to the time from the beginning of the rainfall application to the end of the run. These data were measured in the field for each plot.
RESULTS AND DISCUSSION

The physical properties of Vienna loam and Lowry silt loam including bulk density, total porosity and particle size distribution are shown in Tables 6 and 7, respectively. Vienna loam is a Mixed Udic Haploboroll, moderately well-drained soil. It developed in glacial till of loam or clay loam texture, or both. It is somewhat homogenous and moderately level. Vienna loam is noncalcareous to about the 45 cm depth and is calcareous below. The mean sand, silt and clay contents of Vienna loam are 39.8%, 33.9% and 26.3%, respectively.

Lowry silt loam is a coarse-silty mixed, Typic Halustoll, well-drained loess on uplands and terraces, developed in loess. This soil is noncalcareous in the upper layers grading to calcareous between 0.4 and 0.5 meters. It is moderately low in organic matter. The mean sand, silt and clay contents for the upper 45 cm are 12.8%, 68.7% and 18.5%, respectively.

The bulk density of Vienna loam increases and total porosity decreases with depth. The bulk density and total porosity are almost constant with depth in Lowry silt loam.

1. Kinetic Energy Level Effects on Infiltration

a. Infiltration Rate

The infiltration rate was measured for all treatments using the continuity equation:

\[ i = P - R_n - \frac{ds}{dT} \]  

(32)
Table 6. Some soil physical properties of Vienna loam at Brookings (Agronomy Farm) South Dakota.

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>Bulk density* (g/cm³)</th>
<th>Total porosity* (% vol.)</th>
<th>Particle size distribution**</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>1.24</td>
<td>53.7</td>
<td>42.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>34.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>22.7</td>
</tr>
<tr>
<td>15-30</td>
<td>1.33</td>
<td>50.2</td>
<td>40.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>37.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>21.2</td>
</tr>
<tr>
<td>30-45</td>
<td>1.39</td>
<td>47.9</td>
<td>42.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>32.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>24.8</td>
</tr>
<tr>
<td>45-60</td>
<td>1.45</td>
<td>45.7</td>
<td>38.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>28.3</td>
</tr>
<tr>
<td>60-75</td>
<td>1.54</td>
<td>42.3</td>
<td>38.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>28.3</td>
</tr>
<tr>
<td>75-90</td>
<td>1.63</td>
<td>39.0</td>
<td>38.4</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>28.3</td>
</tr>
<tr>
<td>90-105</td>
<td>1.74</td>
<td>34.8</td>
<td>38.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>28.3</td>
</tr>
<tr>
<td>105-120</td>
<td>1.74</td>
<td>34.8</td>
<td>38.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>28.3</td>
</tr>
<tr>
<td>120-135</td>
<td>1.78</td>
<td>33.3</td>
<td>39.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>33.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>26.3</td>
</tr>
</tbody>
</table>


**Soil Survey, Brookings County, S.D. Series 1955, No. 3.
Table 7. Some soil physical properties of Lowry silt loam at Gettysburg (Private Farm) South Dakota.

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>Bulk density* (g/cm³)</th>
<th>Total porosity* (% vol.)</th>
<th>Particle size distribution**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sand</td>
</tr>
<tr>
<td>0-15</td>
<td>1.32</td>
<td>50.6</td>
<td>12.3</td>
</tr>
<tr>
<td>15-30</td>
<td>1.29</td>
<td>51.7</td>
<td>12.0</td>
</tr>
<tr>
<td>30-45</td>
<td>1.24</td>
<td>53.6</td>
<td>14.0</td>
</tr>
<tr>
<td>45-60</td>
<td>1.26</td>
<td>52.8</td>
<td></td>
</tr>
<tr>
<td>60-75</td>
<td>1.32</td>
<td>50.6</td>
<td></td>
</tr>
<tr>
<td>75-90</td>
<td>1.29</td>
<td>51.7</td>
<td></td>
</tr>
<tr>
<td>90-105</td>
<td>1.30</td>
<td>51.3</td>
<td></td>
</tr>
<tr>
<td>105-120</td>
<td>1.33</td>
<td>50.2</td>
<td></td>
</tr>
<tr>
<td>120-135</td>
<td>1.32</td>
<td>50.6</td>
<td></td>
</tr>
</tbody>
</table>


where \( i \) is the infiltration rate (mm/hr), \( P \) is the application rate (mm/hr), \( Rn \) is the runoff (mm/hr) and \( ds \) is the change in surface storage with respect to the change of time (dT). The last term of the equation was very small, so it was neglected in the calculation.

The relationship of infiltration rate as a function of time for different levels of kinetic energy as calculated by equation (32) is shown in Figures 6 and 7 for Vienna loam and Lowry silt loam, respectively. There was a sharp decrease in the infiltration rate curves of the high kinetic energy after runoff started as well as a reduction in the final infiltration rate values between the low and high kinetic energies. The infiltration rate changed less rapidly after 30 minutes from the time runoff began. Moldenhauer and Long (1964) also noticed a sharp decrease in the infiltration rate after runoff began. They also indicated that the final infiltration rate was reached rather quickly after runoff started.

In this study, the final (or steady state) infiltration rate for the low kinetic energy rate (7.2 and 8.2 J/m²:mm) was twice as high as the value for the high kinetic energy rate (24.4 J/m²:mm) for the Vienna loam soil shown in Figure 6. This phenomenon indicated that the effects of a low kinetic energy on soil surface seal development and the final infiltration rate were less than the effects of the high level of kinetic energy at a constant rainfall intensity.

Seal development is different from one kinetic energy to another. The seal developed faster under the high kinetic energy level than the low kinetic energy level as is evidenced by the decrease in
Figure 6. Infiltration rate for different levels of kinetic energy in Vienna loam soil. Mean of 1, 2, 3, 4, 3, and 4 plots for the energy levels of 0, 7.2, 8.2, 12.4, 19.4, and 24.4, respectively.
Figure 7. Infiltration rate for different levels of kinetic energy in Lowry silt loam. (mean of 3 plots).
The steepness of the curves after runoff started in Figure 6 and 7.

The infiltration rate of Lowry silt loam (Figure 7) decreased faster than the one in Vienna loam (Figure 6). The infiltration rate after 15 minutes from the beginning of the rainfall application and the same kinetic energy (12.4 J/m².mm) decreased to 88 mm/hr and 30 mm/hr for Vienna loam and Lowry silt loam, respectively. This is a result of the differences in the physical properties of the two soils.

Surface aggregate stabilities for Vienna loam and Lowry silt loam are 89% and 73%, respectively. Two factors are responsible for reduction in the infiltration rate during the time of rainfall in this study, the first factor includes the physical properties of the soil such as sensitivity of the surface aggregates to rainfall impact and the porosity of the soil while the second factor relates to the properties of the water such as drop size and kinetic energy.

The final infiltration rate of Lowry silt loam dropped to 14 and 6 mm/hr for the kinetic energy rates of 12.4 and 24.4 J/m².mm, respectively, and for Vienna loam it dropped to about 40 and 21 mm/hr for the same kinetic energy rates. These final infiltration rates emphasize the differences in the physical properties of the two soils such as texture, aggregate stability and organic matter content. Lowry silt loam has a higher percentage of silt and lower percentage of clay compared to Vienna loam. Increasing silt content and decreasing organic matter content increased the soil's susceptibility to sealing (Cary and Evans, 1974, Miller and Gifford, 1974, Bradfield and Jamison, 1939, and Lemos and Lutz, 1957).

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A simple linear regression equation was used to describe the relationship of kinetic energy rate (J/m².mm) and final infiltration rate (mm/hr) for Vienna loam soil as follows:

\[ i = 57.58 - 1.43 \text{KE} \] (33)

where \( i \) is the final infiltration rate (mm/hr) and KE is the kinetic energy rate (J/m².mm). A good correlation was found and the kinetic energy rate explained 80% of the variation of the near final infiltration rate (\( R^2 = 0.80 \)) and there is a significant difference at the 5% level (Table A1 Appendix). The relationship of \( i \) and KE is shown in Figure 8. As the kinetic energy increases the near final infiltration rate decreases.

The infiltration rate of the protected surface where the kinetic energy was reduced to a low value by using a screen or a screen with direct cover in both soils is very high compared to bare treatments. No runoff occurred from Vienna loam for all treatments with a double cover. In this case the kinetic energy was reduced to zero J/m².mm. The Lowry silt loam experiments were conducted with the screen located about 10-15 cm above the surface but with no direct cover on the surface. Some fine spray was observed coming through the screen cover when collecting data on Vienna loam and it is assumed to have occurred on Lowry silt loam also. However, the Lowry data were not repeated with extra cover because of travel distance. Therefore, kinetic energy under the covered treatment on Lowry silt loam was small but not zero. Runoff occurred in those treatments. The comparison of the covered and bare surface will be discussed later.
Figure 8. Final infiltration rate as a function of kinetic energy rate

\[ i = 57.58 - 1.43 \text{ KE} \]

\[ R^2 = 0.80 \]
b. Infiltrability of Bare and Covered Treatments

The infiltration rates as a function of time for dry and wet treatments on bare and covered soil surfaces are shown in Figures 9 and 10 for Vienna loam and Figure 11 for Lowry silt loam. The infiltration rate of the dry-covered treatment is very high in both soils compared to the dry-bare treatment. The high infiltration rate of the protected surface indicated that no seal developed and all of the water infiltrated into the soil surface. The dry-bare treatment showed the development of the seal layer and the infiltration rate dropped sharply after runoff started.

Runoff occurred on the wet-covered treatment (2nd run) presented in Figure 9 and the infiltration rate decreased slightly. Under this condition, there was no seal development but there are some possible reasons for decreasing the infiltration rate such as air entrapment, slaking and soil compaction.

The wet-bare treatment (3rd run) in Figure 9 and the dry-bare treatment (1st run) in Figure 10 provide a comparison between wet and dry aggregates and the time to break down the aggregates and start runoff. In the wet-bare treatment in Figure 9, surface aggregates broke down 3-5 minutes earlier than in the dry-bare treatments in Figure 10. This difference in time is the time required for wetting the surface aggregates of the dry-bare treatment, which is the first step indicated by McIntyre (1958a) in order to start seal formation.

The wet-bare treatments (2nd run) in Figures 10 and 11 for Vienna loam and Lowry silt loam are good evidence for the effects of
Figure 9. Infiltration rate for different surface conditions and 12.4 J/m^2-mm kinetic energy rate (mean of 3 plots).
Figure 10. Infiltration rate for different surface conditions and 12.4 J/m²·mm of kinetic energy rate (mean of 4 plots).
Figure 11. Infiltration rate for different surface conditions and 24.4 J/m$^2$.mm of kinetic energy rate in Lowry silt loam (mean of 3 plots).
seal formation in reducing the infiltration rate and increasing runoff. The seal developed in these two treatments early in the first run (about 17-24 hours). Now, in the second run, runoff occurred after one minute on Vienna loam and less than a minute on Lowry silt loam. The infiltration rate was reduced to 14.7% and 7.9% of the original application rate after 10 minutes in Vienna loam and Lowry silt loam, respectively.

The steady state infiltration rate was reached shortly after runoff began. Reducing infiltrability caused two things to increase, runoff and soil erosion. The soil erosion was noticed in the runoff pan during the collection of the runoff and also was observed in the infiltration data after the seal formed which indicated that some of the seal skin was removed. The infiltration rate varied up and down slightly which is evidence for removing and forming a part of the seal layer which McIntyre (1958a) called a "skin seal". The eroded area can be clearly seen in Figure 12 after the plot was exposed to high rainfall intensity for 60 minutes.

c. Cumulative Infiltration (I)

Cumulative infiltration is the total amount of water which has entered the soil surface from the beginning of the rainfall application to a specific time. Cumulative infiltration was affected by the kinetic energy rate. The relationship of I (mm) and different levels of energy are presented in Figures 13 and 14 for Vienna loam and Lowry silt loam, respectively. There was a significant difference at the 5% level in the amount of water which infiltrated into the profile for
Figure 12. The field unit after exposing to rainfall for 60 minutes in Vienna loam soil.
Figure 13. Cumulative infiltration for different levels of energy
Mean of 1, 2, 3, 4, 3, and 4 plots for the energy levels
of 0, 7.2, 8.2, 12.4, 19.4, and 24.4, respectively.
Figure 14. Cumulative infiltration for different levels of kinetic energy (mean of 3 plots).

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different kinetic energy levels (Table A3, Appendix). As the kinetic energy level of rainfall increased the total quantity of water that entered the soil profile after a given time decreased. For example, after one hour of rainfall application, the amount of water which infiltrated into Vienna loam was 136, 86, 82, 71, 56 and 47 mm for the kinetic energy levels of 0, 7.2, 8.2, 12.4, 19.4 and 24.4 J/m^2.mm, respectively and for Lowry silt loam infiltration amounted to 97, 37 and 22.5 mm for the kinetic energy levels of 0, 12.4 and 24.4 J/m^2.mm, respectively. The results are comparable to the results in Figure 6 where the infiltration rate value after 60 minutes for the low kinetic energy level (7.2 J/m^2.mm) is double that of the high kinetic energy level (24.4 J/m^2.mm).

The amount of water infiltrated under the zero kinetic energy level is high compared to the other treatments. This results from not developing a surface seal in the protected treatments which allows the water to infiltrate rapidly. Cumulative infiltration into Lowry silt loam with a protected surface was less than the amount applied. As mentioned previously, some spray was observed coming through the screen and the kinetic energy was not zero. This may account for the deviation of the covered infiltration from the application curve for Lowry silt loam.

2. Kinetic Energy Effects on Time to Runoff and Time to Infiltrate 50 mm of Water

   a. Time to surface runoff (Trn)

   The time to runoff is the time from the beginning of the rain-fall application until runoff begins. The time to runoff (minutes) for
different kinetic energy rates (J/m².mm) is shown in Table 8. As the kinetic energy rate increases, the time to runoff decreases. The total energy which the surface aggregates received from different levels of rainfall kinetic energy determined the time to runoff. High kinetic energy levels required a short time to achieve the amount of energy needed to break down the aggregates and start runoff. On the other hand, low kinetic energy applications take more time to accumulate the same amount of energy required to break down the aggregates and form the surface seal.

A linear regression equation was obtained to describe the relationship between KE and Trn. The regression is shown in Figure 15 and has an $R^2 = 0.28$ and there is no significant difference at the 5% level (Table A2, Appendix). The linear equation is:

$$Trn = 10.9 - 0.145 \text{KE} \quad (35)$$

where Trn is the time to runoff (minutes) and KE is the kinetic energy rate (J/m².mm). The zero kinetic energy data was not entered into the regression because there was no runoff under this level of energy on the Vienna loam soil.

As explained earlier, the physical properties of the soil and raindrop impact are the major factors affecting the aggregates' stability and the establishment of runoff. The surface aggregates were wetted and as they approached saturation they broke down under the action of raindrop impact. The fine particles were then washed into the pores, reducing their volume. As a result, the infiltration rate decreased, water started ponding on the surface and runoff began.
Table 8. Kinetic energy rate (KE), time to runoff (Trn), total kinetic energy (\(\Sigma KE\)), time to infiltrate 50 mm of water (T_{50}) and final infiltration rate (i) for Vienna loam (mean of 4, 2, 3, 5, 3 and 5 plots for the KE of 0, 7.2, 8.2, 12.4, 19.4 and 24.4, respectively).

<table>
<thead>
<tr>
<th>KE (J/m^2.mm)</th>
<th>Trn minutes</th>
<th>(\Sigma KE^*) J/m^2</th>
<th>T_{50} minutes</th>
<th>i mm/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>----</td>
<td>----</td>
<td>20.6</td>
<td>----</td>
</tr>
<tr>
<td>7.2</td>
<td>10.0</td>
<td>178.2</td>
<td>25.0</td>
<td>50.0</td>
</tr>
<tr>
<td>8.2</td>
<td>14.0</td>
<td>245.1</td>
<td>28.0</td>
<td>45.0</td>
</tr>
<tr>
<td>12.4</td>
<td>8.9</td>
<td>270.0</td>
<td>34.4</td>
<td>41.0</td>
</tr>
<tr>
<td>19.4</td>
<td>8.3</td>
<td>331.3</td>
<td>50.3</td>
<td>29.0</td>
</tr>
<tr>
<td>24.4</td>
<td>7.5</td>
<td>377.3</td>
<td>72.3</td>
<td>23.0</td>
</tr>
</tbody>
</table>

*Total kinetic energy striking the surface is a straight line and calculated as follows:

\[
\Sigma KE = KE \times P \times T
\]  

(34)

where \(\Sigma KE\) and KE are defined above, P is the rainfall intensity (mm/hr) and T is the time of exposing (hours).
Vienna loam
Intensity rate = 123 - 151.9 mm/hr
● Measured data
- Predicted data
Trn = 10.9 - 0.145 KE
\[ \text{R}^2 = 0.28 \]

Figure 15  Time to runoff for different levels of kinetic energy and constant intensity.
b. Time to infiltrate 50 mm of water

The time to infiltrate 50 mm of water is the time from the beginning of the rainfall application until the infiltration of 50 mm into the soil profile. As the kinetic energy rate increases from zero to 24.4 J/m².mm the time to infiltrate 50 mm of water also increases as shown in Figure 16. This is another example of the effects of kinetic energy on the infiltration rate and the amount of water passing through the soil surface during an irrigation. The results show that the seal was formed faster under high kinetic energy levels which slow the entry of water through the surface.

A regression equation was developed to describe the relationship of rainfall energy and time to infiltrate 50 mm of water for different levels of rainfall energy. The equation is:

\[ T_{50} = 21.14 + 0.11 \text{ KE} + 0.08 \text{ KE}^2 \]  

(36)

where \( T_{50} \) is the time to infiltrate 50 mm of water (minutes) and KE is the kinetic energy rate (J/m².mm). The relationship of \( T_{50} \) and KE has an \( R^2 \) of 0.89 and there is a significant difference at the 5% level (Table A3, Appendix).

The kinetic energy rate, time to runoff, total kinetic energy at runoff, \( T_{50} \) and near final infiltration rate are shown earlier in Table 8. Increasing the kinetic energy rate (J/m².mm) will increase the total energy (J/m²) striking the soil surface at the time of runoff which indicated that the kinetic energy required to break down the aggregates and start runoff was different with different levels of rainfall energy. The time to surface runoff decreased with increasing
Time to infiltrate 50 mm of water vs. kinetic energy
Dry-bare surface
Vienna loam

- Observed data
- Predicted data

$$T_{50} = 21.14 + 0.11 \text{ KE} + 0.08 \text{ KE}^2$$
$$R^2 = 0.89$$

Figure 16. Time to infiltrate 50 mm water with different kinetic energy levels and constant intensity.
kinetic energy rate. The near steady state infiltration rate decreased as the kinetic energy rate and total kinetic energy increased. The time to infiltrate 50 mm of water increased with increasing kinetic energy rate and total energy.

3. Effect of Rainfall Intensity on Seal Development and the Final Infiltration Rate

a. Seal development and accumulative energy as affected by rainfall intensity.

The relationship of infiltration rate as a function of time for different levels of rainfall application rate are shown in Figures 17 and 18 for the two levels of kinetic energy 7.2 and 12.4 J/m².mm, respectively. The infiltration rates decreased after runoff started for all intensity levels, but with different values relative to the initial rainfall intensity. The effects of rainfall intensity levels on the soil surface and the infiltration rate can be explained by the time to runoff and near steady state infiltration rate for the two levels of energy in Figures 17 and 18. As the rainfall intensity decreases the time to runoff increases rapidly. The seal developed faster under high intensities compared to the low rainfall intensity. This phenomenon is a result of the total kinetic energy striking the soil surface and meeting the energy requirement for aggregate breakdown and seal formation. There are differences in the kinetic energy required to break down aggregates for different rainfall intensities. As the intensity decreases the amount of energy required to break down aggregates increases. For example, when the intensity dropped from 147 to 53.4 mm/hr in Table 9, the total energy required to break down
Figure 17. Infiltration rate for different rainfall intensities and constant kinetic energy (7.2 J/m².mm) (mean of 2 plots).
Figure 18. Infiltration rate for different rainfall intensities and constant kinetic energy (12.4 J/m².m) (mean of 3 plots).
Table 9. Intensity, time to runoff and total kinetic energy at runoff for dry-bare Vienna loam treatments with a kinetic energy rate of 12.4 J/m²-mm (mean of 3 plots).

<table>
<thead>
<tr>
<th>Intensity (mm/hr)</th>
<th>Time to runoff (minutes)</th>
<th>Total kinetic energy (J/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>147.0</td>
<td>8.9</td>
<td>270</td>
</tr>
<tr>
<td>101.4</td>
<td>17.0</td>
<td>356</td>
</tr>
<tr>
<td>53.4</td>
<td>47.5</td>
<td>524</td>
</tr>
</tbody>
</table>
aggregates increased from 270 to 524 J/m$^2$.mm, respectively for the kinetic energy rate 12.4 J/m$^2$.mm. The results in Table 9 show a similarity to the results in Table 10. As the intensity is reduced from 150 mm/hr to 43.5 mm/hr, the total kinetic energy increases from 178 to 454 J/m$^2$.mm. At the low kinetic energy rate (7.2 J/m$^2$.mm) and low rainfall intensity (43.5 mm/hr) there was almost no runoff, suggesting little seal development under this combination. Thompson and James (1983) also found that the total rainfall energy striking the soil surface to the beginning of runoff increased as the application rate decreased. Thus, these results showed that the energy required to break down aggregates and initiate runoff are different for different rainfall intensities but the same kinetic energy rate.

Low water application intensities together with their corresponding kinetic energies take a longer time to break down enough aggregates and cause water saturation at the surface than higher intensities. At saturation, aggregate breakdown is very rapid resulting in fast seal development (Francis and Cruse, 1983). This scenario explains the different lengths of horizontal lines on the infiltration rate curves followed by a very rapid decrease in the infiltration rate.

This phenomenon would suggest that a drop size distribution with a low enough combination of intensity and kinetic energy (specific power) could be found which would not produce any runoff while a slightly higher specific power might produce considerable runoff.

The total kinetic energy required to break down aggregates with similar intensity and two levels of kinetic energy for Vienna loam and
Table 10. Intensity, time to runoff and total kinetic energy at runoff for dry-bare Vienna loam treatments with a kinetic energy rate of 7.2 J/m².mm (mean of 2 plots).

<table>
<thead>
<tr>
<th>Intensity (mm/hr)</th>
<th>Time to runoff (minutes)</th>
<th>Total kinetic energy (J/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150.0</td>
<td>10.0</td>
<td>178</td>
</tr>
<tr>
<td>79.8</td>
<td>33.0</td>
<td>314</td>
</tr>
<tr>
<td>43.5</td>
<td>87.0</td>
<td>454</td>
</tr>
</tbody>
</table>

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Lowry silt loam are shown in Table 11. Vienna loam required more than twice the total kinetic energy required by Lowry silt loam. This result is supported by the aggregate stability data reported earlier in which Vienna loam had a higher aggregate stability than Lowry silt loam.

The relationship of rainfall intensity (mm/hr) and the time to runoff for Vienna loam is shown in Figure 19. As the application rate decreases the time to runoff increases. This result indicated that the seal developing very slow with low rainfall intensity and takes more time to meet the energy required for aggregate breakdown and the beginning of surface runoff.

An hyperbolic equation between application rate and time to runoff gave a good fit to the data.

\[ P = \frac{a}{T_{rn}^2} + 43 \]  

or in another form:

\[ T_{rn} = \left( \frac{a}{P-43} \right)^{1/2} \]  

where \( P \) is the rainfall intensity (mm/hr), \( T_{rn} \) is the time to runoff (minutes) and \( a \) is a constant of value 14670.

b. Final infiltration rate resulting from surface seal development and rainfall intensity.

A comparison of different rainfall intensities with the near steady state infiltration rate for different soil surface conditions across two levels of kinetic energy is presented in Tables 12 and 13. At the high rainfall intensity and at a kinetic energy level of 12.4
Table 11. Total kinetic energy required to break down aggregates for two kinetic energy rates in Vienna loam and Lowry silt loam.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Kinetic energy required (J/m²) (J/m².mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kinetic energy rate</td>
</tr>
<tr>
<td></td>
<td>12.4</td>
</tr>
<tr>
<td>Vienna loam</td>
<td>270</td>
</tr>
<tr>
<td>Lowry silt loam</td>
<td>107</td>
</tr>
</tbody>
</table>

1/ The values were average of 3 and 4 plots for Lowry and Vienna soils, respectively.
Application rate vs. time to runoff for 2 levels of kinetic energy
Vienna loam

* KE = 12.4 J/m².mm

* KE = 7.2 J/m².mm

Estimated values

\[ T_{rn} = \left( \frac{a}{P-43} \right)^{1/4} \]

Figure 19. Rainfall application rate for 2 levels of kinetic energy of Vienna loam.
Table 12. Intensity and the steady state infiltration rate for Vienna loam with different bare surface conditions and constant kinetic energy rate (12.4 J/m².mm) (mean of 3 plots).

<table>
<thead>
<tr>
<th>Rainfall intensity (mm/hr)</th>
<th>Near steady state infiltration rate (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry surface</td>
</tr>
<tr>
<td></td>
<td>1st run</td>
</tr>
<tr>
<td>147.0</td>
<td>32</td>
</tr>
<tr>
<td>101.4</td>
<td>36</td>
</tr>
<tr>
<td>53.4</td>
<td>22</td>
</tr>
</tbody>
</table>

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Table 13. Intensity and the steady state infiltration rate for Vienna loam with different bare surface conditions and constant kinetic energy rate (7.2 J/m²·mm) (mean of 2 plots).

<table>
<thead>
<tr>
<th>Rainfall intensity (mm/hr)</th>
<th>Near steady state infiltration rate (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry surface 1st run</td>
</tr>
<tr>
<td>150.0</td>
<td>52</td>
</tr>
<tr>
<td>79.8</td>
<td>59</td>
</tr>
<tr>
<td>43.5</td>
<td>43</td>
</tr>
</tbody>
</table>
J/m².mm (Table 12), the near steady state infiltration rate was reduced to 20% of the rainfall application rate on the first run on a dry-tilled soil surface. The seal developed with time until it reduced the infiltration rate to its final value. During the second and third runs for the same treatment, the near steady state infiltration rate was reduced to 14% and 12% of the initial rainfall application rate, respectively. At a low intensity (53.4 mm/hr), the near steady state infiltration rate was reduced to 40%, 38% and 20% for the first, second and third runs, respectively. There was a slight decrease in the final infiltration rate after the first run (dry-bare). This phenomenon indicated that the seal had reached a constant thickness by the end of the first run (dry-bare).

With a low kinetic energy 7.2 J/m².mm (Table 13), the infiltration rate was reduced to 34%, 20% and 20% of the initial value for first, second and third runs, respectively with a high rainfall application (150 mm/hr). At a low rainfall application (43.5 mm/hr), the near steady state infiltration rate was reduced to 98% and 87% for the first and second runs, respectively.

In general, there is a reduction in the final infiltration rate for the three soil surface conditions which are described in Tables 12 and 13. But the reduction is less when the rainfall application is reduced with both levels of kinetic energy. This phenomenon indicated that the rainfall energy impact was lower with low intensity and the soil surface was not sealed as much as by the high intensities. This was discussed further under the section concerning the time to runoff.
The reduction in infiltration rate was lower with the low kinetic energy level compared to the high energy level for the three soil surface conditions.

At low intensity (43.5 mm/hr) (Table 13), the infiltration rate was very high and one of the replications ran for 100 minutes without runoff on the dry-bare plot. Therefore the reduction in the infiltration rate was very low under this kinetic energy and rainfall intensity combination.

4. Effect of Stopping Periods on the Infiltration Process

Two additional covered plots of Vienna loam received continuous water applications for two hours each without runoff. Similar adjoining covered plots also received water applications for two hours but with two interruptions apiece for either 12 minutes or 1 hour periods (Figures 20A and 20B). In Figure 20A the covered treatment was run for 60 minutes, then stopped for 12 minutes without removing the cover and run again for 30 minutes, then stopped for 12 minutes and run again for 30 minutes. The runoff started after 4.5 minutes from the beginning of the second rainfall application and the infiltration rate reached more or less a constant rate of about (82 mm/hr). After the second stopping period, runoff began in 4.5 minutes and the infiltration rate was further reduced to about 33 mm/hr after 30 minutes. Similar treatments were run with one hour stopping periods and similar results were obtained with slightly higher final infiltration rate values as shown in Figure 20B.

Both treatments, the continuously applied water and the one with
Figure 20A. Infiltration rate with/without stopping periods in Vienna loam (mean of 3 plots).
Figure 20B. Infiltration rate with/without stopping periods in Vienna loam (mean of 3 plots).
stopping periods, should not have had seal development because the surface was protected with cheese cloth. However, there are several possible reasons that can be suggested for producing this type of phenomenon:

1) After stopping the rainfall application for 12 minutes or more, the water in the top layer moved down and the big pores became empty as the water was replaced by air. When the water was reapplied to the surface, air became entrapped which reduced water movement through the profile. Runoff started as a result of infiltration rate reduction.

2) Deposition of some fine particles in the soil pores is another possible explanation for the reduction in the infiltration rate.

3) After stopping the rainfall application, there might be some compaction of the plowed layer due to a reduced water potential which resulted in reduced pore sizes and increased the bulk density. Onstad et al. (1984) reported in a study of soil subsidence that hydraulic conductivity decreased with the application of water, while bulk density increased for all soils they studied.

5. Green-Ampt Results and Discussion

The infiltration rate as a function of time for different levels of kinetic energy of dry-bare surface are presented in Figures 21-25 for the Vienna loam and Figures 26 and 27 for Lowry silt loam. The combination of dry and wet bare surfaces for the two soils are shown in Figures A-A19 (Appendix). Each figure shows the calculated infiltration rate by the modified Green-Ampt model according to the concept of
Figure 21. Measured and estimated infiltration rate as a function of time for the kinetic energy of 7.2 J/m².mm.
Figure 22. Measured and estimated infiltration rate as a function of time for the kinetic energy rate of 8.2 J/m$^2$.mm.
Figure 23. Measured and estimated infiltration rate as a function of time for the kinetic energy rate of 12.4 J/m²-mm.

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Figure 24. Measured and estimated infiltration rate as a function of time for the kinetic energy of 19.4 J/m².mm
Figure 25. Measured and estimated infiltration rate as a function of time for the kinetic energy rate of 24.4 J/m².mm
Figure 26. Measured and estimated infiltration rate as a function of time for the kinetic energy rate of 12.4 J/m².mm.
Figure 27. Measured and estimated infiltration rate as a function of time for the kinetic energy rate of 24.4 J/m².mm.
Childs (1969) as compared to the field data. The predicted values of the infiltration rate before the runoff started were lower than the measured values.

The calculated and measured rainfall energy (J/cm²) accumulated on the soil surface for different kinetic energy rates are shown in Tables 14 and 15 for Vienna loam and Lowry silt loam, respectively. The calculated energy (EOP) was predicted by the modified Green-Ampt model when the initial seal conductivity (Ko) was reduced to two times the final seal conductivity (Kf). As the kinetic energy rate (J/m².mm) increases the value of EOP (J/cm²) decreases. This phenomenon indicated that the use of the small nozzle (low kinetic energy rate) required more energy to reduce the Ko to 2*Kf compared with the large nozzle (high kinetic energy rate). The kinetic energy rate and EOP relationship is shown in Figure 28.

The measured rainfall sealing energy, E(t) was calculated as follows:

\[ E(t) = KE \cdot P \cdot T_i \]  

(39)

where KE is the rainfall energy rate (J/m².mm), P is the rainfall intensity (mm/hr) and Ti is the time (hrs) for Kc to reduce from Ko to 2*Kf. The rainfall sealing energy E(t) was found to be similar for all kinetic energy levels within the same soil therefore, it is a good parameter to describe the soil seal formation. The average values of E(t) for Vienna loam and Lowry silt loam are 0.12 and 0.07 (J/cm²), respectively. It is important to notice that the seal formation in both soils can be described by these two values of sealing energy E(t).
Table 14. Calculated and measured total energy, kinetic energy rate (KE), and conversion factor (CF) for different nozzle sizes in Vienna loam soil.

<table>
<thead>
<tr>
<th>Nozzle number</th>
<th>Kinetic energy (J/m².mm)</th>
<th>Calculated energy (J/cm²)</th>
<th>Measured energy (J/cm²)</th>
<th>Conversion factor (CF) 3/</th>
</tr>
</thead>
<tbody>
<tr>
<td>Veejet 8010</td>
<td>7.2</td>
<td>0.35</td>
<td>0.11</td>
<td>0.31</td>
</tr>
<tr>
<td>Veejet 8020</td>
<td>8.2</td>
<td>0.27</td>
<td>0.10</td>
<td>0.37</td>
</tr>
<tr>
<td>Veejet 8030</td>
<td>12.4</td>
<td>0.25</td>
<td>0.13</td>
<td>0.52</td>
</tr>
<tr>
<td>Veejet 8070</td>
<td>19.4</td>
<td>0.18</td>
<td>0.14</td>
<td>0.78</td>
</tr>
<tr>
<td>Veejet 80150</td>
<td>24.4</td>
<td>0.12</td>
<td>0.11</td>
<td>0.92</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>0.12</td>
</tr>
</tbody>
</table>

1/ EOP is the accumulated energy when Kc = 2.0 Kf and is calculated from the computer model.

2/ E(t) is the measured energy and calculated as follows: 
   \[ E(t) = KE \times P \times Ti \]
   where \( P \) is the rainfall intensity (mm/hr) and \( Ti \) is the time (hrs) when Kc = 2 Kf.

3/ Conversion factor (CF) = \( \frac{E(t)}{EOP} \)
Table 15. Calculated and measured total energy, kinetic energy rate (KE), and conversion factor (CF) for two nozzle sizes in Lowry silt loam.

<table>
<thead>
<tr>
<th>Nozzle number</th>
<th>Kinetic energy (J/m²:mm)</th>
<th>Calculated energy (J/cm²) EOP 1/</th>
<th>Measured energy (J/cm²) E(t) 2/</th>
<th>Conversion factor (CF) 3/</th>
</tr>
</thead>
<tbody>
<tr>
<td>Veejet 8030</td>
<td>12.4</td>
<td>0.12</td>
<td>0.06</td>
<td>0.58</td>
</tr>
<tr>
<td>Veejet 80150</td>
<td>24.4</td>
<td>0.08</td>
<td>0.08</td>
<td>1.00</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>0.07</td>
</tr>
</tbody>
</table>

1/ EOP is the accumulated energy when Kc = 2.0 Kf and is calculated from the computer model.

2/ E(t) is the measured energy and calculated as follows:
   \[ E(t) = KE \cdot P \cdot Ti \]
   where P is the rainfall intensity (mm/hr) and Ti is the time (hrs) when Kc = 2Kf.

3/ Conversion factor (CF) = \frac{E(t)}{EOP}
Calculated Total kinetic energy (EOP), J/cm$^2$

$EOP = 0.397 - 0.11 KE$

$R^2 = 0.92$

Figure 28. Total kinetic energy (EOP) as a function of kinetic energy rate (KE).
The sealing energy of Vienna loam is 0.12 J/cm² and of Lowry silt loam is 0.07 J/cm².

When using the modified Green-Ampt model approach for infiltration, the constant E(t) values obtained in this study are a significant advance. If the E(t) values should hold constant for other soils also, then E(t) could be used as a general characterizing soil sealing constant. Perhaps E(t) values could be correlated with standard soil physical properties so E(t) could be predicted and published for other soils.

As a result of the differences between the calculated energy (EOP) and the measured energy E(t), a conversion factor (CF) was used to relate EOP to E(t). Therefore, the energy formula of Wischmier and Smith (1978) could be rewritten as follows:

\[ E_{OA} = CF \left(0.02062 + 0.00379 \ln P\right) P t \]  \hspace{1cm} (40)

where EOA is the accumulative energy with respect to the time, CF is the conversion factor, P is the rainfall intensity and t is the time (hrs). Wischmeier and Smith (1978) equation could be used without a conversion factor only for the high kinetic energy level (24.4 J/m² mm) as shown in Tables 14 and 15. The composite hydraulic conductivity of the seal should be also corrected by the conversion factor and equation 14 becomes:

\[ K_c = (K_0 - K_f) \exp\left[-D.B.(\frac{RR}{4}) CF \frac{E_{OA}}{E_{OP}}\right] + K_f \]  \hspace{1cm} (41)

where all terms were defined previously.

As shown in Equation 27, Kf is strongly dependent on the value of PFc, the soil water potential beneath the seal. As this parameter
is difficult to measure its value is obtained by trial and error
through the computer model by matching the simulated runoff and the
final hydraulic conductivity with the measured runoff and the final
hydraulic conductivity. Since PFc is an estimated parameter, Kf is
also estimated which results in an estimated EOP value. The value of
Tt in equation (39) is also dependent on Kf and therefore, E(t) is
indirectly dependent on PFc. It is significant that the measured
energy parameters E(t) are almost identical under different nozzles for
the two soils (Tables 14 and 15). This is further evidence that the
theoretical analysis provides a good model to describe the infiltration
process under a soil seal.

Vienna loam has higher values of rainfall sealing energy EOP and
E(t) compared to Lowry silt loam. This difference corresponds to the
difference in the physical properties of the two soils. The stable
aggregate percentages of Vienna loam and Lowry silt loam are 89% and
73%, and the unstable aggregate percentages (100-aggregate stability)
are 11% and 27% for Vienna loam and Lowry silt loam, respectively. The
percentage of unstable aggregate, the average rainfall sealing energy
E(t) and the average particle size distribution are presented in Table
16. As the unstable aggregate percentage increased from 11% in Vienna
loam to 27% in Lowry silt loam the value of E(t) decreased from 0.12 to
0.07 (J/cm²) for the two soils. The soil with the higher percentage of
unstable aggregates required less kinetic energy to reduce the initial
seal conductivity to its final value. The unstable aggregate percent-
tage is highly related to the silt content in the soil with respect to
Table 16. Average sealing energy, $E(t)$, unstable aggregate percentage, and the average particle size distribution for Vienna loam and Lowry silt loam.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>$E(t)$ (J/cm$^2$)</th>
<th>% of unstable aggregate</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vienna loam</td>
<td>0.12</td>
<td>11</td>
<td>39.8</td>
<td>33.9</td>
<td>26.3</td>
</tr>
<tr>
<td>Lowry silt loam</td>
<td>0.07</td>
<td>27</td>
<td>12.8</td>
<td>68.7</td>
<td>18.5</td>
</tr>
</tbody>
</table>
the other factors (Cary and Evans, 1974; Lemos and Lutz, 1957; and others). As the silt content more than doubled from Vienna loam to Lowry silt loam, the unstable aggregate percentage also more than doubled. The unstable aggregate percentage may be used to predict EOP for different soils.

The infiltration rate as a function of total kinetic energy (J/m²) for Vienna loam and Lowry silt loam are shown in Figures 29 and 30. From these curves, one can conclude that it takes almost the same kinetic energy to reduce the infiltration rate to specific value under different kinetic energy rates.

The predicted hydraulic conductivity of the surface seal was similar to the estimated value of the infiltration rate as shown in Table A in the Appendix. These results provide further evidence that the surface seal was controlling the infiltration process into the soil profile and is more important than the hydraulic conductivity of the soil layers below.
Infiltration rate vs. total kinetic energy

Dry-bare surface

- KE = 7.2 J/m²/mm
- KE = 12.4 J/m²/mm
- KE = 19.4 J/m²/mm
- KE = 24.4 J/m²/mm

Intensity = 123.0 - 151.9 mm/hr

Figure 29. Infiltration rate for different kinetic energy levels on a bare soil (Vienna loam).
Figure 30. Infiltration rate for two rainfall energy levels as a function of accumulative energy.
SUMMARY AND CONCLUSIONS

Summary

Field experiments were conducted on two South Dakotan soils (Vienna loam and Lowry silt loam) to study the effect of rainfall kinetic energy and intensities on bare soil surfaces. A Purdue type rainfall simulator was used with different Veejet nozzles to produce various raindrop size distributions. Six levels of rainfall kinetic energy (0, 7.2, 8.2, 12.4, 19.4 and 24.4 J/m².mm) were used in this study.

Drop size distributions were measured by the flour method. Droplet velocities were calculated by Seger's procedure (1965) and kinetic energy was subsequently calculated.

The effects of different rainfall kinetic energies and intensities on the time to runoff, the time to infiltrate 50 mm of water and the final infiltration rates under different soil surface conditions were investigated in this study. Soil water content was measured before and after each run.

The modified Green-Ampt model was applied to describe the infiltration rate data, and linear regression techniques used to describe some relationships in this study. The value of PFc used in the model was estimated by trial and error through the computer model by matching the simulated runoff with the measured runoff. The measured rainfall energy, $E(t)$ was determined in this study for the two soils.

A pronounced effect on bare soils was noticed through the
infiltration rate reduction and the development of a surface seal. The time to runoff and the final infiltration rate decreased as the kinetic rainfall energy and intensity increased. The accumulative water infiltration was affected by seal development and energy level.

The protected treatments of Vienna loam were not affected by rainfall energy level and intensity. There was no runoff and the final infiltration rates were not different from the application rates. The modified Green-Ampt model gave a good description of the infiltration rate in both soils.

Conclusion

The rainfall kinetic energy levels and rainfall intensity had a great effect on the two South Dakota soils. Lowry silt loam was more susceptible to rainfall kinetic energy levels than Vienna loam. The total kinetic energy required to break down surface aggregates in Lowry silt loam was low compared to Vienna loam. This phenomenon is a result of the physical properties of the two soils. Vienna loam has a higher aggregate stability (89%) than Lowry silt loam (73%).

The time to runoff and final infiltration rate decreased as the kinetic energy level increased. The time to runoff was also affected by rainfall intensity; as the intensity decreased the time to runoff increased in order to meet the kinetic energy requirement to break down the surface aggregates and start the runoff.

The amount of water which infiltrated into the soil through the surface was higher under the covered treatment than under the bare treatment. It was higher in Vienna loam than in Lowry silt loam.
These data together with the physical properties of these soils lend support to the effectiveness of the surface seal in controlling the infiltration rate.

A good relationship was found between the final infiltration rate and the time to infiltrate 50 mm of water and the kinetic energy rates of the applied water.

The effect of surface seal development was also indicated by the reduction of the final infiltration rate of the bare surface for the runs which included a dry-bare followed by wet treatments.

Air entrapment, slaking, deposition of fine particles and soil compaction possibly had a great effect on reducing the infiltration rate on wet protected treatments with stopping periods.

The major factors affecting the soil surface condition and the infiltration process are:

1) The development of the surface seal as a result of rainfall kinetic energy impact and slaking.

2) The physical properties of the soils such as (aggregate stability, texture, etc.) which determined the soil's susceptibility to surface sealing.

3) The rainfall intensity above the amount necessary to cause aggregate breakdown.

From a theoretical viewpoint the parameters E(t) and PFc can be used to describe soil seal formation for different soils and kinetic energy rates. The rainfall sealing energy E(t) was found to be different for the two soils. The Vienna silt loam has a higher rainfall
sealing energy (.12 J/cm²) than Lowry silt loam (.07 J/cm²). The calculated energy (EOP) by Wischmier and Smith (1978) was found to be different for different levels of energy. Therefore, a conversion factor (CF) was used to relate EOP to the measured energy E(t). A good fit was achieved by using the layered Green-Ampt model for describing the infiltration rate data.

The above results and conclusions are only valid on Vienna loam and Lowry silt loam soils. It may be different for other soils.

**Recommendations**

The following recommendations could be made to avoid the reduction in water infiltration rates and the formation of a surface seal on plowed bare soil:

1) Use sprinkler nozzles with low kinetic energy and intensity. This combination reduces the total energy breaking down aggregates and, if saturation is avoided, aggregate strength may be retained to avoid runoff.

2) Protect the soil surface by using any type of cover as (straw, etc.) to reduce the kinetic energy force to a minimum. But protection of the soil surface causes some problems such as decreasing the soil temperature and delaying the germination of some crops in cool areas.


The computer program has been written by Dr. S. T. Chu, Professor of Agricultural Engineering, Agricultural Engineering Department, South Dakota State University.
1. Define Variables

**EVENT**  - The rate-runoff event name

- **REAL**  **LD1**, **LD2**, **LT1**, **LT2**: Data values for the crust and the tilled layer (cm)
- **REAL**  **K1**, **K2**, **K3**, **K3F**, **PFL**, **PF2**, **PF3**: Data values for the crust and the tilled layers (cm)
- **REAL**  **SC**, **PFC**, **RR**, **SS**, **INT**: Data values for the crust and the tilled layers (cm)
- **REAL**  **KO**, **KF**, **IC**, **KI****: Data values for the crust and the tilled layers (cm/hr)
- **REAL**  **EPD**, **MP**, **KS**: Data values for the crust and the tilled layers (cm)

2. Specify Initial Values:

- **REAL**  **M01**, **M02**, **M03**: Data values for the moisture difference before and after the wetting front of the layers (dimensionless)
- **REAL**  **SDA**, **PDA**: Data values for the surface pondage (cm)
- **REAL**  **EQA**: Data values for the surface pondage (cm)
- **REAL**  **L4A**, **L2A**, **L3A**, **L2B**: Data values for the crust and the tilled layer (cm)

3. Implement the Runge-Kutta Method

**REAL**  **L2U**, **L2V**, **L2W**: Data values for the crust and the tilled layer (cm)

**REAL**  **L3U**, **L3V**, **L3W**: Data values for the crust and the tilled layer (cm)

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USED IN THE RUNGE-KUTTA METHOD (CM)

INFORMATION CAPACITY RATE TO THE TILLED LAYER AND TO THE SUBSOIL LAYER WHEN THE INTERFACE IS NOT PONGED

INFORMATION CAPACITY RATE WHEN THE INTERFACE IS PONGED USED IN THE RUNGE-KUTTA METHOD (CM/HR)

\[
\text{KCM} = \text{KCV} + \text{KNC}\text{TRANSIENT CRUST CONDUCTIVITY USED IN THE RUNGE-KUTTA METHOD (CM/HR)}
\]

INTEGER HR

HR = THE HOUR READING OF THE RAINFALL INPUT DATA (HR)

KO = K1

\[ ZC = LT1 \]

\[ KF = ZCSCNKGO/(PICCZC) \]

D = ALOG(KP/(K0-KF))

D = CONSTANT IN THE LINDEY'S FORMULA

READ RAINFALL INPUT DATA:

READ(S,4)HR,MM,P,IOX

1 FORMAT(IX,13A4/1X,13A4)

WRITE(6,2)EVENT,LO1,LD2,LT1,LT2,K1,K2,K3,K5,SC,R2,P1,P2,P3,PFC,

1 B=EP0.M01.M02.M03.M0P5.S5.INT.K0.KF

2 FORMAT(1H1.4X,13A4//4X,LD1,LT1.4F5.2,LT2,4F5.2./4X,K1,K2,K3,K5,SC,R2,P1,

PM1,P2,P3,PFC,B,F5.2,4=F5.2/4X.4X,MO1,M02,M03,K5.K0,KF,F5.2)

READ(S,3)HR,MN,P,IOX

2 FORMAT(IX,1H1,4I2.1X,2I2.2X,F5.2,I2.II)

HR,MN = HOUR AND MINUTE READING FROM THE INPUT DATA

P = RAIN DEPTH READING FROM THE RAIN INPUT DATA

IOX = INDEX TO SPECIFY THE START AND THE END OF THE RAIN

IOX = 1 REPRESENTS THE START OF A RAIN

IOX = 2 REPRESENTS THE END OF A RAIN

IF(IOX NE.11) GO TO 100

TRX = HR*60.*MN

TRX = TRX/60.

TRX = THE START OF A BREAK POINT RAIN PERIOD (HR)

PX = 0.0

PMX = P-INT-CMOD1

C P = RAIN DEPTH AT TIME = TRX (CM)

PMX = RAIN DEPTH IN EXCESS OF THE INTERCEPTION AND THE CRUST

C LAYER STORAGE (CM) AT TIME = TRX

WRITE(6,4)HR,MN,P

4 FORMAT(5X,TIME,3X,RAIN,3X,RAIN,5X,INFL,1X,INFL,1X,1X,

1X,SURF,1X,RAIN,5X,INTERACE,1X,SURFACE,1X,CRUST,5X,5X)

2 HN = 3X,DEPTH,1X,RATE,5X,RATE,1X,DEPTH,1X,PONDO*

3 LX,EXCS,4X,POINDAGE,1X,FROnt DEPTH,3X,KC8/1X,CM,1*

4 LX,CM/HR,5X,CM/HR,1X,CM,1X,CM,1X,CM,1X,CM,1X,CM,10X,CM,

5 5X,CM,3X,CM/HR,5X,12.1X,12.2X,P5.2,6X,P5.2)

A=0

4 TR = COUNTER FOR PRINTING

GO TO 100

TRY = HR*60.*MN

TRY = TRY/60.

C TRY = THE END OF A BREAK POINT RAIN PERIOD (HR)

PY = P

TRY = THE END OF A BREAK POINT RAIN PERIOD (CM)

PY = TRY/HR

C TRY = RAIN DEPTH AT TIME = TRX (CM)

P=TRY/HR

C TRY = REPEATE BREAK POINT RAIN INTENSITY (CM/HR)

PMY = P-INT-CMOD1
C PHI=RAIN DEPTH IN EXCESS OF THE INTERCEPTION AND THE CRUST
C LAYER STORAGE (CM) AT TIME=TRY
IF(PHI<0.0) GO TO 120
C
C 5 CRUST LAYER
WRITE(*,5)HR+MN+P
5 FORMAT(5X,I2,1X,I2,2X,F5.2)
KTR=KTR+1
DT=TRY-TRX
IF(IP.LE.0) GO TO 122
EOA=EOA*1.020262*0.00379*ALOG10(IP)+IP*DT
C EOA=RAIN ENERGY (J/CM2)
112 TRX=TRY
PX=PY
PMX=PMY
GO TO 100
120 IF(IPMIX*GE.0) GO TO 130
TRX=-IPX/IPY*TRX
C TIME WHEN THE INTERCEPTION STORAGE IS FILLED (HR)
TA
C TA=THE START TIME OF A ROUTING PERIOD (HR)
IF(IP.LE.0) GO TO 122
EOA=EOA*1.020262*0.00379*ALOG10(IP)+IP*TA-TRX
C KCA=TRANSIENT CRUST CONDUCTIVITY (CM/HR)
L2A=LA-ZC
FA=2*L2A*IP/PIT
6 FORMAT(5X,*10D15.5)
KTR=KTR+1
LAYER=INDEX TO IDENTIFY THE LAYER IN WHICH THE WETTING FRONT
C LOCATED
C
C START ROUTING PERIOD (HR)
150 DT=1/60
C DURATION OF A ROUTING PERIOD (HR)
TA=TA+DT
IF(TA*.0001*.LT.TRY) GO TO 160
TG=TRY
GO TO 150
160 IF(LAYER.EQ.31) GO TO 300
C
C 6 TILLED LAYER
C RUNGE-KUTTA METHOD ARE USED TO CALCULATE THE INFILTRATION
C CAPACITY
L2A=LA-ZC
CLA=(DT/32)*(LA+PP2)/LC/LCA/L2A/KCA
IF(IP.LE.1) GO TO 210
EOU=CLA*(1.020262*0.00379*ALOG10(IP)+IP).+DT/2.
GO TO 212
210 EOQ=EOA
212 KCU=F*(K-O*EXP(K1*DA+M*AL-RR/4)+EOQ/EOQ)
L2A=LA+CLA/2.
PHX=DT/M2*1.020262*LC/L2A+PP2/LC/CKU+L2U/CKU
KV=KCU
L2V=L2A+CLA/2.
JLV=(DT/32)*(LC+L2V+PP2)/LC/CKV+L2V/CKV
IF(IP.LE.2) GO TO 220
EOA=CLA*(1.020262*0.00379*ALOG10(IP)+IP).+DT

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GO TO 222

222 EOW=EDW

227 KCW=KF*(KD-KF)*EXP(-D+D0/(1.+RR/4.)+EDW/EDP)

227 KCB=KCW

EOW=EDW

L2=2*L2-O1
DLW=(OT/M2)*(2*C+L2+PF2)/(12/C/KH*L2+<Cd)
DL=1DLA+2*ULU+2*DLV+O1/6.

IC=O2+NO2/CT

C

L2=INFILTRATION CAPACITY RATE (CM/HR)

IO=IP+SDA/UT

C

IC=INFILTRATION RATE

LB=LA+IP/OT/M2

II=INFILTRATION RATE AT THE GROUND SURFACE (CM/HR)

SDA=SDA*(IP-II)/CT

L1Y2=3

F9=FA*(L2-LA)*<92

GO TO 600

260 L8=L02

OT=(LD2-LA)=M02/II

TB=TA+JT

SO8=SDA+IP=11/OT

L1YS=3

F9=FA*(L2-LA)=M02

GO TO 409

WRITE(6,9) T9,F3

9 FORMAT(ISX,'WATER REACHED SUBSOIL T=',F6.3,' F=',F5.2)

KTR=KTR+I

EDW=EDW+LO2LD2+0.037*I+ALOG10(I+1.0)*PDO

KCW=KF*(KD-KF)*EXP(-D+D0/(1.+RR/4.)+EDW/EDP)

GO TO 50G

270 L9=LA+DL

C

IFLD<GE*LD2) GO TO 290

SDB=SDA*(IP-IC)/OT

F9=IC*GT

TB=TA+DT

F9=SDB*GT. S5) GO TO 280

C

SS=SURFACE STORAGE CAPACITY (CM)

R8=RA

GO TO 600

280 R8=RA+SDB=S5

SDB=S5

GO TO 600

290 L8=L02

DT=(LD2-LA)+M02/II

TB=TA+OT

SDB=SDA+IP/IC)/OT

LAYER=3

F9=FA*(1.0)

IF(ISDB<GE*S5) GO TO 295

GO TO 265

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109

295 QB=RA+SDS-SS
SDS-SS
GO TO 246
C
C 7. SUBSOIL LAYER
300 LS=L4-LO2
IF(RCA-GT+0.) GO TO 500
IM2=(IZC+LT2.1/IZC/KCA+LT2/KCA)
C IM2 INFILTRATION CAPACITY RATE CALCULATED FROM GROUND SURFACE
TO INTERFACE (C/M/HR)
IF(I(N3+K3+KCA) K3=KCA
IM3=(L3A+PF3.1/IZC/KCA+LT2/KCA+L3A/K3)
C IM3 INFILTRATION CAPACITY RATE CALCULATED FROM GROUND SURFACE
TO WETTING FRONT (C/M/HR)
IF(IM2 +GT. IM3) GO TO 503
C
C INTERFACE NOT PONDOED
DLA=0. (M/M)
IF(IP +LE. 0.) GO TO 310
EOU=EOCA+10.JL0.2+0.3037*(ALOG10(IIP1)+IP+DT.2).
GO TO 312
310 EOU=EOCA
312 KC=KF*(K0-KF)+EXP1-0.904(I.-RR/4.)*EOU/EOC1
L3M=L3A+OLY/2. 
IF(K3=GT+KCA) K3=KCA
DLA=(10/43)+(1/IZC/LT2+L3U*PF3.1/IZC/KCU+LT2/KCU+L3U/K3)
KCU=KCU
L3V=L3A+OLV/2. 
ULV=(1/70.43)+(1/IZC/LT2+L3U*PF3.1/IZC/KCV+LT2/KCV+L3V/K3)
IF(IP +LE. 0.) GO TO 314
EOU=EOU+10.020.2+0.3037*ALOG10(IIP1)+IP+DT.2
GO TO 316
314 EOU=EOCA
316 KCW=KF*(K0-KF)+EXP1-0.904(I.-RR/4.)*EOU/EOC1
KCB=KCW
EOB=EOU
L3A=L3A+OLY
IF(K3=GT+KCA) K3=KCA
DLA=10/43)+(1/IZC/LT2+L3U*PF3.1/IZC/KCW+LT2/KCW+L3U/K3)
L3A=10.2*OLY+2*OLV+OLW/6.
IC=(OLY+OLV)/OT
I0=IP+SDA/DT
IF(IO +GT. IC) GO TO 120
L3=LA-(10*DT.1/"D")
P3=FA-13Gre
SD=0.
PDB=0.
IT=10
RB=RA
GO TO 600
320 LS=L4+DL
P3=FA+OLM+AS
SD=10-IC+GT
P2B=0.
IT=IC
IF(SDB +GT. SS) GO TO 340
RB=RA
GO TO 600
340 RB=RA+SDS-SS
SDS-SS

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C

: INTERFACE PONDOED

\[
\begin{align*}
& \text{IN} = \frac{ZC \cdot LT2 \cdot PDA}{ZC/KCA} + \frac{(LT2 - PDA)}{KCA} \\
& \text{IN} = \text{FLOW INFILTRATION CAPACITY RATE CALCULATED FROM GROUND} \\
& \text{SURFACE TO WATER TABLE (CM/HR)} \\
& \text{OU} = \text{POU} + LT2 \cdot POU \cdot (\frac{ZC}{KCA} \cdot LT2 - POU) \cdot (\frac{ZC}{KCA} \cdot LT2 - POU) \\
& \text{OU} = \text{INFILTRATION CAPACITY RATE CALCULATED FROM WATER} \\
& \text{TABLE TO WETTING FRONT (CM/HR)}
\end{align*}
\]

513

\[
\begin{align*}
& \text{OLA = D}T^2 + Q30U \cdot DPA^2 + \text{M}0U (1 - 0.02062) \cdot 10.377 \cdot G010 (\text{IP}) \cdot \text{IP}^2 \cdot \text{D}T^2 \\
& \text{GO TO 514}
\end{align*}
\]

512

\[
\begin{align*}
& \text{EOU} = \text{EOA} \cdot \text{EXP} - \text{D}A^2 \cdot (1 + \text{R}^2) \\
& \text{L3U} = \text{L3A} \cdot \text{OLA} \cdot 2^2 \\
& \text{PDU} = \text{PDA} \cdot \text{DPA} \cdot 2^2, \text{C}
\end{align*}
\]

514

\[
\begin{align*}
& \text{PDV} = \text{PDA} \cdot \text{DPA} \cdot 2^2, \text{C}
\end{align*}
\]

C

\[
\begin{align*}
& \text{PDU} = \text{PDV} \cdot \text{PDU} \cdot 2^2, \text{C}
\end{align*}
\]

\[
\begin{align*}
& \text{IN} = \frac{ZC \cdot LT2 \cdot PDU}{ZC/KCv} \cdot LT2 \cdot PDU \cdot (\frac{ZC}{KCV} \cdot LT2 - PDU) \cdot (\frac{ZC}{KCV} \cdot LT2 - PDU) \\
& \text{OUV} = \text{POU} + LT2 \cdot POU \cdot (\frac{ZC}{KCV} \cdot LT2 - POU) \cdot (\frac{ZC}{KCV} \cdot LT2 - POU) \\
& \text{LDV} = \text{D}T^2 \cdot M031 \cdot \text{OUV} \\
& \text{OPV} = \text{D}T^2 \cdot M031 \cdot \text{OUV} \\
& \text{IF} (\text{IP} \cdot \text{LE} 1) \text{GO TO 516}
\end{align*}
\]

516

\[
\begin{align*}
& \text{EO} = \text{EOA} \cdot \text{EXP} - \text{D}A^2 \cdot (1 + \text{R}^2) \\
& \text{L3V} = \text{L3A} \cdot \text{DLV} \cdot 2^2 \\
& \text{PDV} = \text{PDA} \cdot \text{DPA} \cdot 2^2, \text{C}
\end{align*}
\]

513

\[
\begin{align*}
& \text{KCw} = \text{KF} \cdot \text{M031} \cdot \text{EXP} - \text{D}A^2 \cdot (1 + \text{R}^2) \cdot \text{EO}^2 \\
& \text{KCw} = \text{Kc} \cdot \text{Cv} \\
& \text{EG} = \text{EG} \cdot \text{Cv} \\
& \text{E}3 = \text{E}3 \cdot \text{Cv} \\
& \text{L3} = \text{L3A} \cdot \text{DLV} \\
& \text{PDV} = \text{PDA} \cdot \text{DPA} \cdot 2^2, \text{C}
\end{align*}
\]

\[
\begin{align*}
& \text{IF} (\text{IP} \cdot \text{LE} 0) \text{GO TO 516}
\end{align*}
\]

516

\[
\begin{align*}
& \text{EO} = \text{EOA} \cdot \text{EXP} - \text{D}A^2 \cdot (1 + \text{R}^2) \cdot \text{EO}^2 \\
& \text{L3} = \text{L3A} \cdot \text{DLV} \cdot 2^2 \\
& \text{PDV} = \text{PDA} \cdot \text{DPA} \cdot 2^2, \text{C}
\end{align*}
\]

\[
\begin{align*}
& \text{IF} (\text{IP} \cdot \text{LE} 1) \text{GO TO 516}
\end{align*}
\]

516

\[
\begin{align*}
& \text{EO} = \text{EOA} \cdot \text{EXP} - \text{D}A^2 \cdot (1 + \text{R}^2) \cdot \text{EO}^2 \\
& \text{L3} = \text{L3A} \cdot \text{DLV} \cdot 2^2 \\
& \text{PDV} = \text{PDA} \cdot \text{DPA} \cdot 2^2, \text{C}
\end{align*}
\]

516

\[
\begin{align*}
& \text{EO} = \text{EOA} \cdot \text{EXP} - \text{D}A^2 \cdot (1 + \text{R}^2) \cdot \text{EO}^2 \\
& \text{L3} = \text{L3A} \cdot \text{DLV} \cdot 2^2 \\
& \text{PDV} = \text{PDA} \cdot \text{DPA} \cdot 2^2, \text{C}
\end{align*}
\]
IF (PDV .LT. 0.) PDV=0.2
OUV=(PDV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

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OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.

IF (POV .LT. 0.) POV=0.
OUV=(POV+L3V+PF3)/1.0
L3V=L3A+LUV/2.
P3V=PDA+GPU/2.
LA=LB
FA=FB
SDA=SDP
PDA=PDP
RA=RB
IF(TA<LT TRY) GO TO 130
TRY=TRY
WRITE(0,5) HR, MN, P
KTR=KTR+1
GO TO 900
900 IF(TRY<2, TRY) GO TO 910
GO TO 700
STOP
END

ENTRY
Table A.

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<th>TIME</th>
<th>RAIN RATE CM/HR</th>
<th>INFIL. RATE CM/HR</th>
<th>SURF. RAIN CM</th>
<th>INFIL. INFL. RT SURF. RAIN CM</th>
<th>RAIN INFIL. RT SURF. RAIN CM</th>
<th>DEPTH RT POND. EXCS. CM</th>
<th>PONDAGE RT FRONT DEPTH CM</th>
<th>RETENT CRUST</th>
<th>CRUST CM</th>
<th>INTEGRATION CRUST CM</th>
<th>KEPT CRUST CM</th>
<th>KEPT CRUST CM</th>
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**WATER REACHED TILLED LAYER T = 11.011 F = 3.41**

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### Table A1. Final Infiltration Rate as Function of Kinetic Energy

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- **Root MSE**: 4.88673
- **Dep Mean**: 35.88235
- **C.V.**: 13.61876

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Table A1 (continued)

**FINAL INFILTRATION RATE AS FUNCTION OF KINETIC ENERGY**

**ANALYSIS OF VARIANCE PROCEDURE**

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Table A1 (continued)

**FINAL INFILTRATION RATE AS FUNCTION OF KINETIC ENERGY**

**ANALYSIS OF VARIANCE PROCEDURE**

**DUNCAN'S MULTIPLE RANGE TEST FOR VARIABLE: FINAL**

*NOTE:* THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE, NOT THE EXPERIMENTWISE ERROR RATE

**ALPHA = 0.05**  **DF = 12**  **MSE = 25.2806**

**WARNING:** CELL SIZES ARE NOT EQUAL

**HARMONIC MEAN OF CELL SIZES = 3.09278**

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**CRITICAL RANGE MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.**

<table>
<thead>
<tr>
<th>DUNCAN GROUPING</th>
<th>MEAN</th>
<th>N</th>
<th>KE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>51.500</td>
<td>2</td>
<td>7.2</td>
</tr>
<tr>
<td>A</td>
<td>44.667</td>
<td>3</td>
<td>8.2</td>
</tr>
<tr>
<td>B</td>
<td>38.400</td>
<td>5</td>
<td>12.4</td>
</tr>
<tr>
<td>C</td>
<td>29.000</td>
<td>3</td>
<td>19.4</td>
</tr>
<tr>
<td>C</td>
<td>23.500</td>
<td>4</td>
<td>24.4</td>
</tr>
</tbody>
</table>
Table A2.

### TIME TO RUNOFF

#### ANALYSIS OF VARIANCE

<table>
<thead>
<tr>
<th>Source of Sum of Mean</th>
<th>F Value</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>12.40876178</td>
<td>12.40876178</td>
</tr>
<tr>
<td>Error</td>
<td>31.82723822</td>
<td>2.44824909</td>
</tr>
<tr>
<td>C Total</td>
<td>44.23600000</td>
<td>5.068</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Root MSE</th>
<th>Dep Mean</th>
<th>Adj R-Sq</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.564688</td>
<td>8.46</td>
<td>0.2805</td>
</tr>
<tr>
<td>C.V.</td>
<td>1.49513</td>
<td></td>
</tr>
</tbody>
</table>

#### PARAMETER ESTIMATES

<p>| Variable of | Parameter Estimate | Standard Error | T for H0: Parameter = 0 | Prob &gt; |T| |
|-------------|--------------------|----------------|--------------------------|---------|
| Intercept   | 10.94341700        | 1.17474773     | 9.316                    | 0.0001  |
| KE          | -0.14517247        | 0.06448339     | -2.251                   | 0.0423  |</p>
<table>
<thead>
<tr>
<th>SOURCE</th>
<th>DF</th>
<th>SUM OF SQUARES</th>
<th>MEAN SQUARE</th>
<th>F VALUE</th>
<th>PR &gt; F</th>
<th>R-SQUARE</th>
<th>C.V.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODEL</td>
<td>3</td>
<td>12.9293333</td>
<td>4.3097778</td>
<td>1.51</td>
<td>0.2653</td>
<td>0.292281</td>
<td>19.9412</td>
</tr>
<tr>
<td>ERROR</td>
<td>11</td>
<td>31.306000000</td>
<td>2.84526391</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CORRECTED TOTAL</td>
<td>14</td>
<td>44.236000000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOURCE</td>
<td>DF</td>
<td>ANOVA SS</td>
<td>F VALUE</td>
<td>PR &gt; F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KE</td>
<td>3</td>
<td>12.9293333</td>
<td>1.51</td>
<td>0.2653</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table A2 (continued)

TIME TO RUNOFF
ANALYSIS OF VARIANCE PROCEDURE

DUNCAN'S MULTIPLE RANGE TEST FOR VARIABLE: TIME
NOTE: THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE,
NOT THE EXPERIMENTWISE ERROR RATE

\[ \text{ALPHA} = 0.05 \quad \text{DF} = 11 \quad \text{MSE} = 2.84606 \]

WARNING: CELL SIZES ARE NOT EQUAL.
HARMONIC MEAN OF CELL SIZES = 3.24324

NUMBER OF MEANS | 2 | 3 | 4
CRITICAL RANGE   | 2.91034 | 3.04647 | 3.13593

MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.

<table>
<thead>
<tr>
<th>DUNCAN GROUPING</th>
<th>MEAN</th>
<th>N</th>
<th>KE</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>10.000</td>
<td>2</td>
<td>7.2</td>
</tr>
<tr>
<td>AA</td>
<td>9.000</td>
<td>5</td>
<td>12.4</td>
</tr>
<tr>
<td>AA</td>
<td>8.467</td>
<td>3</td>
<td>19.4</td>
</tr>
<tr>
<td>AA</td>
<td>7.300</td>
<td>5</td>
<td>24.4</td>
</tr>
</tbody>
</table>
Table A3.

**TIME TO INFILTRATE 50 MM OF WATER**

**ANALYSIS OF VARIANCE**

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>DF</th>
<th>SUM OF SQUARES</th>
<th>MEAN SQUARE</th>
<th>F VALUE</th>
<th>PROB&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODEL</td>
<td>2</td>
<td>6974.69038</td>
<td>3487.34519</td>
<td>82.912</td>
<td>0.0001</td>
</tr>
<tr>
<td>ERROR</td>
<td>20</td>
<td>841.21918</td>
<td>42.06095922</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C TOTAL</td>
<td>22</td>
<td>7819.90957</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROOT MSE</td>
<td></td>
<td>6.455442</td>
<td>R-SQUARE</td>
<td>0.8924</td>
<td></td>
</tr>
<tr>
<td>DEP MEAN</td>
<td></td>
<td>39.99565</td>
<td>ADJ R-SQ</td>
<td>0.8816</td>
<td></td>
</tr>
<tr>
<td>C.V.</td>
<td></td>
<td>16.42695</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**PARAMETER ESTIMATES**

| VARIABLE | DF | PARAMETER ESTIMATE | STANDARD ERROR | T FOR HO: PARAMETER=0 | PROB > |T| |
|----------|----|-------------------|----------------|-----------------------|--------| |
| INTERCEP | 1  | 21.14078259       | 3.13519601     | 6.743                 | 0.0010 |
| K       | 1  | 0.10459003        | 0.54612010     | 0.192                 | 0.8499 |
| KESW    | 1  | 0.08026615        | 0.02069669     | 3.841                 | 0.0010 |
Table A3 (continued):

**TIME TO INFILTRATE 50 MM OF WATER**

**ANALYSIS OF VARIANCE PROCEDURE**

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>DF</th>
<th>SUM OF SQUARES</th>
<th>MEAN SQUARE</th>
<th>F VALUE</th>
<th>PR &gt; F</th>
<th>R-SQUARE</th>
<th>C.V.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODEL</td>
<td>5</td>
<td>6972.5361284</td>
<td>1394.7077237</td>
<td>29.11</td>
<td>0.0001</td>
<td>0.895422</td>
<td>17.5564</td>
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<tr>
<td>ERROR</td>
<td>17</td>
<td>817.37095232</td>
<td>48.03854702</td>
<td>26</td>
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<td></td>
</tr>
<tr>
<td>CORRECTED TOTAL</td>
<td>22</td>
<td>7820.9060522</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SOURCE</td>
<td>DF</td>
<td>ANOVA SS</td>
<td>F VALUE</td>
<td>PR &gt; F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KE</td>
<td>5</td>
<td>6986.5361284</td>
<td>29.11</td>
<td>0.0001</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table A3 (continued):

<table>
<thead>
<tr>
<th>TIME TO INFILTRATE 50 MM OF WATER</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANALYSIS OF VARIANCE PROCEDURE</td>
</tr>
<tr>
<td>DUNCAN'S MULTIPLE RANGE TEST FOR VARIABLE: TIME</td>
</tr>
<tr>
<td>NOTE: THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE, NOT THE EXPERIMENTWISE ERROR RATE</td>
</tr>
<tr>
<td>ALPHA = 0.05, DF = 17, MSE = 48.0806</td>
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<tr>
<td>WARNING: CELL SIZES ARE NOT EQUAL. HARMONIC MEAN OF CELL SIZES = 3.31579</td>
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<tr>
<td>NUMBER OF MEANS: 2, 3, 5</td>
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<tr>
<td>CRITICAL RANGE: 11.3436, 11.9061, 12.2942, 12.5131, 12.6833</td>
</tr>
<tr>
<td>MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DUNCAN GROUPING</th>
<th>MEAN</th>
<th>N</th>
<th>KE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>72.250</td>
<td>4</td>
<td>24.4</td>
</tr>
<tr>
<td>B</td>
<td>51.133</td>
<td>3</td>
<td>19.4</td>
</tr>
<tr>
<td>C</td>
<td>35.429</td>
<td>7</td>
<td>12.4</td>
</tr>
<tr>
<td>D</td>
<td>28.000</td>
<td>3</td>
<td>8.2</td>
</tr>
<tr>
<td>D</td>
<td>25.000</td>
<td>2</td>
<td>7.2</td>
</tr>
<tr>
<td>D</td>
<td>21.000</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>
INfiltration RATE VS TIME

Vienna loam
Dry and Wet bare plot #21

○ ○ ○ Dry-act.
× × × Wet-act.
— — — Dry-pred
— — — Wet-pred

Figure A: Measured and estimated infiltration rate as a function of time for the kinetic energy of 7.2 J/m²-mm.
FIGURE A1. MEASURED AND ESTIMATED INFILTRATION RATE AS A FUNCTION OF TIME FOR THE KINETIC ENERGY OF 7.2 J/M²-MM.
FIGURE A2. MEASURED AND ESTIMATED INFILTRATION RATE AS A FUNCTION OF TIME FOR THE KINETIC ENERGY OF 8.2 J/M2-MM.
INfiltration Rate VS Time

Vienna Loam

Dry and Wet Bare Plot #8

- • Dry-Act.
- • WET-Act.
- DRY-Pred
- WET-Pred

Figure A3: Measured and estimated infiltration rate as a function of time for the kinetic energy of 8.2 J/m²-mm.
INfiltration rate vs time

Vienna loam
Dry and wet Bare Plot #9

- DRY-ACT.
- WET-ACT.
- DRY-PRED
- WET-PRED

Figure A4. Measured and estimated infiltration rate as a function of time for the kinetic energy of 8.2 J/m².mm.
INfiltration rate vs time

Vienna loam
Dry and wet bare plot #1

Dry-act.
××× Wet-act.

Dry-pred
--- Wet-pred

Figure A5. Measured and estimated infiltration rate as a function of time for the kinetic energy of 12.4 J/m²-mm.
FIGURE A6. MEASURED AND ESTIMATED INFILTRATION RATE AS A FUNCTION OF TIME FOR THE KINETIC ENERGY OF 12.4 J/M2-MM.
FIGURE A7. MEASURED AND ESTIMATED INFILTRATION RATE AS A FUNCTION OF TIME FOR THE KINETIC ENERGY OF 12.4 J/M2.MM.
FIGURE A8. MEASURED AND ESTIMATED INFILTRATION RATE AS A FUNCTION OF TIME FOR THE KINETIC ENERGY OF 12.4 J/M2-MM.
FIGURE A9. MEASURED AND ESTIMATED INFILTRATION RATE AS A FUNCTION OF TIME FOR THE KINETIC ENERGY OF 19.4 J/M2.MM.
FIGURE A10. MEASURED AND ESTIMATED INFILTRATION RATE AS A FUNCTION OF TIME FOR THE KINETIC ENERGY OF 19.4 J/M²-MM.
FIGURE A11. MEASURED AND ESTIMATED INFILTRATION RATE AS A FUNCTION OF TIME FOR THE KINETIC ENERGY OF 19.4 J/M².MM.
Infiltration rate vs time
VIENNA LOAM
DRY AND WET BARE PLOT #7

- DRY-ACT.
- DRY-PRED

Figure A12. Measured and estimated infiltration rate as a function of time for the kinetic energy of 24.4 J/m²·mm.
FIGURE A13. MEASURED AND ESTIMATED INFILTRATION RATE AS A FUNCTION OF TIME FOR THE KINETIC ENERGY OF 24.4 J/M2.MM.
FIGURE A14. MEASURED AND ESTIMATED INFILTRATION RATE AS A FUNCTION OF TIME FOR THE KINETIC ENERGY OF 24.4 J/M2·MM.
FIGURE A15. MEASURED AND ESTIMATED INFILTRATION RATE AS A FUNCTION OF TIME FOR THE KINETIC ENERGY RATE OF 12.4 J/M2.MM.
FIGURE A16. MEASURED AND ESTIMATED INFILTRATION RATE AS A FUNCTION OF TIME FOR THE KINETIC ENERGY RATE OF 12.4 J/M²-MM.
INfiltration rate vs time
Lowry silt loam
Dry and wet bare plot #1

Figure A17. Measured and estimated infiltration rate as a function of time for the kinetic energy of 24.4 J/m². mm.
INfiltration rate vs time
Lowry silt loam
Dry-bare plot # 2
- - DRY-PRED

Figure A18. Measured and estimated infiltration rate as a function of time for the kinetic energy rate of 24.4 J/m²-mm.
FIGURE A19: MEASURED AND ESTIMATED INFILTRATION RATE AS A FUNCTION OF TIME FOR THE KINETIC ENERGY RATE OF 24.4 J/M²·MM.