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ESTIMATING SPRINKLED INFILTRATION FROM TIME TO PONDING MEASUREMENTS

By

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ABSTRACT

ESTIMATING SPRINKLED INFILTRATION FROM TIME TO PONDING MEASUREMENTS

By

Patricia Ann Smolenski Crowley

The current method for recommending maximum sprinkler application rates, based upon standardized approximate ponded infiltration curves, overestimates allowable rates. Furthermore, the method does not include measured effects of tillage or consider application patterns of moving irrigation systems.

A simple time to ponding (t_p) model designed for this study requires only a single t_p function and a representative application pattern function to estimate the t_p and the conditions at t_p for sprinkler irrigation. These estimates may then be used as input to a ponded model, such as the Philip (1957) model, so that post-ponded infiltration can be additionally estimated. The model assumptions require that both input functions be defined in terms of rate as a function of cumulative depth.

The t_p function describes a set of field-observed constant sprinkled rate vs. t_p pairs (r^2>0.86 for conventional tillage). Factors influencing infiltration, such as tillage, become intrinsically embedded in the function. Desired rates (10 mm/h to 95 mm/h) can be conveniently selected and observed by using a portable sprinkling infiltrometer that was designed to meet the Bubenzer (1979) criteria for rainfall (irrigation) simulators. The six-nozzle intermittent-type infiltrometer is a hybrid between the Tovey (1963) and the Zegelin and White (1982)

infiltrometers, and up to six dry data pairs and 15 wet data pairs (21 pairs total) can be measured with it in one hour.

The application function of moving sprinkler irrigation systems is represented by a parabolic form that requires estimates of the maximum application rate and the period or total depth of application. Maximum rates ranged between 15 mm/h and 99 mm/h for 80 center pivots evaluated in the field.

Rate vs. t_p pairs reported in the literature were used to test the model's performance in comparison with a numerical solution to Richard's (1931) equation (Smith 1972). This model duplicates or closely matches the estimates calculated by the more sophisticated model. Four application scenarios, which deliver the same cumulative depths but with different maximum rates and periods, and 103 measured t_p functions were used to compare effects of tillage, residue, wheel traffic, rate pattern and irrigation strategy on sprinkler infiltration.

This work is dedicated

to

Francis D. Hole,

teacher of soil science,

who

enkindled in his students, farmer and freshman, an awakened perception

of their

Roots in the Great Nurturer and their

Branches into Unfolding Creation.

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θ_0 soil moisture by volume near saturation

θ_g soil moisture by mass

θ_i initial soil moisture by volume

θ_v percent moisture by volume

A a parameter in the Philip model that is a function of K_{sat}

a coefficient parameter of the rate as a function of time version of the time to ponding function

b exponential parameter of the rate as a function of time version of the time to ponding function

c coefficient parameter of the rate as a function of depth version of the time to ponding function $(a^{1/(b+1)})60^d$)

d exponential parameter of rate as a function of depth version of the time to ponding function (b/(b+1))

D cumulative depth, applied or infiltrated, although in units of depth, is sometimes referred to as an amount or volume

D_a total depth of water applied during the application period

$\%D_a$ percent of the applied water that infiltrated by the end of the application period

D_{np} the depth associated with r_{np}

D_p depth of water infiltrated from the time of ponding to the end of the application period

D_{tot} total depth of water infiltrated during the application period

D_{tp} depth of water infiltrated by time to ponding

$\%D_{tp}$ percent of the applied water that infiltrated by the time to ponding

f coefficient parameter of ponded function (S/2)

g exponential parameter of the ponded function

h maximum rate of parabolic application pattern (mm/h)

i infiltration rate

k minimum ponded infiltration rate, estimated by $a180^b$

K hydraulic conductivity

K_0 hydraulic conductivity near saturation

K_{sat} saturated hydraulic conductivity

p period of parabolic application pattern (h)

r application rate, which before ponding, equals the infiltration rate

r_{cons} a constant application rate

r_{np} an application rate which does not pond in a particular time period

r_{tp} rate of application (infiltration) at tp

S sorptivity, a parameter in the Philip model which measures capillary suction at a given θ

t time

t_1 ponded (virtual) time that corresponds to D_{tp} and r_{tp} at t_p.

t_2 ponded (virtual) time that corresponds to the end of the application period $(t_1+(p-t_p))$

t_3 ponded (virtual) time that corresponds with the end of the ponded state

t_e the real time that corresponds to t_3

t_{np} the time associated with an r_{np}

t_p time to ponding of application pattern on a particular soil, measured in real time which is the same as the application time.

ω tension, suction, or matric potential

LIST OF TILLAGE ACRONYMS

MBW	Moldboard plowed, wheel track
MBN	Moldboard plowed, non-wheel track
CPW	Chisel plowed, wheel track
CPN	Chisel plowed, non-wheel track
NTW	No-tilled, wheel track
NTN	No-tilled, non-wheel track
CPW1	Chisel plowed, wheel track, mid-season
CPW2	Chisel plowed, wheel track, late-season
CPN1	Chisel plowed, non-wheel track, mid-season
CPN2	Chisel plowed, non-wheel track, late-season
DPW	Disk plowed, wheel track
DPW	Disk plowed, wheel track
PMBW	Potato MBW
PMBN	Potato MBN
PPTW	Potato Paratill, wheel track
PPTN	Potato Paratill, non-wheel track

INTRODUCTION

Excessive ponding of irrigation water has many undesirable effects both in the short and the long term. From the irrigation manager's perspective, excessive ponding can translate into: 1) a lack of effectiveness of the irrigation effort itself, with much of the applied water never reaching its intended destination in the root zone, despite efforts to insure sprinkler uniformity, 2) movement of beneficial nutrients and crop-protection materials away from their intended destinations; and 3) possible liability in the contamination of ground and surface waters used by other consumers. From a general environmental perspective, excessive ponding is undesirable if it leads to the long-term degradation of the soil resource or pollution of water resources used, not only for drinking and other direct human consumption, but for recreation and wildlife habitat.

Excessive ponding is often present during sprinkler irrigation in Michigan (Loudon and [Crowley] Brown, Reports to the USDA-SCS 1984, 1985, 1986, and ASAE Paper 86-2506, 1986), and can be observed even on "high intake" soils generally considered to have no associated design restrictions (Vitosh and Fisher 1981). At the beginning of this study, there was very little information available on which soils were being irrigated in southern Michigan, or on the characteristics of the irrigation systems that were being used. There was no sprinkling infiltrometer available that adequately simulated sprinkler irrigation, and in the literature, there existed "a vast gulf between scientists who were developing elaborate theoretical computer models of soil moisture flow problems and practicing hydrologists and irrigation specialists who dealt with real hydrological problems" (Smith 1976). Tillage comparisons were universally evaluated in terms of runoff and erosion, processes whose component hydrologic parts are difficult to separate, and the measurable parameters used as input for physical models were often numerous, difficult to measure in the field, highly variable, non-intuitive, or not relevant to sprinkled infiltration. Other variables, such as surface residue, important to the sprinkled infiltration process, were not included in any physical infiltration model.

The objective of this work is to contribute to the understanding of infiltration under sprinkler irrigation so that the negative impacts associated with sprinkler irrigation can be minimized by limiting the ponding of applied water. This objective will be pursued in the following manner:

------Review the infiltration literature and critique the present recommendations for acceptable maximum application rates.

------Survey the soils classifications for southern Michigan, organize them into a comprehensive classification from an irrigation perspective, and estimate the areal extent of the irrigated soils.

------Estimate the characteristics of the irrigation systems presently used as reported in 80 systems evaluations.

------Characterize the application pattern of moving irrigation systems with a simple geometric form that has physical meaning.

------Design a sprinkling infiltrometer that adequately simulates sprinkled irrigation applications.

------Design a simple but realistic time to ponding function which can be effectively linked to a ponded function under the ponded conditions present at the time to ponding for any application pattern and which uses a single simple integrative function to characterize the surface conditions important to sprinkled infiltration as input.

------Systematically field test the infiltrometer under the dominant irrigated soil, tillage, and cropping practices, and characterize the surface conditions with a single integrated and reproducible function typical of pre-irrigation moistures.

------Use the model to evaluate alternative application strategies and estimate the efficacy of changing irrigation system characteristics (such as maximum application rate) or tillage practices for different soils.

The most significant outcomes of this study were:

------The identification of the Oshtemo and Montcalm/Spinks soil series as the dominant irrigated soils of southern Michigan, occupying more than 65% of the irrigated area in the top five irrigated counties.

------The estimation of the range of existing maximum application rates from about 20 to 65 mm/h and the realization that low pressure systems are not always high maximum application systems.

------The introduction of the parabola as an adequate function for moving sprinkler irrigation application patterns.

------The design of a sprinkling infiltrometer that simulates irrigation application and makes it easy to observe the times to ponding for selected constant rates.

------The design of a simple time to ponding function for predicting time to ponding under varying application patterns which uses a single representative field measured function as input and links to the Philip ponded model with the appropriate conditions at the time of ponding.

------An understanding of the effect of high maximum application rates on different soils, tillages and initial moisture conditions, and the identification of alternatives for ameliorating the effects of high maximum rates using different tillages and changing application depths.

LITERATURE REVIEW

This chapter reviews the literature associated with physical ponding and time to ponding, ponded and time to ponding models, the measurement of infiltration, the effect of soil surface conditions and infiltration under moving sprinkling irrigation systems.

I. Time to ponding

Time to ponding determination is of importance in the study of infiltration under sprinkler irrigation (Slack 1978) because infiltration before ponding involves the unsaturated flow of water which distributes itself in the soil uniformly with no preference for macropores, while after ponding, there will be a surface film of free water, and the pattern of wetting may become quite non-uniform because of the influence of macropores and surface flow (Clothier and White 1981, Clothier and Heiler 1983). Avoiding ponding may also help to maintain surface soil structure and deliver more of the water to the root zone (White et al. 1989). Clothier and Heiler further suggest that, at high irrigation rates, surface redistribution of free water can far exceed any non-uniformity in the application process.

The definition of the time to ponding is not absolutely clear in the literature. Some researchers, like Chu (1978), simply define ponding as the event which separates the stage of infiltration without surface ponding from the stage of infiltration with surface ponding.

Others, like James and Larson (1976) define it to be the onset of runoff. In the field, Bridge and Ross (1985) observed that when water application rates were high, a definite time-to-ponding could be easily determined because it happened quite quickly, while when rates were lower, ponding occurred more gradually, with some parts of the plot showing surface water accumulation before others. Although variability was to be expected in the field, they felt comforted by the first detailed description of ponding in the literature, made by Rubin and Steinhardt (1964), who described much the same phenomenon as Bridge and Ross had in the field but on packed columns of Rehovet sand in the laboratory. Rubin and Steinhardt defined three stages involved in the ponding process for their observations on the column: 1) the retardation of absorption, 2) puddle formation, and 3) completion of the water mantle. Bridge and Ross described the field ponding process as a coarser version of the same phenomenon: 1) the surface glistens with a film of water, 2) puddles form in depressions which grow as runoff from higher areas of the plot fills them, and 3) puddles coalesce and run off to the outside of the plot. For their purposes, they then selected the end of the second stage to be defined as surface ponding. Rubin and Steinhardt, on the other hand, selected the time when small puddles, 1 to 3 cm in diameter, were formed to designate the time of ponding. Since water was indeed ponded throughout this second stage, they found it useful to name the transition between the first and second stage as "incipient ponding", another term commonly found in the literature. Some researchers prefer the use of incipient ponding as the field manifestation of the predicted ponded time because the presentation of the second stage is dependent on local surface microrelief (White et al.

1981), though in some laboratory experiments the soil surface is made planar so that incipient ponding is also the time to ponding. Some of the elements of subjective judgement were avoided by Clothier et al. (1981) who measured the surface pressure potential with a small cylindrical porous ceramic tensiometer 5 mm in diameter and 200 mm long which was connected to a pressure transducer and then placed in a shallow bed of fine contact sand on the soil surface intermediate in the range of the microrelief. The time to (incipient) ponding was then determined to be when the surface pressure potential equalled zero (Rubin 1969 as cited by Chong 1983). Unfortunately, only a small part of the plot is sampled by the tensiometer (Bridge and Ross 1985) and those who experienced using the tensiometer did not feel that it added significantly to their sense of judgement (personal communication, I. White 1988).

II. Ponded models

After the onset of ponding, there are a variety of models that can predict infiltration behavior successfully. The most common of these are the Kostiakov, Horton, Holtan, Green and Ampt, and Philip models. Several of these have undergone multiple transformations over the years, the most notable of these being the Green and Ampt model, as they have been reinterpreted in ways unimagined by their creators. A literature review of the Horton, Holtan, and Green and Ampt models can be found in Appendix A; the Kostiakov and Philip models will be reviewed here.

A. The Kostiakov model

One of the main physical properties of the soil which determines the rate and nature of motion of soil water is the permeability of the soil (Rode 1965). The rate of absorption of water by soil is described by the absorption coefficient, a parameter which was first introduced by Kostiakov (1932). Kostiakov showed that this coefficient varied during the absorption process at any given moment t by the equation:

$$K_t = K_{in}t^{-h}$$

where K_t = absorption coefficient at time t,
K_{in} = initial value of the absorption coefficient,
and h = a parameter < 1.

and

$$K_{in} = K_o T^h$$

where T = time required for a steady flow to be established during the filtration of water through a soil (Filtration here is considered to be the second stage of the infiltration process, a process of three stages described by Rode (1965) to include: absorption, filtration while absorption continues, and redistribution after absorption ceases), and
K_o = Darcy's filtration coefficient, or saturated hydraulic conductivity.

It was shown by Lewis (1937 as cited by Swartzendruber and Huberty 1958) and Kuznik (1951 as cited by Rode 1965), that Kostiakov's formula may be used to find the connection between the overall infiltration volume and the time. Their general equation is:

$$I = at^b$$

where I = cumulative infiltration volume at t,
a,b = parameters, and
t = time from outset of infiltration.

This is the model usually referred to in modern literature as Kostiakov's model, and is a simple power function whose exponent is positive and between 0 and 1 (Mein and Larson 1971, Swartzendruber and Huberty 1958). This model is also sometimes seen in the differentiated form as:

$$i = ct^{-b}$$

where i = infiltration capacity (Skaggs 1982) or the rate at which water will infiltrate, or infiltrability (Hillel 1980), the volume of water entering a unit soil surface area per unit time; and
b,c = parameters.

The parameters in both the volume and rate equations are determined by a linear least-squares fitting of experimental data to the equation $\log(I) = \log(a) + b \log(t)$. For this reason, the parameters a and b are difficult to predict because they have no unique and precise physical meaning (Mein and Larson 1973, Skaggs 1982, Philip 1954, Hillel 1980). It has been noted that they seem to be a function of soil type and initial conditions (Skaggs 1982), and Tisdall (1951) correlated both a and b with initial volumetric soil moisture content. Kincaid et al. (1969) said that the parameter a is a function of initial volumetric soil moisture content and soil type, and b is a function of soil type, although he still used fitted parameter a and b values, while Dixon (ASAE Paper 77-2062, 1977) said that parameters a and b are interrelated; the parameter a being a function of microroughness and macroporosity, and b being a function of microroughness, macroporosity and effective surface head, but his work on this matter, although often quoted, has not appeared in referenced publications. He also said that typical values for the parameter a ranged from 0 to 20.

Both Horton (1940) and Philip (1957) highlighted the limitations of the equation, pointing out that the differentiated (rate) version of the formula implied that i approached zero as t goes to infinity, rather than to some constant non-zero rate. While this may still be useful in describing horizontal infiltration, it does not fully describe vertical infiltration (Skaggs 1982, Hillel 1980). Furthermore, they note that at t=0, i goes to infinity. Philip also has shown that a and b are not constants, but vary with time: b = 1/2 when t is small; and b goes to 1 and a = K_{sat} at t equal to infinity. Nevertheless, while the equation does not describe infiltration conditions beyond the experimental conditions, it "describes the infiltration rate at the lower end of the time scale quite well" (Philip 1957).

There are several modifications of Kostiakov's model in the literature, most adding terms to correct for i going to zero as t goes to infinity, so that i becomes instead a non-zero constant value equal to K_{sat} (Sozykin 1939 as cited by Rode 1965; Shafique and Skogerboe 1983; and Swartzendruber 1974).

As originally conceived, the Kostiakov model is applicable only to the case of rainfall or other application rate sufficient to cause immediate ponding on the soil surface (Idike et al. 1980), and the simplicity of the equation has encouraged its use in flood-irrigation studies (Fok 1967 as cited by Mein and Larson 1971). Free, Browning, and Musgrave (1940 as cited by Swartzendruber and Huberty 1958) found good fit for 68 soil profiles. Tisdall (1951) found high correlations for infiltration into three different soils using Kostiakov's model (he referred to it as Pennefather's equation), and says it held true for about sixteen hours, although the parameters a and b can be determined after only a few hours.

Dixon (ASAE Paper 77-2062, 1977) said that only the Kostiakov equation gives a consistently accurate fit regardless of the measurement source (border irrigation infiltrometer, wet and dry infiltrometer runs, sprinkled water infiltrometers, and ponded water infiltrometers with both open and closed tops) and has chosen the Kostiakov equation to accompany his air-earth interface concept.

B. The Philip model

The Richard's flow equation relates the Buckingham-Darcy equation, which describes the flux through an unsaturated porous media, to the equation of continuity, a conservation of mass equation (Richards 1931, Swartzendruber and Hillel 1973). The first mathematically rigorous solution of the Richard's equation as it was applied to vertical infiltration was contributed by J.R. Philip (Hillel 1980). Much of the work of Philip centers on the properties of soil diffusivity, $D(\theta)$, taken from the mathematics of heat flow (Smith 1983). The non-linearity of unsaturated conductivity as a function of soil moisture, $K(\theta)$; diffusivity, $D(\theta)$, which expresses K as a function of soil moisture and tension (ω); and $C(\theta)$, the specific water capacity, which links $K(\theta)$ to $D(\theta)$, prevented exact analytical solution of Richard's equation except for a few limited cases (Skaggs 1980). Consequently, the difficult analytical solution for Richard's equation (unsteady flow) proposed by

Philip (Mein and Larson 1971) was based on a concentration dependent diffusion equation (Whisler and Bouwer 1970).

Most mathematical treatments of unsaturated soil water flow focus on the description of flow induced by capillary potential gradients. This is a reasonable approach because when the upper boundary is suddenly saturated and a high flux is imposed, flow into a dry soil is dominated by capillary flow dynamics. Philip treated the addition of gravity induced flow by successive perturbation to the capillary potential induced flow (horizontal) case by using a rapidly converging numerical technique in the form of a series in which the power for t increased by 1/2 in each successive term, where the coefficient of each term after the second was a correction for the previous term (Smith 1983).

Hence x, the vertical distances to the wetting front, is described by

$$x = at^{1/2} + bt + ct^{3/2} + dt^2 + \ldots$$

where a, b, c, and d are explicit functions of θ stemming from particular values of θ_i, θ_o and the functions of $K(\theta)$ and $D(\theta)$ (Kunze and Nielsen 1982).

Philip proposed that only the first two terms of his series solution be used as a concise algebraic infiltration equation:

$$i = \frac{S}{2}t^{-1/2} + A,$$

or

$$I = St^{1/2} + At.$$

The original solution assumed that an infinitely deep uniform soil at a constant initial soil moisture became submerged under a thin layer of water so that the surface layer instantly reached near-saturation, θ_o, and that the water supply remained constant (Hillel 1980). The sharpness of the wetted front, so important in the Green and Ampt assumption, is simply related to the change in diffusivity of the wetted soil and dry soil (Hillel 1980).

The parameters of the Philip equation are S and K, since A is usually assumed to be some function of K (Sharma 1979). Sorptivity, S, is described by Philip as a measure of capillary uptake or removal of water by soil without gravitational effects (Scott et al. 1983) and is one of the most important parameters governing the early portion of infiltration. In a single parameter, it embodies the influence of matric tension and K on the transient flow process that follows a step function change in θ_o or ω.

Both S and A have physical meaning (Talsma 1969); S being a function of $\omega(\theta)$ and $K(\theta)$ and can be obtained by methods given by Philip if $D(\theta)$ and $\omega(\theta)$ are known (Skaggs et al. 1969). The detailed procedure is available in Kirkham and Powers (1972). The main disadvantage of calculating S in this way is that both $D(\theta)$ and $K(\theta)$ must be known prior to the calculation. Measurements of $D(\theta)$ are tedious and time consuming and for practical purposes, Chong and Green (1983) advise that we should avoid this method if other alternatives are available. Strictly speaking, one should write $S(\theta_o,\theta_i)$ or $S(t_o,\theta_i)$, since sorptivity has meaning only with θ_i and imposed boundary conditions (Hillel 1980). Philip also defined "intrinsic sorptivity", a parameter which takes into account the viscosity and surface tension of the fluid.

The sorptivity S is proportional to the difference between the initial and saturated water content of the soil and the square root of the soil water diffusivity. The diffusivity is averaged in such a way as to give more weight to the diffusivity near the soil surface than at the wetting front (Gardner and Mayhugh 1958 as cited by Gardner 1967). A higher initial soil moisture in the soil reduces S approximately linearly. A higher head of water ponded on the surface of the soil also tends to increase the sorptivity and hence the infiltration rate. These effects tend to disappear with the passage of time, as the first term in the equation becomes less important. Under all the conditions of infiltration into a uniform soil, the infiltration rate eventually approaches the same final value asymptotically (Gardner 1967). Not only does sorptivity vary with initial soil moisture, it varies for different soils, depending on their structure (Bouwer 1978 as cited by Chong and Green 1983)

Both Sharma et al. (1979, Sharma 1980) and Chong (1983) have extensive reviews of the meanings, estimates and measurements of S. It can be calculated from known soil properties, determined experimentally (Collis-George 1977), measured in the field, or fitted by regression. In most field conditions, S and K_{sat}, and therefore A, can be measured easily and reliably (Sharma et al. 1980). Measuring S consists of timing the initial vertical flow of water into an undisturbed profile. This method relies on the assumption that during the measurement time of 1 to 2 minutes, the first term of $I=St^{1/2} + At + Bt^{3/2}$ etc. dominates flow (Talsma 1969). For horizontal flow, sorptivity equals the cumulative flow (depth) divided by time to the 1/2 power (Hillel 1980)

Other determinations of S besides the simplified instantaneous profile method include measurement of infiltration using the ponded single or double ring infiltrometers, the unsaturated infiltration method as suggested by Dirkson (1975 as cited by Chong and Green 1983) and developed by Clothier and White (1981), and estimates from constant sprinkling infiltrometer measurements using time-to-ponding models such as those developed by Mein and Larson (1971), Parlange and Smith (1976), Kutilek (1980), and Clothier and White (1981) (Chong and Green 1983).

Brutsaert (1976) concluded that S is log normally distributed on a basin-wide scale. His conclusion was based on the equation which expresses $S(\theta)$ as a function of K_{sat}, since K_{sat} is log normally distributed (Nielsen et al. 1973) and should have a similar distribution. The log normal distribution has been demonstrated by Chong and Green (1983) and Sharma et al. (1980) with field measured data. The assumption that $S(\theta)$ is normally distributed may not be in much error, since the measured variation in S over a large area was within one order of magnitude (Sharma et al. 1980).

Estimates of A vary considerably: for long values of time, Philip (1957) provided another analysis which showed that $i=K_0$ and, for the same reason, A approaches K_{sat} when time goes to infinity (Ghosh 1980). If Philip's methods are used to define A from $D(\theta)$ and $h(\theta)$, the resulting value will be approximately $K_{sat}/3$, and the infiltration rate will not be correctly predicted for long times. Nevertheless, many researchers have used $A=K_{sat}/3$ in their work (Youngs 1968, Swartzendruber and Youngs 1974, and Sharma et al. 1980). Whereas others have selected more intermediate proportions of K_{sat}, Brakensiek and Rawls (ASAE Paper 81-2504, 1981) selected A to be 0.67 K_{sat} in the hopes that the solution will be more predictive over the entire time interval as t goes to infinity, and Whisler and Bouwer (1970) set A = 0.75 K_{sat} for cumulative infiltration amounts at ten hours.

It is difficult to compute Philip's parameters by his methods and they are normally fitted. A regression fit to experimental data over long times will tend to give $A=K_{sat}$ (Skaggs et al. 1969,1980). But, because infiltration measurements are more often conducted over short times, the measured infiltration values continue to decrease throughout the experimental period with the resulting fitted value of A being very low or even negative. Changing A to be consistent with expected values of K_{sat} will cause a large overprediction of infiltration at early times, whereas using the fitted values for early times will underestimate the infiltration at long times (Skaggs et al. 1969).

The Philip model and the Kostiakov model become identical in form when the Kostiakov model is modified by adding a second term so that $i=K_{sat}$ at long times (Swartzendruber and Hillel 1973). The Philip model fixes the exponential term associated with time at -1/2 when calculating the infiltration rate.

Watson (1959), Heerman and Kohl (1980), and Collis-George (1974) all found that the Philip model underpredicts i at long times. On the other hand, Nielsen et al. (1961) tested Philip's theory under field conditions, and another test was made by Green et al. (1964) and both found good agreement between the theoretically predicted water content distribution and the experimental data. (Gardner 1967).

Although there are still unresolved problems associated with the Philip model, such as accurately separating sorptive and gravitational flow contributions for all situations, and although it may not be more reliable than other equations under field situations, Philip's analysis, coupled with the experiments of Colman and Bodman (1944) went far towards providing a useful picture of the physical processes governing infiltration (Gardner 1967).

III. Preponded models

Efforts to analyze rainfall infiltration have been based either on empirical approaches (Kincaid et al. 1969, Dillon et al. 1972) or on attempts to solve the highly non-linear flow equation for flux (non-ponded) boundary conditions (White et al. 1981). The first successful calculation of the development of soil water content profiles during constant-rate (sprinkled) infiltration using basic soil water properties was made by Rubin and Steinhardt (1963), who used a finite difference method to solve the flow equation. Rubin (1966) mathematically demonstrated that infiltration curves under ponded conditions were not the same as those obtained under sprinkled or rainfall conditions, the greatest difference being noted in the early stages of post ponding infiltration (Amerman 1983). Although all the non-ponded curves are of the same general shape, and seem to be approaching the same limiting rate, they do not constitute horizontally displaced parts of the curve (Rubin 1966).

In 1969, Childs pointed out that the infiltration process could be thought of as the consequence of the conductivity and the potential gradient at the surface in accordance with Darcy's law or as the rate of increase of the total amount of water stored in the soil profile (Brakensiek 1979, Brakensiek and Rawls 1983). This second point of view became the springboard off which many new approaches were launched.

Thus any infiltration rate equation and its integral could be applied to any sprinkled rate-time distribution without regard to actual clock time. Roger E. Smith (1972) solved the theoretical partial differential equation for unsaturated soil moisture flow by a numerical method designed to accurately simulate infiltration from various patterns of rainfall. He concluded that an infiltrated volume relation appeared to be a good predictor of time to ponding under complex rainfall patterns after demonstrating that "as long as rainfall rate exceeds the saturated infiltration rate, ponding and subsequent delay of ponding occurs at very nearly the time when the accumulated volume of infiltrated water reaches a constant which is associated with the particular rate of rainfall when ponding occurs".

Reeves and Miller (1975) obtained numerical solutions to a Richards equation which considered hysteresis and surface crusting and which also supported the cumulative infiltration depth approach (Skaggs 1982). This opened the door to the reinterpretation of ponded models, such as the Green and Ampt by Mein and Larson (1971, 1973), for preponded conditions. A flood of new time-to-ponding equations for constant rate applications (r_{cons}) began to appear in the literature. Mein and Larson used the parameters of the Green and Ampt:

$$D_{tp}=S_{av}M/(r_{cons}/(K_{sat}-1))$$

where $$M=\theta_0-\theta_i$$

and $$r_{cons}>K_{sat}.$$

(See Appendix A for more information on the Green and Ampt model). Philip and Knight (1974) improved a general approximate solution that Parlange (1972) developed which was found to accurately predict the infiltration behavior of constant rate applications to soils in the laboratory (White et al. 1979, Perroux et al. 1981) and in the field (Clothier et al. 1981, White et al. 1981). Their model, as represented by the simplified Perroux et al.(1981) model, was compared with the White et al. (1981) model, the Parlange and Smith (1976) model, the Talsma and Parlange (1972) model, and the Kutilek (1980) model against measured sorptivity, hydraulic conductivity and time-to-ponding produced by a drip infiltrometer (Bridge and Ross 1985). Measurements using this instrument most resembled the Parlange and Smith model. The Perroux et al. model was designed for use when the $r_{cons}>>K_{sat}$:

$$t_p=S^2(\theta_0,\theta_i)/2(r_{cons})^2.$$

An equation that can be used when $r_{cons}<5K_{sat}$ is the White model, which is one that makes the same assumptions as the Green and Ampt model:

$$t_p=S^2((\theta_0,\theta_i)/(2r_{cons}(r_{cons}-K_{sat}).$$

The Parlange and Smith model, again for $r_{cons}>>K_{sat}$, is:

$$t_p=S^2\ln(r_{cons}/(r_{cons}-K_{sat}))/2K_{sat}r_{cons}.$$

The Kutilek model, sometimes referred to as the Philip t_p model because it is a version of the Philip ponded model, is:

$$t_p=S^2(1-(A/2r_{cons}))/2r_{cons}{}^2(1-(A/r_{cons}))^2.$$

Chu (1978) used the Mein and Larson version of the Green and Ampt model to model infiltration under a non-constant rate by partitioning the time intervals into segments of constant rate. There is much attention being given to time shifts, dimensionless time, compressed time and "pseudo time" in an effort to cope with the transition between preponded and ponded time since the ponded conditions do not begin at time zero. There are also many additional variables introduced when diffusivity is involved with the solution.

IV. Direct and indirect measurements of sprinkler irrigation infiltration

Infiltration under sprinkler irrigation may be estimated directly through the use of infiltrometers, or indirectly by measuring properties, such as soil texture, which are used as inputs to models that estimate infiltration behavior. Since infiltration under sprinkler irrigation usually occurs under both ponded and preponded conditions, there are basically two kinds of infiltrometers that can be used to simulate those conditions: cylinder-type, or ponded, infiltrometers and sprinkling infiltrometers.

A. Direct measurements

1. Cylinder-type, or ponded infiltrometers

The double-ring infiltrometer method of measuring ponded infiltration basically involves pressing or driving two concentric steel cylinders into the soil to or through any impeding layer, and either filling the rings with water and recording the velocity of the change in the supply head or recording the velocity of the water supply needed to keep the supply head constant (USDA-ARS 1956). The outer ring, or buffer ring, is kept filled so as to encourage vertical infiltration only in the inner measuring ring. The problems associated with this method are:

1) the rate of the water intake varies curvilinearly with the size of the cylinder (Aronovici 1955 as cited by Parr and Bertrand 1960),

2) the rate of water intake varies with the supply head (Schiff 1953, Aronovici 1955, both as cited by Parr and Bertrand 1960),

3) the method of placement of rings into the soil may cause the soil to shatter or compact (Parr and Bertrand 1960),

4) the measurements are naturally highly site-specific and variable and getting a representative mean and standard deviation requires many measurements (Burgy and Luthin 1956, 1957, both as cited by Parr and Bertrand 1960),

5) the side of the metal may cause unnatural seepage planes which cause unnaturally high infiltration rates (Parr and Bertrand 1960)

6) soil air may become entrapped before the wetting front and impede downward water movement (Parr and Bertrand 1960), and

7) the presence of large biopores may increase the rate through which infiltration takes place and affect the basic assumptions involved in the computation of the infiltration rate (Clothier and White 1981).

A good approximation to vertical flow (effective saturated hydraulic conductivity) can be obtained when the inner ring is large enough that the ratio of Bouwer's critical pressure head (defined as the center of the pressure head range where most of the changes in hydraulic conductivity occurs) to the infiltrometer diameter approximates zero (Bouwer 1984). Because of the many problems measuring ponded infiltration, new measurement methods continue to be developed: One of these is the velocity head permeameter (personal communications, Merva 1988) which economizes on installation time and water consumption, and makes it easy to gather the large number of observations needed to sufficiently characterize ponded infiltration, given the limitations involved. Another is the Perroux-White ponded disk permeameter (CSIRO Disc Permeameter Instruction Manual 1988) which controls the supply potential to a very small depth. It sits upon a cylinder that is inserted into the soil about 2 mm, but has no outer cylinder to restrict flow to a vertical direction.

A devise that operates along similar lines is the disk permeameter (Clothier and White 1981), which was designed to measure sorptivity and unsaturated hydraulic conductivity directly and includes a ponded water source held under suction. There is no soil intrusion component involved with this devise, which rests upon a layer of sand confined by an "O"-ring set upon the surface of the soil. Holding the water source under suction confines water movement to pores up to a particular size, depending on the suction-pore size relationship of the soil. For the same reason, the unsaturated hydraulic conductivity measurements would then be three dimensional rather than vertical, but air entrapment problems would be diminished. The unsaturated condition could be then used to estimate flow conditions similar to those found in non-ponded conditions. Exclusion of biopore activity might make the soil measurement seem less variable.

2. Sprinkling infiltrometers

Estimates of non-ponded infiltration due to sprinkler irrigation has been accomplished primarily through the use of sprinkling infiltrometers which are similar to rainfall simulators. Bubenzer (1979) compiled a list of six desirable criteria for the design of rainfall simulators which he presented to the USDA-sponsored Rainfall Simulation Workshop:

1. Drop size distribution similar to that of natural rainfall.
2. Drop velocity at impact near terminal velocity.
3. Intensity corresponding to natural conditions.
4. Uniform application over plot and random drop size distribution.

5. Total energy applied near that of natural rainfall.

6. Reproducible storm patterns.

An infiltrometer designed to measure infiltration due to sprinkler irrigation includes the same basic criteria except that the characteristics of sprinkler irrigation would be substituted for those of natural rainfall. Drop size distribution for irrigation nozzles can be obtained sometimes from nozzle manufacturers or estimated using a drop size distribution model (Solomon et al. 1985) requiring nozzle size and pressure head. A limited amount of drop size distribution information is published (Solomon et al. 1985, Kohl and DeBoer 1984, Kohl 1974). The droplet sizes from medium sized agricultural sprinklers range from about 0.3 mm to 5 mm, with the modes about 1.5 to 2 mm. (Kohl 1974). Droplets from low pressure sprinklers ranged between 0.3 mm to about 3.5 mm with modes between 1 and 1.5 mm (Kohl and DeBoer 1984). Various methods also exist to measure droplet sizes directly. (Eigel and Moore ASAE Paper 82-2588, 1982).

Drop size velocity from irrigation systems is a function of the average velocity of the emerging water, gravity, and drag (Stillmunkes and James 1982). The downward discharge of water under pressure and the relatively short distances that the droplets fall from irrigation systems make it likely that drop velocity at impact will be greater than terminal velocity (Rawitz et al. 1972).

Application rates from sprinkler irrigation systems differ according to the type of system and the type of nozzles used. The rate from a solid set system is constant, while a linear set is variable over the wetted diameter and the wetted diameter is constant. A center pivot system has an increasing wetted diameter from pivot to end gun. Dillon et al. (1972) developed a relationship which indicates that the maximum application intensity is inversely proportional to the wetted diameter of a sprinkler and provides a reasonable estimate of maximum rate. (DeBoer et al. ASAE Paper 83-2024, 1983).

Impact nozzles generally produce greater instantaneous application rates than spray nozzles (Stillmunkes and James 1982) but maximum application rates can be much higher using spray nozzles because their wetted diameters are smaller. Intensities approaching 115 mm/h have been measured for reduced pressure sprinklers (Deboer et al. ASAE Paper 83-2024, 1983).

The total energy of an infiltrometer-produced application depends on the droplet size and velocity at impact and the kinetic energy/volume is only a function of the square of the droplet impact velocity. According to a sensitivity analysis done by Stillmunkes and James (1982), droplet size is more important that nozzle trajectory, nozzle height, and average velocity at the nozzle in determining kinetic energy/unit area for droplet sizes less than 3 mm.

There are two kinds of sprinkling infiltrometers: drop formers and nozzle-based. Amerman (1983) summarized many of the reviews presented at the Rainfall Simulator Workshop in 1979. Drop forming infiltrometers regulate application rate by the spacing and size of the drop-formers and pressure head. Drop size is controlled by the size of the drop-forming tube and the variable control of the air flow around the tube. Desired mean drop size can be reproduced easily, but the range of drop sizes is much smaller than that of rainfall or sprinkler irrigation. In order to randomize the pattern of drops falling on the surface, some mechanism that moves the tubes must be used. Drop forming infiltrometers have been able to simulate up to 85% of natural rainfall kinetic energy (Hamon 1979).

Nozzle-based infiltrometers can be classified as either continuous or intermittent sprinkling infiltrometers. Intermittent application is used because it is not currently possible to buy spray nozzles capable of simulating the desirable kinetic energy and droplet size distributions while at the same time delivering low rates of application. Intermittency can simulate 100% of kinetic energy and provide reasonable drop size distributions while controlling the rate of application.

Zegelin and White (1982) designed a sprinkling infiltrometer to test infiltration theory. Intermittency of application was achieved by the use of a solenoid valve controlling the on-off flow through a single nozzle. They achieved 92% coefficient of uniformity for all application rates (1-45 mm/h) when they used a minimum on-time of 0.5 second. Intermittency can also be achieved by allowing only a fraction of the water produced at the nozzle to pass through a slot which spins beneath the nozzle. Amerman et al. (1970) achieved 87-92% coefficient of uniformity over an application range of 2.4 to 75 mm/h using these slots.

Sloneker and Moldenhauer (1974 as cited by Amerman 1983) speculated that drainage during the off-time resulted in increased near-surface soil water suction, but Zegelin and White (1982) argued that after initial wetting had been accomplished, intermittency should have little effect, and they demonstrated that the effect was indeed damped out near the surface.

There has been very little work done to assess runoff plot arrangement when infiltration is calculated to be the difference between the application rate and the runoff rate. Like the ring infiltrometer, there are size and boundary problems that significantly affect the amount of runoff collected. Infiltrometer plot areas are as small as 0.84 m^2 (Blilie and Disrud ASAE Paper 80-2064, 1980), and as large as 3-4 m in diameter (Hamon 1979). Swartzendruber and Hillel (1975 as cited by Amerman 1983), attempted to account for the time-lag between the time of application and the time of runoff.

One of the first methods of measuring infiltration rates for the purposes of designing sprinkler irrigation systems was devised by Tovey (Tovey 1963, Tovey and Pair 1966). The Tovey infiltrometer was used to determine infiltration rates and storage capacities of Central and Northeast Oregon (Simpson and Shearer 1971).

Water was sprayed from an opening in a circular shield surrounding the nozzle which allows only a fraction of the total water emitted from the nozzle to be applied to the soil. The excess water was then recirculated. Screens and knife edges were added to the edges of the shield opening to help prevent distortion of the spray pattern.

First the field soil moisture was brought up to field capacity. Then catch cans were placed one foot apart in concentric circles radiating at five foot intervals from the sprinkler to measure the application rates. The time to ponding was noted in association with the catch cans and the greatest application rate which delivered the desired amount of water without ponding was selected as a safe application rate for the particular soil, crop, and tillage method measured. This rate was then recommended for a stationary system.

The results of the Oregon tests by soil texture are given below:

TEXTURE	STEADY STATE INFILTRATION RATE (mm/h)	NO OF OBSERVATIONS
sicl	5.1	2
sil	7.1	21
l	7.6	12
vfsl	9.7	3
fsl	14.7	3
sl	9.4	9
lfs	15.7	3
ls	21.6	2
fs	20.3	1

Another method of determining sprinkler infiltration rate was proposed by Shockley (Shockley, D. 1968. Mimeographed report, Soil Conservation Service, Portland, Oregon), as cited by Dillon et al. (1972) which involves a stationary center pivot irrigation system. The test is performed at the soil moisture near the level at which irrigation will occur and when the surface soil condition is similar to that occurring through most of the growing season. Catch cans are placed at five foot intervals perpendicular to the stationary sprinkler lateral near the end tower and the time from onset of sprinkling application to the time until water ponds around the individual catch cans is noted. The average intake rate is determined by dividing the depth of catch by the time to ponding. This test is repeated several times in different places and the infiltration rate versus time graphed on log-log paper, and the line of best fit is determined. The time to ponding associated with the highest rate was used to set the minimum percent speed the system could be run in order to avoid ponding.

B. Indirect measurements

Other measurements of soil properties can be used to predict infiltration. Brakensiek et al. (1981) fitted the Brooks and Corey (1964) effective saturation-capillary pressure equation to 1085 soil moisture characteristics for ten soil texture classes ranging from sand to clay. The fitted parameters (pore size index, bubbling pressure and total porosity) were then normalized and used to predict the Green and Ampt parameters of wetting front capillary head and effective saturated hydraulic conductivity.

In another study, Rawls et al. (1982) conducted a comprehensive literature and data search of 1323 soils with 5350 horizons in order to generalize the relationships between soil water tension and hydraulic conductivity. From the data collected, relationships for predicting water retention volumes and saturated hydraulic conductivities, given particular tensions for the USDA textural classes were developed. Although the generalized functions for unsaturated hydraulic conductivity cannot accurately define any particular soil, they help to provide an estimate when more detailed data are not available.

In 1983, Rawls et al. attempted to characterize the Green and Ampt parameters again with regard to agronomic practices. This time in addition to particle size distribution, they included percent organic matter and bulk density change due to a specific tillage operation. If the soil is susceptible to crusting, surface cover and random roughness are also required to characterize the final crusted conductivity of a crust with an assumed thickness. (Brakensiek and Rawls 1983).

The measurement of sorptivity in situ can also be used to estimate infiltration using the Philip equation. It can also be used to give information about hydraulic conductivity, soil water potential, and soil water diffusivity, when combined with associated water content measurements (White and Perroux 1987).

V. Soil surface conditions

A list of 68 factors which researchers believe significantly influence infiltration behavior can be made by reading the reviews of Parr and Bertrand (1960), Johnson (1964), Hillel (1980), and Skaggs et al. (1980). The factors that will be discussed in this review will be primarily confined to those associated with the studies of soil surface conditions. Perhaps the statements that most reveal the underlying motivations of researchers who study soil surface conditions and tillage were written by Free (1960 as cited by Burwell and Larson 1969) and Moldenhauer and Burwell (1966), who suggested that the objective of soil management should be to create soil conditions to meet without "failure" the stress designs of rainstorms; that point of "failure" defined as that time that runoff is initiated. In this light, it is important to understand that most of the body of literature which links surface conditions to infiltration implicitly defines infiltration as the preponded and ponded water which does not run off into the study collection container. Researchers concentrating on the time to ponding, however make a distinction between preponded and ponded infiltration, and in the same way, advance the point of "failure" to the time when ponding is initiated. It is also rare that soil surface condition researchers have used their work to understand infiltration models.

Most of the factors they have chosen to study, such as roughness, surface sealing, and residue, are not part of physical models, and other factors, such as porosity and bulk density are only tangentially related. It's as if there are two worlds of infiltration research, the theoretical and the applied, and only occasionally do they meet in a truly meaningful way.

In 1986 the United States Environmental Protection Agency reported to Congress the results of a extensive government survey which found widespread groundwater contamination from agricultural sources (U.S. EPA 1987). This created public pressure for the study of transport pathways from agricultural soil surfaces to groundwater. Since water travels fastest in its saturated form, even a seemingly small pathway like that of flow through macropores during ponding, has not been ruled out as a significant source of contamination. Thus, in this discussion of soil surface factors which increase infiltration in the sense of decreasing runoff, it is important to keep in mind which of the factors are involved in the avoidance of ponding, and which of them are additionally involved in the avoidance of runoff.

A. Macropore flow

The term macropores was defined by Clothier and White (1981) as "planar voids, vughs (irregularly-sided voids) or channels greater than 1 mm in diameter". A complete description of voids and their classification by size and shape was compiled by Brewer (1976). Thus macropores include not only biopores but pores caused by cracking and tillage. Macropores are present in well-structured soils and often result in heavier-textured soils exhibiting a higher average saturated conductivity than lighter-textured soils (Ritchie et al. 1972 as cited by Thomas and Phillips 1979, Clothier and Heiler 1983). Introduction of an exotic, deeper-burrowing, surface venting species of earthworm to a silt loam with an average saturated conductivity of 9 mm/h resulted in a four to eight-fold increase in average saturated conductivity (Clothier and Heiler 1983). The number and activity of earthworms have been observed to increase when the soil was covered by mulch (Graff 1969, Teotia et al. 1950, both as cited by Ehlers 1975) and when tillage intensity was reduced (Becker and Meyer 1973, Schwerdtle 1969, both as cited by Ehlers 1975). The number and percent volume of earthworm channels in a surface horizon approximately doubled during the 4 years of no-till practice as compared to a tilled plot measured by Ehlers (1975). The maximum infiltrability of conducting channels in the untilled soil was computed to be more than 60 mm/h, although the volume of those channels amounted to only 0.2% of the volume measured (0.32 m^3).

Thomas and Phillips (1979) tell us that studies of macropore transport are not new, with the first study showing significant macropore transport reported over a century ago. They review a collection of studies from 1966 to 1977, including one by Ritchie et al. (1972 as cited by Thomas and Phillips 1979) which defines the concept of "displacement" as that flow of water which travels through the soil matrix in the classical Darcian sense as opposed to flow down macropores. Thomas and Phillips made four points which have bearing on this study: 1) in some soils with strong structure and rapid water addition, nearly all the water flows down the soil macropores, with essentially no displacement. (Quisenberry and Phillips 1976 as cited by

Thomas and Phillips 1979); 2) that gravitational flow through macropores can occur readily in soils that are well below "field capacity" (Aubertin 1971 as cited by Thomas and Phillips 1979); 3) that the value of an irrigation will not be so high as anticipated since some of the water and soluble chemicals may move much further beyond the root zone than previously anticipated; and 4) conversely, when irrigation is used as a salt-leaching practice, much of the salt in the surface will be bypassed. Tillages practices which disturb macropore continuity in the soil surface layer still leave macropores beneath that layer, by which water saturated at the boundary can still travel (fingering).

Since macropore transport takes place under saturated conditions it is not important in hastening the time to ponding, but it is important to the avoidance of runoff and erosion and to the recharge and possible contamination of groundwater.

B. Surface roughness

Surface roughness is a soil condition which affects both the time to ponding and the initiation of runoff, but mostly the latter. Two defined types of surface roughness are produced by tillage (Allmaras et al. 1966, Burwell et al. 1966). The first is the obvious kind of roughness oriented with the travel direction of the tillage implements and the second type is a randomly oriented roughness. Though the first type seems very important, soil conditions researchers have chosen to limit their studies to the second type, also disregarding residue in their estimates. The most commonly accepted measure of random roughness is accomplished by taking the standard deviation of the logarithm of the heights after the effects of oriented roughness have been subtracted.

Burwell and Larson (1969) reported that, depending on soil type (loam and sandy clay loam), random roughness accounted for about 90% of the variation in the estimated kinetic energy needed to initiate runoff in an rainfall infiltrometer study comparing the effects of random roughness and porosity. In another study, it accounted for 50% (Burwell et al. 1966). On the other hand, in a study done by Lindstom and Voorhees (1980) which compared wheel tracks versus non-wheel tracks on clay soils, even though differences in random roughness were measured and differences in the energy needed to initiate runoff were observed, random roughness did not consistently explain enough variation to be noted.

Allmaras et al. (1967) showed that water content and initial porosity at the time of tillage most affected roughness and porosity on a loam and two other soils, with roughness and porosity decreasing after plowing as the soil moisture increased up to the upper plastic limit. After the plastic limit was reached, surface roughness and porosity as a result of tillage began to increase again.

Values of random roughness after tillage reported in the literature range from 5.7 cm for a plowed surface to 0.5 cm for an untilled surface on a sandy clay loam (Burwell and Larson 1969). Lindstrom and Voorhees' values ranged more from 1.9 cm to 0.9 cm. Lindstrom and Onstad (1984) estimated the average random roughness "on planted fields in the Corn Belt to be about 1 cm".

Random roughness is included with percent slope in a model to estimate ponded surface storage in a Ph.D dissertation written by Linden (1979 as cited by Linden and Van Doren 1986), and Moore and Larson (1979) developed a model to calculate surface storage from point data.

Moore and Larson (1980) used the surface storage model as a submodel in a general infiltration-runoff model which also included an erosion, sedimentation and consolidation submodel and a Mein-Larson version of the Green and Ampt model. Generally speaking, surface storage is usually calculated to be about half the random roughness on a flat slope. This is quite a contrast to the model proposed by Musgrave and Norton (1937) and used in Chow's Handbook of Applied Hydrology (1964), which shows three "strictly mathematical" treatments holding from 3 to 5.5 cm of storage at a slope of 5%. One other estimate of surface storage by Shockley (Shockley, D. 1968. Mimeographed report, Soil Conservation Service, Portland, Oregon), as cited by Dillon et al. (1972) sets surface storage values at 2.5 cm at 3-5% slope.

Random roughness and the associated macroporosity and surface storage capability derived from tillage is a temporary phenomenon decreasing over time with the greatest loss of surface storage occurring during the pre-ponding application of water (Moore and Larson, 1979). In Moore and Larson's study of changes in random roughness and surface storage due to "rainfall" generated at a rate of 76 mm/h from a simulator, newly plowed surfaces lost about 0.4 cm of random roughness and surface storage. Cultivation after tillage increases random roughness and disrupts the surface seal (Mannering et al. 1966), but the positive effects of the cultivation are short-lived and only last until the next precipitation event (Burwell and Larson 1969, Arstad and Miller 1973). The larger clods and aggregates formed under wetter or more compacted tillage conditions are not as stable in contact with water as those clods formed at or near the upper plastic limit, the soil moisture at which the least surface roughness was created by plowing. Though the large clods create greater surface roughness, that roughness does not last as long (Johnson et al. 1979). A rough surface tends to concentrate the dispersed material in the microdepressions while leaving the clod peaks more porous (Larson and Gill, 1973). How fast a complete seal can be formed depends on the surface roughness after tillage (Burwell et al. 1968).

Although surface roughness is primarily a factor important to runoff avoidance, it can have some preponding effects where crusts are not yet formed. If the study of surface roughness was more developed, irrigation recommendations could be made in terms of runoff in case it is not possible to design systems so that they could avoid ponding in a practical way.

C. Surface crusts

If the soil surface is left unprotected, it will be subjected to the direct impact of falling droplets from rain or irrigation which will tend to destroy the aggregates and form a thin surface seal or crust (Musgrave 1955 as cited by Parr and Bertrand 1960). As water passes over the surface, the finer particles are deposited among the larger particles, making a seal and giving the soil a slick appearance (Duley 1939, Tackett and Pearson 1965).

Droplet kinetic energy and its accumulation over time is believed to be the main factor related to surface sealing (Moldenhauer and Kemper 1969; Stillmunkes and James 1982; Thompson and James 1985). General exponential decay models have been written to describe the changes in crust behavior as a function of time and droplet impact (Seginer and Morin 1970 as cited by Morin and Benyamini 1977). Soil crusting cannot be entirely avoided by protecting the soil surface from droplet impact. Crusts and high bulk densities at the surface can also be caused by the spontaneous slaking of aggregates under saturated wetting and drying conditions (Hillel 1960 as cited by Hillel 1980; Horton 1940; O. Baumer, personal communication, 1988, SCS, Lincoln, Nebraska).

Although surface crusts are usually not more than 0.1 mm thick in most areas and 2 to 3 mm in the microdepressions (McIntyre 1958), they can drastically affect the overall infiltration rate by lowering the effective saturated conductivity of the surface layer up to 20 times the effective saturated conductivity of the uncrusted profile (Duley 1939). McIntyre (1958) measured the permeability of a 0.1 mm thick crust layer at 1.8 x 10^{-3} cm/h and a 2.0 mm depressional crust at 1.8 x 10^{-2} cm/h.

The tendency to form a crust depends on the texture, structure, and chemical nature of the soil at the surface (Burgy and Scott 1952, Scott and Burgy 1956, both as cited by Parr and Bertrand 1960). Sands have little crusting tendency and soils containing sodium have a high crusting tendency. Non-inherent processes can also influence soil composition and structure: for example, soil structure at the surface can be altered by tillage, and the chemical composition of the soil can be altered by the quality of the irrigation water added (Chen and Banin 1975; Frenkel et al. 1978; Oster and Schroer, 1979; all as cited by Hillel 1980).

Nevertheless, factors such as texture, structure, tillage practices and cropping history, important in the formation of crusts, lose their importance in relationship to infiltration as the duration of droplet application on bare soil continues (McCalla 1942, Barnett and

Rogers 1966, Kemper and Miller 1974, Thomasson 1978, all as cited by Thompson and James 1985; Duley 1939). Duley (1939) found no large differences in the application rates minus the runoff rates in a sampling of soils with different textures (clay loam, sandy loam, silt loam, and silty clay loam). Mannering, in his Ph.D dissertation (J.V. Mannering. 1967. The relationships of some physical and chemical properties of soils to surface sealing. Unpublished Ph.D. thesis. Purdue Univ., Lafayette, Ind., as cited by Larson and Gill 1973) showed that for a wide variety of soil textures, the difference between the application rate and the runoff rates into soils with crusts averaged only 40% of those with an unsealed surface. Edwards and Larson (1969), point out that the low conductivities of the saturated surface seals are partially offset by the strong suction gradients which tend to move water through the surface at rates considerably higher than the saturated hydraulic conductivities of the seals.

A method has been developed to assess crust strength in the field (R. Grossman, personal communication, 1988, SCS, Lincoln, Nebraska) but acquiring the skill to use it objectively is difficult. Because the crust formation process is exponential in nature, it is most likely that irrigated fields in the humid region with the tendency to form surface seals would develop them early in the growing season (Moore and Larson 1979) with the crusting properties associated with infiltration, like hydraulic conductivity and thickness, quickly approaching an asymptotic value (Thompson and James 1985).

The importance of crusting to time of ponding is not clear from the literature because almost all of the surface crusting studies measured infiltration as a function of runoff. Since runoff is highly variable and the runoff process very complex, separating out the important variables in a sophisticated model is difficult (Moore and Larson 1980). The times to ponding measured before and after crust formation has not been studied, however the degree of change in time to ponding that could be expected for the times after the crust was formed would be predicted to be low. The formation of crusts on bare tilled irrigated soils in the humid region is probably not as dependent on the droplet size of the irrigation system as much as it would be in an arid region because of the greater influence of the droplet sizes of the rainfall received. The presence of a crust does have important consequences in the displacement of water after ponding, as macropore transport would be limited.

D. Residue, mulches, vegetative cover and biotic activity.

Probably the most important surface condition that affects both preponded and ponded infiltration is the degree to which the soil surface is protected by vegetative cover or residue. As in the cases of other surface condition research, the infiltration attributed to residue and mulches is generally considered to be the application minus the runoff collected, so the fraction of preponded and ponded infiltration is not apparent. Mulches and crop residues placed or left on the surface of the soil protect the soil surface from direct droplet impact, preventing or retarding crust formation as discussed above (Mannering and Meyer 1963, Lindstrom et al. 1981). An especially dramatic example of the effect of mulch on infiltration response was reported by Duley (1939) when he demonstrated that straw-removal resulted in 1/6 infiltration rate from original rate with straw, and similar results with burlap.

The quantity and quality of the residues both determine the extent of soil protection and the rate of material decomposition. These are, in turn, determined by the crop type and tillage method. For example, the percentage of the soil surface covered with plant residue following soybeans in the corn-soybean rotation studied by Erbach (1982) was nearly as great as that following corn. However, the soybean residue was much more easily destroyed by tillage than was the corn residue (Erbach 1982). Burwell et al. (1968) reported that the percentage of the soil covered with residue was more important than random roughness, porosity, or the amount of residue in explaining the differences in the amounts of energy needed to induce runoff. Stein et al. (1986) calculated that the placement of residue on a field can increase overall infiltration by absorbing and retarding runoff in critical pathways more than the absolute amount can (see also Mannering and Meyer 1963).

The chemical properties of the mulch or residue affect the rate of decomposition and can affect the absorption of added water. Some crop residues (oil crops) and mulches (plastic) are hydrophobic. Mulches and crop residues retard the evaporation of soil water and can result in higher antecedent soil moisture levels at the surface. They affect soil temperature depending on their light reflectance values and affect associated biota, thus increasing or decreasing macropore development, microbial activity, or weed cover and root development. Mulches and residues can themselves create macropore openings in the surface and can help to improve soil structure by creating a spongy interface on the soil surface as they decompose. Differences in climate can affect rate of decomposition and decomposition by-products, and the by-products can affect infiltration in the same way that the mulch and residue can (Johnson 1957, 1958, both as cited by Parr and Bertrand 1960). By-products can also turn into colloidal materials which could assist in the creation of a surface seal.

In some respects, most importantly in the avoidance of runoff, the presence or absence of residue can be considered to be a variation of the condition of surface roughness, but the effects of residue are more dominant than random roughness in the preponded infiltration stage because of the more lasting protection from crusting and the sorptivity of the material itself. It is desirable to have a better sense of the sorptivity of residue in association with the soil moisture and tension of the surrounding soil as it affects time to ponding.

Vegetative cover influences the soil surface in some ways that are similar to mulches and residues, however a vegetative cover also implies that roots will be using the moisture stored in the soil and that the soil moisture near the soil surface will be changed (Musgrave 1955 as cited by Parr and Bertrand 1960, Skaggs et al. 1969). Vegetative cover can be more variable than mulches and residues in that the amount of coverage may vary from planting to harvesting in one season (row crops), or from cutting to cutting (forage crops). Vegetative cover also collects and channels water flow down a stem, creating application rates and patterns quite different than the source delivering water above the cover canopy. For this reason, it is impractical to study vegetative cover as part of an application rate time to ponding experiment.

The activity of biota can increase or decrease infiltration.

Earthworms and other burrowing fauna create macropores that increase infiltration in the same way that surface cracks do (Hopp and Slater 1948 as cited by Parr and Bertrand 1960, Johnson 1964). Microbial activity can decrease infiltration when the soil surface is ponded (Christiansen 1944, Pillsbury and Appleman 1945, both as cited by Parr and Bertrand 1960), and increase infiltration by improving soil structure during periods of drying (Johnson 1958, McCalla 1942, both as cited by Parr and Bertrand 1960). Larger animals can create surface compaction which decreases infiltration.

E. Tillage

Tillage, or lack of it, affects the soil surface directly by altering residue placement, random roughness, fillable porosity, bulk density, size and stability of aggregates, and runoff patterns (Johnson and Moldenhauer 1979; Burwell and Larson 1969; Lindstrom et al. 1981; Klute 1982) in a non-uniform way (Cassell 1982). Tillage can destroy surface crusts, and change soil structure and pore size distribution as well as remove weeds and the competition for soil water. Tillage can also help to create surface fractures, as with subsoilers like the Paraplow, or create specially designed surface depressional storage areas, as with reservoir tillage equipment like the Dammer Diker (manufactured by the Ag. Engineering and Development Co, Richland, Washington). Additionally, tillage can create compaction at the surface through the action of wheel traffic. Incorporation of soil amendments may affect surface soil structure. The changes due to tillage are numerous, complex and often of short duration. Therefore the time elapsed to the last tillage operation, the water application and temperature history are often as important as the type of tillage performed.

Since soil conditions produced by a given tillage implement or combination of tillage implements differ markedly depending on other factors such as soil type, soil moisture at time of tillage and cropping history, tillage could be better analyzed by assessing the resultant soil conditions than by the description of the operations only (Allmaras et al. 1966). This is the logic behind using the Colvin index:

Colvin et al. (1984) designed a uniform tillage index which describes row topography, residue cover, roughness and depth of tillage. This, along with a description of the soil profile, has an appreciable potential to standardize the description of surface conditions that affect infiltration, runoff, and soil erosion. Row topography is measured by determining the difference between the heights associated with oriented roughness, and the percent residue is measured by the Laflen et al.(1981) line transect method. Despite its merit, this index has not been widely adopted by researchers.

In the last twenty years, many evaluations of alternatives to conventional tillage (In Michigan, this usually means using a moldboard or disc plow for primary tillage followed by a disc for secondary tillage) have been made, mostly with regard to their efficacy in reducing runoff and erosion. Researchers have focused on measuring residue, bulk density, and occasionally, random roughness, for their comparisons, and have avoided making hydraulic property measurements such as water retention, hydraulic conductivity and diffusivity as a function of θ or suction. This is due mainly to the complexities and difficulties of adequate sampling (Klute 1982). Some researchers often evaluate tillage effectiveness in terms of how much residue it leaves or how much roughness it creates, and at times are somewhat biased in their designs and results towards one condition or the other.

There is not a very strong sense of the role of soil texture in their work. The three tillage systems that offer improved infiltration behavior over the conventional systems are: no-till, chisel plowing, and controlled traffic systems.

The no-till system leaves the most residue on the surface (Lindstrom et al. 1981), and some feel that this, in itself, is the ultimate measure of effectiveness (Laflen et al. 1980 as cited by Moldenhauer et al. 1983) against the problems of runoff and erosion. While this has been generally true, no-till has not been found to consistently reduce runoff in all cases (McGregor et al. 1975, Siemens and Oschwald 1976, 1978, all as cited by Lindstrom et al. 1981) and in several studies, it produced the most runoff of any of the tillage systems studied (Lindstrom and Onstad 1984).

No-till on a silt loam had a higher θ_v than conventional tillage to a depth of 60 cm, and this translated into higher yields. (Blevins et al. 1971). Similar results were found by Jones et al. (1969) and Johnson et al. (1984) on other silt loams. However, it should by noted that the extra water conserved under no-till can occasionally be detrimental under conditions in which excessive θ contributes to denitrification losses (Blevins et al. 1983).

For the above reasons, it would seem more correct to conclude that the practice of no-till may increase or decrease cumulative infiltration, depending on soil conditions, climatic history, length of time the practice has been in place, and the tillage practice before no-till was started (DeBoer et al. ASAE Paper 87-2115, 1987).

The other system which leaves a greater amount of residue at the surface than conventional tillage is the chisel plowing system, but the amount of residue left can be quite variable. In addition to the extra residue, it also creates a rougher soil surface. Studies by Burwell et al. (1968, 1969) showed that chiseling (or other treatments providing a cloddy surface condition) infiltrated at least 50% more water than the non-chiseled (packed and consolidated) counterpart before runoff began. However, during the runoff phase, the intake rates were not affected by tillage treatment when there were not residues on the surface. Falayi and Bouma (1975) found similar results before runoff occurred, but little tillage effect during subsequent steady state infiltration. Robertson et al. (1979) say that chisel plowing is best adapted to fine-textured soils and is more effective in erosion control than moldboard plowing on slopes.

In some countries, tillage operations are designed to be done in the same tracks year after year, and compaction researchers often praise the merit of such controlled traffic systems. The measured saturated hydraulic conductivity of rows in a study where traffic was restricted to the same path on an Acuff loam in Big Springs, Texas over a three year period increased three-fold (Koshi and Fryrear 1973). With a cotton-bur mulch applied to the same situation, the saturated hydraulic conductivity increased eight-fold.

VI. Sprinkler irrigation and infiltration

One of the goals in sprinkler irrigation design is to deliver water to the soil so that ponding does not occur. When a new system is purchased, a routine effort is made to match the system features to the soil, but if the system nevertheless causes ponding and runoff, or a previously-owned system is bought and transported to a new location, the operator may be faced with the alternative of matching the soil condition to meet the system features. Before ponding occurs, the uniformity of water delivery is a function of the system hardware and the unsaturated redistribution process in the soil. However, after ponding occurs, the uniformity of the water delivered is subject to the same forces governing surface irrigation. (Heerman and Duke 1983, Clothier and Heiler 1983).

Early sprinkler systems were fixed, that is, the source of water did not move and a constant application rate was delivered to a point on the ground for the whole irrigation period. In these systems, the uniformity of application was more often a concern from a hardware point of view, with rates and cumulative amounts differing somewhat from place to place. The first person to measure the times to ponding associated with different sprinkled rates was Rhys Tovey (1963, Tovey and Pair 1966), whose portable infiltrometer used impact and spray irrigation nozzles to generate the rates to be observed. (See the infiltration measurement section in this review for a description of his method). His collection of time-rate pairs formed a sprinkled intake curve, or time to ponding curve, that had the same general appearance as a ponded intake curve and could be easily used to recommend sprinkler rates for fixed systems. All one had to do was select a time-rate combination slightly less than that on the curve. By 1971, many of the irrigated soils of Oregon were characterized using this method (Tovey and Pair 1966, Simonson and Shearer 1971).

The development of moving irrigation systems, especially the center pivot system, provided a leap forward for the irrigation operator by reducing labor requirements and increasing the uniformity of application (Pair 1968). This development also made it possible to easily exploit undulating terrain with slopes as high as 15 to 20% (Kelso and Gilley ASAE Paper 83-2517, 1983). By 1968, Pair (1968) reported that runoff had been often observed under center pivots because many of the agricultural soils that were being irrigated had sprinkled infiltrabilities of less than 9 mm/h, which the average application rates under center pivot systems usually exceeded. Kincaid et al. (1969) measured runoff amounts as large as 22 percent of the amount applied under a high pressure system on a silt loam, and DeBoer and Beck reported maximum application rates as high as 115 mm/h (ASAE Paper 83-2024, 1983). Because the application rates changed from low to high to low again as the moving system passed over a point, people were no longer sure how to design a pattern that would not cause ponding.

Heerman and Hein (1968) determined the design requirements for placing sprinklers on center pivots by assuming that the application patterns of the sprinklers could be estimated by triangles or ellipses. The amounts of water caught over a period of time in cans placed across the wetted diameter of a stationary system usually manifest a smooth curvilinear pattern, but data from a tipping bucket arrangement can produce a pattern that may be hard to characterize. Kelso and Gilley (ASAE Paper 83-2517, 1983) pictured a tipping-bucket measured application pattern that is smooth, but Slack (1980) had difficulty characterizing the application pattern measured by his tipping bucket system. Kelso and Gilley also measured the rate of application caught in plots below the full corn canopy, and though the patterns were similarly smooth, the maximum rates differed from 5 to 35 mm/h from the above canopy maximum rates, demonstrating the unpredictability of canopy effect.

In 1972, Dillon et al. presented the first comprehensive model to predict time to ponding and runoff under a moving sprinkler irrigation system. After evaluating the crop, soil profile storage and climatic factors to determine system requirements, they used an elliptical form to characterize the application function. A Tovey type time to ponding function, generated using a stationary center pivot as the water source at a typical pre-irrigation θ_i (Shockley, D. Mimeographed report (*sic*). 1968. Soil Conservation Service. Portland Oregon; Vittetoe, G. 1970. Mimeographed report (*sic*). State Conservation Engineer. Soil Conservation Service, Temple, Texas; both as cited by Dillon et al. 1972), was used to characterize the soil intake function. After determining the depth associated with the area between the application curve and the time to ponding curve, they subtracted the surface storage depth correlated to slope as appraised by Shockley to estimate the final runoff values for different soils, crops, climates, and slopes. The Texas Soil Conservation Service had time to ponding functions for two other "intake families" presented in the Kostiakov form which were mentioned in the paper. Predicted vs. actual times to ponding were within 6 minutes for 5 observations on three fields.

Kincaid et al. had earlier developed a time to ponding model for moving sprinkler irrigation (1969), which used a ponded infiltration function in the Kostiakov form as the controlling soil intake function. They recognized however, that 1), the intersection of the ponded infiltration function and the application function was not the time to ponding, since they were not independent functions, and 2), that the ponded function had to be adjusted somehow after ponding to provide for the water that had already infiltrated during the pre-ponding stage. They used Cook's assumptions (1946 as cited by Kincaid et al. 1969) to select the time to ponding as the time when the cumulative applied depth equaled the cumulative ponded infiltrated depth. After time to ponding, the ponded intake function was adjusted by subtracting the time to ponding from the initial time.

Gilley (1984) combined the work of Dillon et al. and Kincaid et al. with the ponded infiltration functions used for border irrigation by the Soil Conservation Service and presented ponding and runoff predictions for the entire set of intake families (USDA/SCS Engineering Handbook, 1964).

The Mein and Larson version of the Green and Ampt infiltration model as modified by Moore et al. (1981) was used by Slack (1980) to predict ponding under two sprinkler irrigation systems. He measured K_{sat}, θ_i and the application pattern. Unfortunately the application patterns that he measured with the tipping bucket were very irregular, and the skewed triangles he used to characterize the patterns were very approximate, with triangular patterns characterizing the same system showing two different maximum rates, one 40% greater than the other. One field that he observed was a sandy loam covered by alfalfa and the other was a sandy clay loam after a sweet corn harvest. He defined actual ponding as when 75% of the surface was ponded. Through a judicious selection of two different characterizing application patterns, he found a close match between his predicted and actual times to ponding for the alfalfa field. Although there was nothing to recommend his selection of system, field, or sample size, his work does highlight the differences that can exist between idealized and actual application patterns, and should not be considered evidence that the model didn't work, as is sometimes implied.

Because the irrigation system can be changed with regard to intensity and droplet size, irrigation researchers have initiated studies of the effect of droplet size and application intensity on aggregate stability and crusting (Levine 1952, Thompson and James 1985). Levine compared the ponded infiltration rates of six materials which were previously subjected to three droplet size diameter ranges sprinkled at rates of 12 mm/h for one hour, finding the sands to be the least affected and the silt loam and silty clay loam to be the most affected. He also measured the amount of material that passed through a 2 mm screen subjected to different droplet sizes and rates. The material on top of the screen was simply described as sieved aggregates, 2 to 5 mm in size. The results show that 3-6% of the aggregate mass passed through the screen when subjected to the 0-5 mm droplet diameters range, 18-27% with the 5-15 mm range and 28-40% with 15-25 mm range. However the rate of water application (from 10 mm/h to 46 mm/h) was unimportant. Levine measured droplet size with a method developed in 1895 (Weisner as cited by Levine 1952).

As mentioned in the infiltration measurement section of this review, there has been some effort to measure droplet size and distribution associated with many agricultural nozzles (Kohl 1974; Kohl and DeBoer 1984; Solomon et al. 1985) and droplet size information often can be obtained from the manufacturer of a particular nozzle. A model that will estimate droplet size distribution was written by Solomon et al. (1983), given nozzle size and operating pressure. Droplet size distribution information can be combined with a droplet trajectory model to predict impact energy distributions for sprinklers (Stillmunkes and James 1982) which can then be used to estimate crusting properties as discussed earlier in the surface crusting part of this review.

In a unique attempt to explore sprinkler system modification as a means to avoid ponding, Addink et al. (1975) modified the symmetrical application pattern to see if runoff could be reduced.
Their approach was based on the observation that soil intake rates are greater at earlier times, and in the laboratory, they used a travelling spray bar with variable numbers of nozzles to produce different rates in constant step patterns. Of the three patterns they produced, the one that was most successful in reducing runoff was the one in which rates were sharply increased and then brought down, in a forward skewed step pattern that resembles a generalized intake function.

When the existing application patterns do result in ponding, the system operator can try to modify the surface conditions to match the system in the same way that surface conditions are changed to meet the characteristic rainfall patterns of the climate. The kinds of tillage studies done under irrigation are identical to those done for rainfall in the sense that they generally assess runoff rather than time to ponding. Kincaid, Busch, McCann, and Nabil (Final Report on "Evaluation of Very Low Pressure Sprinkler Irrigation and Reservoir Tillage for Efficient Use of Water and Energy" submitted to the Dept. of Energy, Bonneville Power Administration, March 1987) found that reservoir tillage under very low pressure irrigation systems reduces runoff on sloping fields. They also reported that reservoir tillage is most important in the period after the surface seal has been developed and before the canopy cover is complete, and differences in the stability of the dikes during this period were attributed to the soil moisture at the time of tillage. Aarstad and Miller (1973) found that increasing surface roughness through the use of furrow basins and high residue levels, reduced runoff from about 40% to near 0%. The developers (Lyle and Bordovsky 1981) of a new low energy precision application system (LEPA) automatically included basin tillage (Lyle and Dixon 1977 as cited by Lyle and Bordovsky) as part of their overall design concept.

The largest set of papers with regard to irrigation and infiltration is concerned with the advent of low pressure systems (Gilley and Mielke 1980; Lyle and Bordovsky 1981; Gilley 1984; Von Bernuth and Gilley 1985). Low pressure systems are defined (Gilley 1984) as those operating at 130-200 kPa (20-30 psi) as opposed to conventional systems which operate at 410-590 kPa (60-85 psi). Up to 50% of the energy used by conventional systems can be saved by using low pressure systems (Gilley and Mielke 1980). The trend toward energy conservation encouraged the development of new sprinklers that could operate below the traditional pressures (Kelso and Gilley ASAE Paper 83-2517, 1983). The logic behind the concern over the adoption of low pressure systems lies in three assumptions: 1) that the wetted radius of the lower pressure nozzles results in less overlap of sprinklers and more chance for nonuniformity of application, 2) that the decreased wetted radius of the sprinkles translates into higher maximum rates in the application pattern, and 3) that because the reduced pressure systems need larger nozzles to deliver those higher rates, they emit larger droplets. In a field comparison of three systems: a high pressure impact system, a low pressure impact system, and a spray nozzle system, (Gilley and Mielke 1980) the measured runoff from the spray nozzle system was 28%, the high pressure impact system was 25%, and the low pressure impact system was 9% of the applied amount. There was no mention of the maximum rates, droplet sizes, or application amounts associated with these systems. The unexpected high runoff from the high pressure was attributed to a lower density of plant population.

The last part of this review contains a collection of studies and reviews discussing application pulses (Busch et al. 1973; Amerman 1983; Clothier and Heiler 1983; and Zegelin and White 1982). The most common type of moving sprinkler irrigation uses impact sprinklers which generate pulses of water, rather than a continuous spray. Schleusener and Kidder 1960 (as cited by Busch et al. 1973) pointed out that true application rates based on the actual time water falls at a point location are 50 to 90 times greater than the apparent sprinkler rate. Sloneker and Moldenhauer 1974, (as cited by Amerman 1983) showed that decreasing the frequency of intermittent application resulted in an increased energy requirement to initiate runoff. Zegelin and White (1982) cited Gardner (1964), Levin and van Rooyen (1977), and Zur (1976), who all reported that the effect of a pulsed water supply is soon dampened with depth and time. They verified these conclusions by measuring the soil water tension at the soil surface under the intermittent conditions produced by their infiltrometer. Clothier and Heiler (1983) used the Philip version of the ponded Green and Ampt model to analyze the pulses theoretically. As each pulse lands on the soil surface, the soil surface will pond at least instantaneously, and the length of time it takes to infiltrate can be calculated by the Green and Ampt model. Each time a new pulse lands, the sorptivity is different. When the length of time to infiltrate equals the intermittent period, the soil surface is still ponded as the last pulse falls on a ponded condition. When the intermittent time is small and the soil is dry, each pulse of water is absorbed quickly, even near saturation, thus explaining the observations of Zegelin, White, Sloneker, and Moldenhauer. As the amount of water in a pulse increases and the intermittent time gets larger, the percentage of temporary ponding increases, with the possibility of macropore flow also increasing. Willardson et al. (1974 as cited by Heerman and Duke 1983) observed that with the same rate of water applied, high frequency intermittent applications caused less soil disturbance than low frequency intermittent applications.

METHODS

This chapter of the dissertation not only describes the data collection and analysis procedures involved with the use of the sprinkling infiltrometer and infiltration models, it also describes the methods and results of preliminary endeavors that were critical to the investigation as a whole. The first five of the seven sections in this chapter describe these preliminary endeavors: 1) the current recommendations, 2) the irrigated cropland soils of southern Michigan, 3) application patterns, 4) the sprinkling infiltrometer, and 5) model development and use. The last two sections describe the field measurements and the process of combining the field measurements with the model. The results associated with the last two sections are in the chapter on Results.

I. Current recommendations

A. Theory and practice

The current system for recommending maximum sprinkled application rates for Michigan soils can be found in the Michigan Irrigation Guide by Vitosh and Fisher (1981) of the Michigan State University Cooperative Extension and the Michigan Soil Conservation Services (SCS). The recommendation system is based on the theory that ponded infiltration and sprinkled time to ponding can be described by the same function if expressed in terms of rate as a function of depth (Childs 1969). See

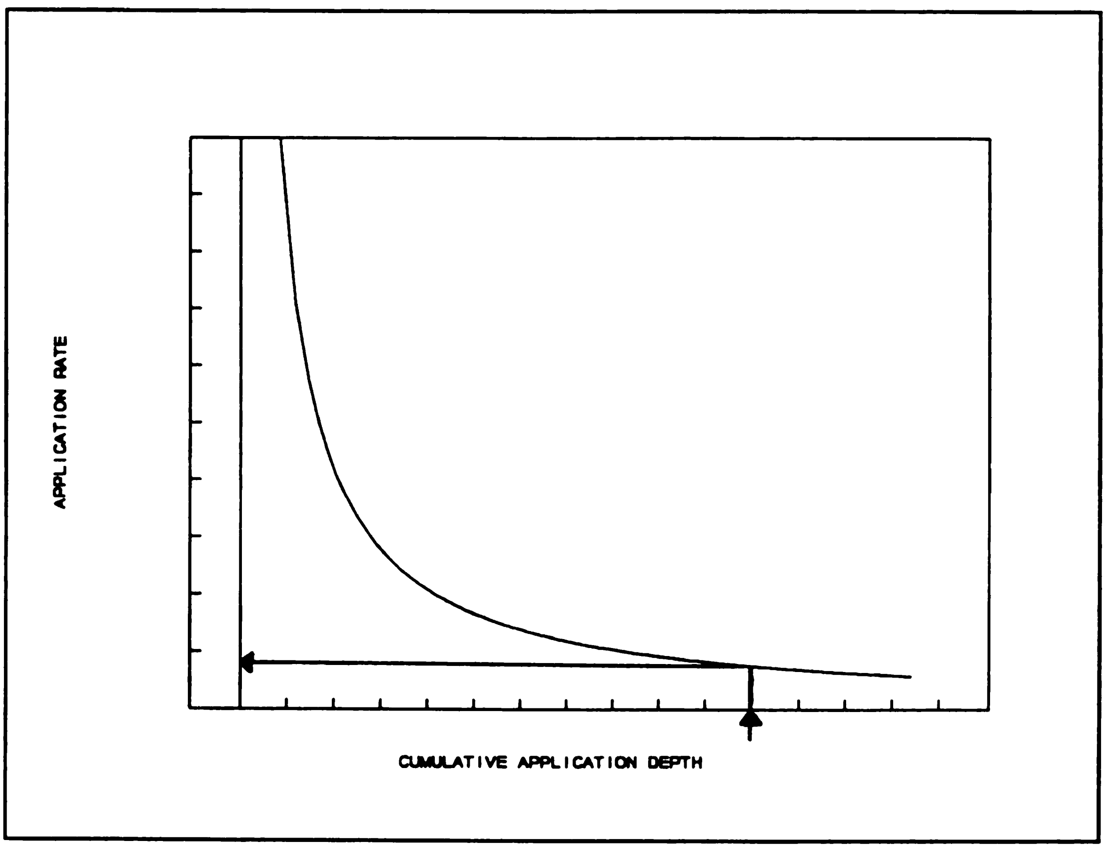

Figure 1. General infiltration function expressed in terms of rate as a function of accumulated depth of water applied.

Figure 1. According to this theory, the maximumnon-ponding constant sprinkler rate corresponds to the desired application depth on the appropriate ponded function. The ponded functions used for making recommendations are the eight soil intake family functions used for designing border irrigation described in the USDA/SCS National Engineering Handbook (USDA/SCS, 1983). Charles S. Fisher, a previous State Soil Scientist for the Michigan SCS office, assigned intake family designations to Michigan soils based on surface texture and possible restricting profile layers (Fisher, personal communication, 1989).

The Michigan Irrigation Guide presents recommendations in the form of a table which was constructed using the following function:

$$i=60ab(I/a)^{(b-1)/b}$$

where a,b are parameters associated with the intake families as described in the USDA/SCS National Engineering Handbook (1983),
I=application depth (in.),
i=maximum constant application rate (in./h).

This function can be derived from the substitution of time as a function of depth into the SCS intake rate equation found in the Engineering Handbook (1983). The maximum constant application rate obtained from this function is considered to be the base value associated with low (0 to 2%) slopes and high (more than 4000 lbs) amounts of surface residue on the surface.

To estimate maximum rates for slopes of 2-6%, the base value is multiplied by 0.75; for slopes of 6-12%, the base value is multiplied by 0.5. Adjustment for residue depends on the amount of residue left on the surface by weight (lbs) or percentage of residue. The conversion from weight to percentage of residue was obtained from Dwight

Quisenberry, the former SCS State Agronomist for Michigan. The adjustment table for corn and soy residue is:

AMT OF RESIDUE (lbs)	CORN %	SOY %	RESIDUE ADJUSTMENT FACTOR
> 4000	>75		1.0
3-4000	60-70		0.9
2-3000	50-60		0.8
1-2000	25-50	30-60	0.7
< 1000	<25	< 30	0.6

Thus the recommended constant maximum rate for a 2-6% sloping Kalamazoo sandy loam which is moldboard plowed can be calculated in the following way:

Kalamazoo = intake family 1: a=0.0701, b=0.785. The basic constant maximum application rate is 1.59 in/h. The 2-6% slope makes it necessary to adjust the basic rate by multiplying by 0.75, and the 5% of residue associated with moldboard plowing would further reduce the rate by 0.6. The final adjusted constant maximum application rate would then be:

$$1.59 * 0.75 * 0.6 = 0.72 \text{ in/h}$$

The table which appears in the Michigan Irrigation Guide shows the calculated base rates for seven intake families and application depths from 1 to 5 inches. The base values are those associated with >4000 lbs of residue and 0-2% slopes. The table indicates that there are "no restrictions within practical design criteria" of any kind for intake family 4. For intake family 3, there are recommended base values suggested for slopes of 6-12% for application depths of over 3.5 inches. There are "no limitations" for intake families 1.5 and 2 for slopes less than 6%. The "no limitations" designation gives the user an inflated sense of security since rates calculated for base values can be radically altered by the adjustments for slope and residue, as in the Kalamazoo example.

The final adjusted maximum constant application rates associated with a variety of soil and tillage conditions as calculated using the Michigan Irrigation Guide equation is tabulated using metric units in Table 1. Two application depths, 12.7 mm (0.5 in) and 25.4 mm (1 in), were used because they are the more common in humid Michigan. The asterisks indicates where the Michigan Irrigation Guide table would indicate that there were "no restrictions within practical design criteria". Note that this designation would include moldboard plowing on an Oshtemo sl. The intake family designation made no allowances for differences in surface texture, and tillage is distinguished only by differences in the levels of surface residue. Maximum rates for variable application rate patterns as occur under moving sprinkler systems are not considered.

B. Measured values

Alongside the recommended rates and amounts in Table 1 are rates which represent measured data taken from observed sprinkled rates on the same soil and tillage conditions. Measurements of application rate vs. time to ponding pairs were cumulated and regressed to yield mean generalized functions best representing the data ($n>60$). The technique for measuring and modeling the data is presented later in

Table 1. Michigan Irrigation Guide (1981) recommended maximum constant rates vs. the maximum constant rates as predicted using the sprinkling infiltrometer.

MAXIMUM SPRINKLER RATES FOR CONSTANT APPLICATION SYSTEM						RECOMMENDED		MEASURED	
						APPLICATION DEPTH (mm)			
						12.7	25.4	12.7	25.4
SOIL NAME	SURF TXTR	TILL TYPE	INTAKE FAMILY	RESID FACTR	NO LIM	RATE (mm/h)			
Montcalm									
	ls	NT	2	1	*	112	85	46	35
	ls	PT	2	0.6	*	67	51	9.2	4.6
	ls	MB			*	67	51	10.1	5.2
	sl	MB			*	67	51	1.6	0.4
	sl	DP			*	67	51	0.3	0.0
Oshtemo									
	sl	NT	1.5	1	*	87	65	31	19
	sl	CP	1.5	0.9	*	78	58	20	13
	sl	MB	1.5	0.6	*	52	39	6.0	2.5
Kalamazoo									
	sl	NT	1.0	1		49	40	20	6.3
	sl	CP	1.0	0.6		29	24	18	11.5
	sl	MB				29	24	3.7	1.0

this dissertation, in previous reports to the SCS (Crowley and Merva, Infiltration and Water Quality of Irrigated Cropland, Report to the USDA,SCS 1989) and in "The MSU Sprinkling Infiltrometer: A Devise to Measure Time-to-Ponding", Crowley, Granskog and Merva, ASCE National

Water Conference, University of Delaware, 1989. Non-ponded times were also included in the determination of a general function so as to increase the value of the measurements on treatments that could not be easily induced to pond. Including such non-ponded data increased predicted time to ponding when compared to the inclusion of ponded data pairs only. As expected, the maximum application rates can be larger when the applied depths are smaller. The maximum rates associated with the 25.4 mm application depth range between 30 to 80% of those associated with the 12.7 mm application depth. In general, no-till and chisel plowed tillages yielded the highest predicted maximum rates from measured data: from one-half to one-third of the Michigan Irrigation Guide's recommended rates. Moldboard and paratilled rates were about 5-10 times less than recommended rates for 12.7 mm amounts and from 10 to 25 time less for 25.4 mm amounts. However, disk-plowed and moldboard plowing after disking, as on the Montcalm sandy loam, resulted in predicted rates of 40 to 1000 times less than recommended rates.

Since these are exactly comparable quantities according to generally accepted infiltration theory, it is unsettling to see differences of this magnitude. One of the most disturbing aspects of the comparison can be seen by looking at the sprinkling infiltrometer values associated with the "No Restrictions" designation in the Michigan Irrigation Guide table. Although some relatively high values can be found with asterisks in the same row, the lowest values of all can also be found there. Even the conditions showing relatively high values are much lower than those predicted by the Michigan Irrigation Guide and are likely to pond and cause significant runoff and erosion on sloping land.

C. Application time and moving systems

Table 2 shows the application times associated with the predicted rates from the measured data for the two application depths for constant and parabolic application patterns. The application time needed to apply a given amount of water without ponding is less for no-till and moldboard generally than it is for other tillages. Furthermore, it is generally faster to apply two applications of 12.7 mm than one application of 25.4 mm because of the differences between their respective constant maximum rates.

Moving irrigation systems can be represented by parabolic application patterns. Parabolic patterns may allow higher rates to be applied for the same application depth than constant patterns, and if the rates are significantly higher, the application times will be shorter. For example, it takes 25 hours to apply 25.4 mm of water to the moldboard-tilled Kalamazoo sandy loam at a constant rate of 1.0 mm/h, but only 19 hours to apply the same amount of water with a parabolic application system with a maximum rate of 2 mm/h. However, if the predicted maximum rates are similar, the application times are similar, or even longer, with a parabolic application pattern. As in the case of the constant application rate, applying half the amount at two times is often much faster than applying the whole amount at the same time, due to the higher allowable rate.

Table 2. Maximum sprinkled no-ponding rates and times for constant and parabolic application patterns derived from measurements made using the MSU infiltrometer.

	MAXIMUM RATES FOR CONSTANT PATTERNS (FIXED SYSTEMS)				MAXIMUM RATES FOR PARABOLIC PATTERNS (MOVING SYSTEMS)			
	25.4 mm		12.7 mm		25.4 mm		12.7 mm	
	RATE mm/h	TIME h	RATE mm/h	TIME h	RATE mm/h	TIME h	RATE mm/h	TIME h
KALAMAZOO S.LOAM								
MB	1.0	25	3.7	3.4	2.0	19	6.8	2.8
CP	12	2.2	18	0.7	16	2.4	24	0.8
NT	6.3	4.0	20	0.6	11	3.8	34	0.6
OSHTEMO S.LOAM								
MB	2.5	10.2	6.0	2.1	4.1	9.3	9.9	1.9
CP	13	2.0	20	0.6	17	2.2	26	0.7
NT	19	1.4	31	0.4	26	1.5	43	0.5
MONTCALM S.LOAM								
MB	0.4	64	1.6	7.9	0.8	47.6	3.2	5.9
DP	0.0	----	0.3	42.3	0.2	191.5	0.7	27.2
MONTCALM L.SAND								
MB	5.2	4.9	10.1	1.3	7.8	4.9	15	1.2
PT	4.6	5.5	9.2	1.4	7.0	5.4	14	1.4
NT	35	0.7	46	0.3	43	0.9	57	0.3

D. Towards a new set of recommendations.

At the writing of this dissertation, there are not enough experimental data to make a new set of recommendations to replace the Michigan Irrigation Guide's. However, it is clear that a new set of recommendations based on time to ponding measurements will be a more conservative set of maximum sprinkling rates. Rates for application depths of less than or equal to 25.4 mm will be substituted for the 1 to

5 inches of the previous table and the new set of recommendations will include maximum rate estimates for both moving and fixed irrigation systems. The new table of recommendations will highlight the most common tillage rather than the one with the highest intake rate and show the infiltration benefits of alternative irrigation system rates and tillages. The next year of field measurements will be an attempt to bracket the range of existing soil conditions, with the inclusion of a commonly irrigated loam and a repeat of measurements on a loamy sand. While at this point, the rates to avoid ponding are used to compare to the Guide's, later in this dissertation, there is an examination of rates that result in limited ponding during application and at the end of application.

II. The irrigated cropland soils of southern Michigan

A. Literature and resources review

Because of the labor-intensive nature of collecting time to ponding measurements, only a few soils could be included in this study. Therefore, it was necessary to target the soils to be measured by selecting series that were the most representative of irrigated agriculture in Michigan. A review of existing published classification systems used for Michigan soils revealed that none was comprehensive enough to provide a sense of relationship between one irrigated soil series to another, nor was there any documentation of a soil series' irrigated areal extent. A combined classification, based on natural relationships and management properties, was designed to enable the most beneficial research site selection by answering questions like: Which soil series are the most commonly irrigated in Michigan? How does a particular series compare with another irrigated series? Which series are most likely to be irrigated in the future? The answers to these questions were found by combining the existing classification systems; grouping the clusters of soils which emerged with like attributes; determining the areal extent of each; and seeking guidance from professional soil classifiers as to the appropriateness of the resultant classes. As a result of this process, the Oshtemo soil was selected for the first year's work and the Montcalm/Spinks for the second.

The five major existing classification systems that were combined were: 1) the irrigation group (Vitosh and Fisher 1981); 2) the soil intake family (Vitosh and Fisher 1981; USDA/SCS National Engineering Handbook 1983); 3) the soil management unit (Mokma 1978); 4) the Michigan land capability tables (USDA/SCS 1972); and 5), the Guide to

Michigan Soil Series (Mokma and Stroesenreuther 1982, Mokma and Frederick 1987). The irrigation group was based on texture, profile, available water capacity, intake rate and soil drainage (Vitosh and Fisher 1981); the intake family was thought to be based upon the permeability of the most restricting profile layer as reported in the soil series interpretation records (USDA/SCS, personal communication, Fisher 1989); the soil management unit was based on the dominant profile texture and the natural drainage characteristics (Mokma 1978); the Michigan land capability tables were based on parent material, natural drainage, permeability and classified into erosion classes (regular and erodible) by those attributes in combination with percent slope (USDA/SCS 1972); and the Guide to Michigan Soil Series gave the taxonomic classification, description of profile textures, originating landforms, thermal regime, number of stories, soil family, drainage class and management unit (Mokma and Stroesenreuther 1982, Mokma and Frederick 1987, Soil Survey Staff 1987).

Once these classifications and their attributes were assigned to all the irrigable soils, like combinations were grouped into an independent classification system. This was then evaluated by N. Stroesenreuther, SCS State Soil Scientist; L. Berndt, SCS Assistant State Soil Scientist; G. Thoen, SCS Area Soil Scientist; and D. Mokma, Michigan State University Department of Crop and Soil Science Professor of Soil Classification. Inappropriate inclusions and defunct series names were deleted, recorrelated names were included, and some series were reclassified, based on the insight of the soil scientists. This process also highlighted many sources of incongruity in the classification system.

According to a 1980 survey of irrigated area by crop and county as cited in the "Impact Evaluation of Increased Water Use by Agriculture in Michigan" (Michigan State University Agricultural Experimental Station 1982), a total of 400,000 A (162,000 ha) was irrigated in Michigan and more than 50% of that was in corn. The report predicted a 200% rise in irrigated acreage by the beginning of the year 2000. Five counties accounted for about 46% of all the area irrigated, and 69% of that area was in corn. Other row crops with significant irrigated area included potatoes at 8.5% of the state total, and beans (soy and dry) at 6.5%. The top five irrigated counties, in order of irrigated area, are: St Joseph (14%), Montcalm (10.5%), Van Buren (8.3%); Branch (7.9%), and Calhoun (5.1%). This survey, along with estimates from the district conservationists in the five counties, the county soil maps (USDA/SCS: 1983, 1960, 1982, 1986, 1986), and to some extent, the Federal Natural Resources Inventory (USDA/SCS 1982) was used to estimate the areal extent of the different soil groups.

B. The combined classification and area tables

The combined classification resulted in seven tables, three of which will appear in this section, and four of which can be found in Appendix B. Table 3 is a one-page summary of the general resultant classification system, Table 4 is a summary of the estimated acreage of irrigated row crops by soil series and county, and Table 5 gives estimates of the classes which have the most areal potential for future irrigation expansion (in the five top irrigated counties) with estimates of the proportions now irrigated. In Appendix B, Table B-1 provides more information about the soil and has cross-references to similar soils; Table B-2 is an index to Michigan soils by name, a re-compiled version of the in-depth classification table, alphabetized for easy reference and including the many surface soil textures associated with a particular soil series; Table B-3 contains estimates of the portions of soils now irrigated which are erosion prone; and Table B-4 estimates of all potentially irrigable soils which are erosion prone.

In this chapter, Table 3 gives the four major classifications of Michigan irrigated soils based on intake families. Three of the major classes have two subclasses which are functions of water-holding capacities and other profile characteristics. Table 3 also gives the estimated total area of each class for the primary irrigated counties of Michigan: St. Joseph, Branch, Van Buren, Montcalm and Calhoun. The dominant soil series in each subclass is mentioned here also. Please refer to the first two tables in Appendix B for more in-depth descriptions of the classes.

Table 3. General Michigan irrigated soils classification.

SOIL CLASSES	SOIL AREA BY CLASS (Acres) x1000 OF FIVE MOST IRRIGATED COUNTIES*		
	regular	erodible	total
A. SOILS WITH RAPIDLY PERMEABLE HORIZONS AND INTAKE FAMILIES OF 3.0-4.0"/h.			
A1. Sands with rapidly permeable horizons. (Intake family = 4.0"/h), 3.84" in 60". e.g. Plainfield.	5	12	17
A2. Sands and loamy sands with rapidly permeable fine sandy horizons. (Intake family = 3.0"/h), 4.92" in 60". e.g. Coloma	2	9	11
B. SOILS WITH MODERATELY TO MODERATELY-RAPID PERMEABILITY AND INTAKE FAMILIES OF 1.5-2.0"/h.			
B1. Loamy sands and sandy loams, moderately to moderately rapid permeability and low water holding capacities. (Intake family = 2.0"/h), 4.5-5.3" in 60". e.g. Spinks or Montcalm.	170	89	259
B2. Loamy sands and sandy loams, moderately to moderately rapid permeability and higher water holding capacities. (Intake family = 1.5"), 6.6-8" in 60". e.g. Oshtemo.	109	135	244
C. SOILS WITH MODERATE TO SLOW PERMEABILITY AND INTAKE FAMILY = 1"/h.			
C1. Sandy loams and loamy sands with moderate to slow permeability and relatively lower water holding capacity. (6.8-7.5" in 60"). e.g. Kalamazoo.	65	139	204
C2. Sandy loams with moderately slow to slow permeability and high water holding capacity. (9.3-11" in 60"). e.g. Elmdale.	4	9	13
D. SOILS WITH SLOW TO VERY SLOW PERMEABILITY DUE TO FRAGIPANS OR FIRM TILL AND INTAKE FAMILY = 1.0"/h.			
Sandy loams with slow to very slow permeability due to fragipans or orsteins above 24". (1.0"/h), 3.8" in 60". e.g. McBride.	7	46	53
TOTALS	362	439	801

* St. Joseph, Branch, Van Buren, Montcalm and Calhoun

Table 4 gives the estimated acreages resulting from a survey of the county soil maps and discussions with district conservationists. The values presented are the estimated acreages of soil classes which are presently in irrigated row-crops. The classes in the table refer to the classes as outlined in Table 3.

Table 4. Estimated acreage of irrigated row crops by soil type. (1988 Phone Survey of District Conservationists)

Class	St. Joseph	Branch	Van Buren	Calhoun[1]	Montcalm[1]	TOTALS
A1						
Plainfield			530			530
A2						
Coloma			1150			1150
B1						
Ormas		4810				4810
Spinks	15940		8610	1580		26130
Mancelona					1510	1510
Montcalm					11200	11200
B2						
Hillsdale		480		7150		7630
Oshtemo	32600	2820	6810	1580		43810
C1						
Fox		17250				17250
Kalamazoo			750	7150		7900
D2						
McBride					4800	4800
TOTALS	48540	25360	17850	17460	17510	126720

[1] To some extent, the Federal Natural Resources Inventory was used to estimate values for Montcalm and Calhoun counties since Montcalm still uses an old soil survey, and Calhoun did not yet have a completed soil survey.

Table 5. Irrigated and potentially irrigable acreage and percentage (slopes less than or equal to six percent, with profile characteristics similar to those presently irrigated) of top five irrigated counties in Michigan.

Soil Class	Irrigated Acreage	Potentially Irrigable Acreage	Percent Irrigated	Not Irrigated	Percent of Total Classes Not Irrigated
A1	530	16670	3	16140	4
A2	1150	11070	10	9920	3
B1	43650	172690	25	129040	33
B2	51430	157870	33	106440	28
C1	25150	120660	21	95510	25
C2	0	8060	0	8060	2
D2	4800	25180	19	20380	5
	126710	512190	25	385490	100

C. General conclusions

In 1988, the most-irrigated soil series was Oshtemo, with about 44,000 acres, or about 35% of all irrigated cropland in the top five irrigated counties in Michigan. Second ranked, with 30% of all irrigated cropland, was Spinks/Montcalm, followed by Fox (14%) and Kalamazoo (6%). Assuming that only land with less than six percent slope is irrigated, one-third of the total amount of irrigated land would be classified as erosion-prone according to the Michigan land capability tables. The Oshtemo series is particularly susceptible to erosion, with almost 60% of the series with less than six percent slope falling into the susceptible category. Not surprisingly, Oshtemo has the largest acreage in the erosion susceptible category, with 20% of all irrigated land being erosion-prone Oshtemo. Oshtemo and Hillsdale have similar estimated permeabilities (1.5"/h) and water holding capacities (6.6" in 60" (class B2)) and comprise 41% of all irrigated land. Similarly, if Spinks is grouped with Ormas, Mancelona, and Montcalm, with estimated permeabilities of 2.0"/h and water holding capacities of 4.5-5.5" in 60", the group (class B1) makes up 35% of all irrigated land in the top five counties. Lastly, if Fox and Kalamazoo are considered together (1"/h; 6.8-7.5" in 60"), they (class C1) rank third, with 20% of all irrigated land. Therefore, 96% of all irrigated lands fall into these three classes. Class C1 also contains a significant percentage of land susceptible to erosion (12%), while class B1 is considered to have no land susceptible to erosion (in its proportion with less than six percent slope). Only about one-quarter of the potentially irrigable lands are estimated to be in irrigation as of 1988, and 90% of the non-irrigated portion of all potentially irrigable lands are included in the three classes, each between 25 to 33% of the whole.

The Oshtemo soil was selected as the first soil series to be examined in the field because it is extensively irrigated, the most vulnerable to erosion, and has the second largest areal potential for new irrigation expansion: approximately 72,000 acres. The Spinks/Montcalm has the largest areal potential for new irrigation expansion at about 81,000 acres, and Kalamazoo the third, at 63,000 acres.

D. Discussion

The resulting classification was critical in targeting research sites during the period of this research, and it will be referred to again when looking for other research sites in the future. It might also be useful to researchers who are doing economic evaluations and predictions of future irrigation growth. The areal estimates and the erosion-classification were particularly insightful. I learned that

Montcalm and Spinks are very similar series, and would never have realized the extent of Oshtemo soil if the survey had not been done.

After the first year in the field, I began to recognize that infiltration of sprinkled water might be even more dependent upon topsoil texture than expected. Because a single series classification usually includes several surface textural classifications, and all the classification information was gathered with the series as the basic systematic unit, the resultant classification was not as useful as I initially hoped from an sprinkled infiltration perspective.

Further work is needed to clarify classification where one soil series has multiple topsoil textures, or at least determine the relative areal proportions of the different surface textures, so that I might avoid studying a minor variant of a major soil.

III. Application patterns

A. Triangles, ellipses and parabolas

Bittinger and Longenbaugh (1962) derived the mathematical equations for the application rate and depth of single "commonly available" sprinklers having conical (triangular in cross-section) or elliptical patterns and moving in either a straight line or circular path. To determine the application rate arriving at a point on the ground from a single elliptical pattern sprinkler moving at a constant rate on a straight path, (such as near the end of a center pivot) one needs to know five variables: 1) the maximum application rate of the sprinkler, 2) the radius of the sprinkler, 3) the distance from the center of rotation to the sprinkler, 4) the distance from the center of rotation to the point, and 5) the angle of rotation of the sprinkler line from the point (in radians). Bittinger and Longenbaugh also showed that the circular path solution could be adequately approximated by the straight line solution when the sprinkler was five times the sprinkler pattern radius from the pivot. Although they selected the ellipse as the only other pattern to describe sprinkler patterns, no reason was offered for their selection decision. Kincaid et al. (1969) compared the triangular and elliptical application functions, as modified by Heerman and Hein (1968), to the cumulative application depth as a function of time of one sprinkler and found that the elliptical pattern agreed more closely with the measured application than the triangular one did. Dillon et al. (1972) and Gilley (1984), citing Kincaid, used ellipses in their analyses.

In the search for nozzles to fit the infiltrometers used in this study, it was found that sprinkler patterns vary a great deal, with some even exhibiting a slight depression in application rate near the center of the pattern. The triangular pattern, while having the advantage of needing only two variables to describe it, assumes that the rate increases linearly to the center. The ellipse, on the other hand, describes the center of the pattern well, but needs five variables to describe it.

The parabola is a geometric shape that describes the trajectories of bodies under the influence of gravity (Ellis and Gulich 1978) and uses only two variables. Considering the variety of actual patterns generated by nozzles in the field, the parabola is just as adequate a descriptor of sprinkler application rate patterns as the ellipse. The parabola is easily manipulated to derive the rate or depth as a function of time functions, and this is important if one wishes to estimate the time to ponding without resorting to a large computer (Dillon et al. 1972).

The main use of the parabola in this work is to describe the passing application pattern delivered by a moving irrigation system to a point on the ground over time. It can also be used to describe the pattern of sprinkling over the distance covered by the sprinkler (wetted diameter), but, though related, the two concepts are different. The sprinkler pattern over the wetted diameter is basically fixed, changing only with system pressure. The passing application pattern delivered to a point on the ground, while having a fixed maximum rate, has a shorter or longer application period, depending on the system speed.

The three main equations describing the rate pattern of a moving system as a parabola are:

$$D_a = 2hp/3 \qquad (1)$$

where D_a = total depth of application,
h = maximum rate of application, and
p = period of application.

One advantage of this equation is that when h is equal to 1.5 length/time, the total depth (length) is equal to the period of application (time). This makes the presentation of the concept easy to understand.

A general rate equation based on the parabolic form is:

$$r_t = 4ht/p + 4ht^2/p^2 \qquad (2)$$

where t = time passed since first wetted,
r_t = the rate at any time during application since first wetted.

The depth equation is obtained by integrating Eq. (2) with respect to time:

$$D_t = 2ht^2/p - 4ht^3/3p^2 \qquad (3)$$

where D_t = the cumulative depth at any time.

B. Maximum application rates

The design maximum application rate for a center pivot system is a function of: 1) the maximum crop evapotranspiration over the time of pivot rotation needed to deliver the amount of water to be applied during an irrigation, 2) the wetted diameter of the sprinkler; and 3) the soil intake rate and storage capacity. In Michigan, the crop evapotranspiration might be something like 25 mm in 4 days. Since the probability of rain is greater for a humid region than for an arid

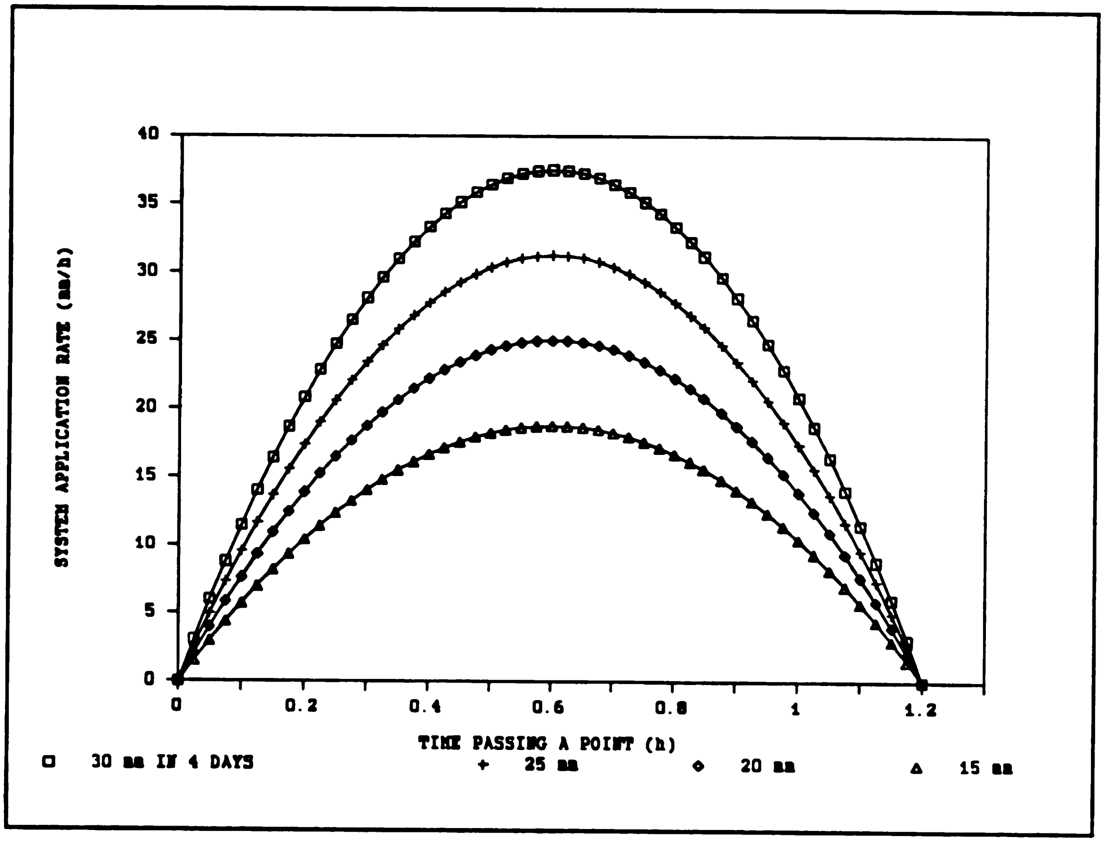

Figure 2. Maximum application rates as a function of design evapotranspiration for a constant travel speed.

region one, the probability of cloudy or cooler days may be also greater. If systems are designed for arid climates, it is likely that the design evapotranspiration rates are higher than necessary for Michigan conditions. If the design evapotranspiration rates can be adjusted, maximum application rates could be reduced. See Figure 2.

The wetted diameter of a sprinkler is primarily a function of system pressure and sprinkler type, with lower pressure systems and spray nozzles less able to throw water away from the nozzle. See Figure 3.

Once a maximum application rate is selected for an irrigation system, it is difficult to change. However, the system speed can be

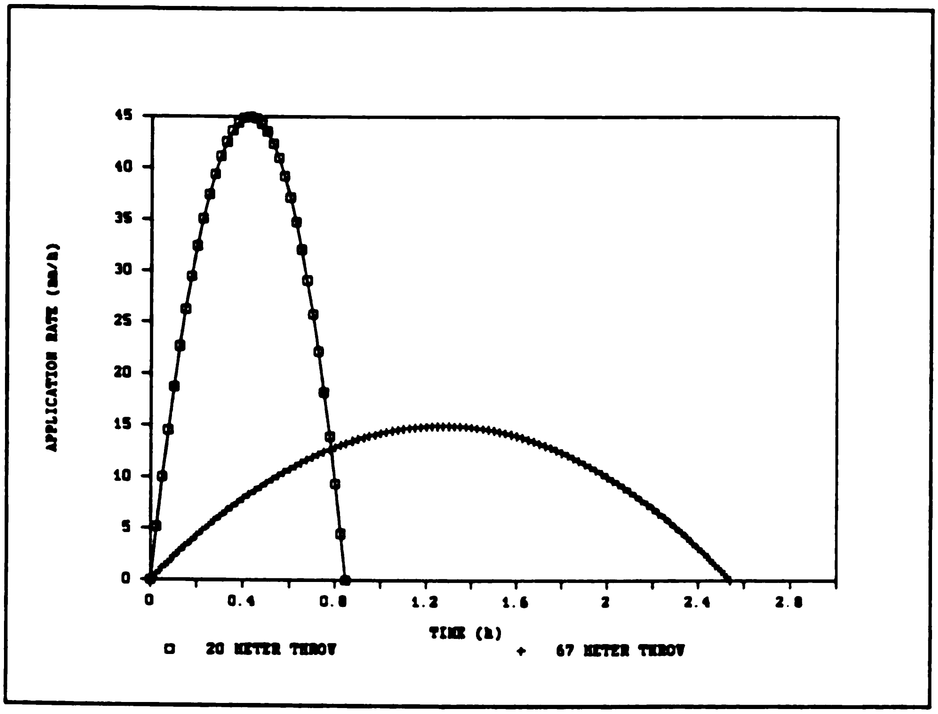

Figure 3. Two sprinkler application patterns passing a point, each delivering 25.4 mm of water. (Two different irrigation systems).

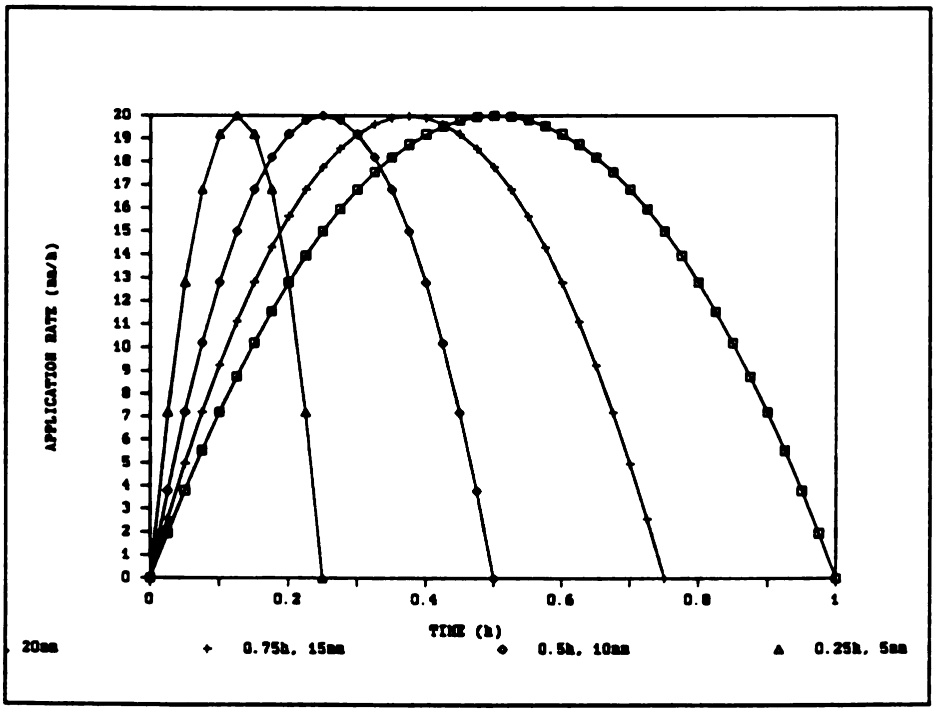

Figure 4. Point application pattern changes as a function of system speed. (The same irrigation system).

changed to apply different depths of water and to change the time it takes to reach the maximum application rate, which can be important in determining the time to ponding. See Figure 4.

Assuming a more or less constant wetted diameter from pivot to end, the nozzles nearer the pivot will have a longer time to deliver the same amount of water to a point on the ground and thus require a lesser maximum rate. As one goes from pivot to end, the area affected by a fixed distance on the system increases arithmetically ($r_{i+1}^2-r_i^2$), so that the high maximum rates on the end affect a large proportion of the field. Smaller towable systems travel faster so that they can be moved to another section of field in a timely manner, and usually the next circle to be irrigated intersects with the first in the outer section, making that intersected area more vulnerable to ponding (Loudon and [Crowley] Brown, report to the SCS 1984).

C. Existing system survey of two counties

The Irrigation System Evaluation and Scheduling Demonstration Project was a five-year project initiated in 1983 by the SCS and the Department of Agricultural Engineering at Michigan State University, and included the St. Joseph County SCS, the Cooperative Extension Service of Michigan State University, the St. Joseph County irrigators, and the Michigan Department of Agriculture. After the demonstration project was completed, the program was extended to other counties and funded by the Michigan Energy Conservation Project. The goals of both projects were to: encourage efficient use of the water supply; control the moisture environment of crops; promote the desired crop response; minimize soil erosion and loss of plant nutrients and chemicals from runoff or deep leaching; control undesirable water loss; protect water quality; and reduce energy consumption to a minimum. These goals were to be accomplished by evaluating the pumping plant, delivery system, and distribution system and by scheduling irrigation application events using accurate information about rainfall, crops, and soil types.

The comprehensive system evaluations that these programs sponsored provided a glimpse into the status of existing technology in Michigan. The lengths, maximum application rates and pivot pressures collected from eighty center pivot systems measured in St. Joseph and Kalamazoo counties during the last eight years are presented here in the next three figures.

The system length was measured in relationship to the catch cans set at measured intervals to determine overall delivery system uniformity. Systems varied in length from 141 to 647 m, and averaged 368 m.

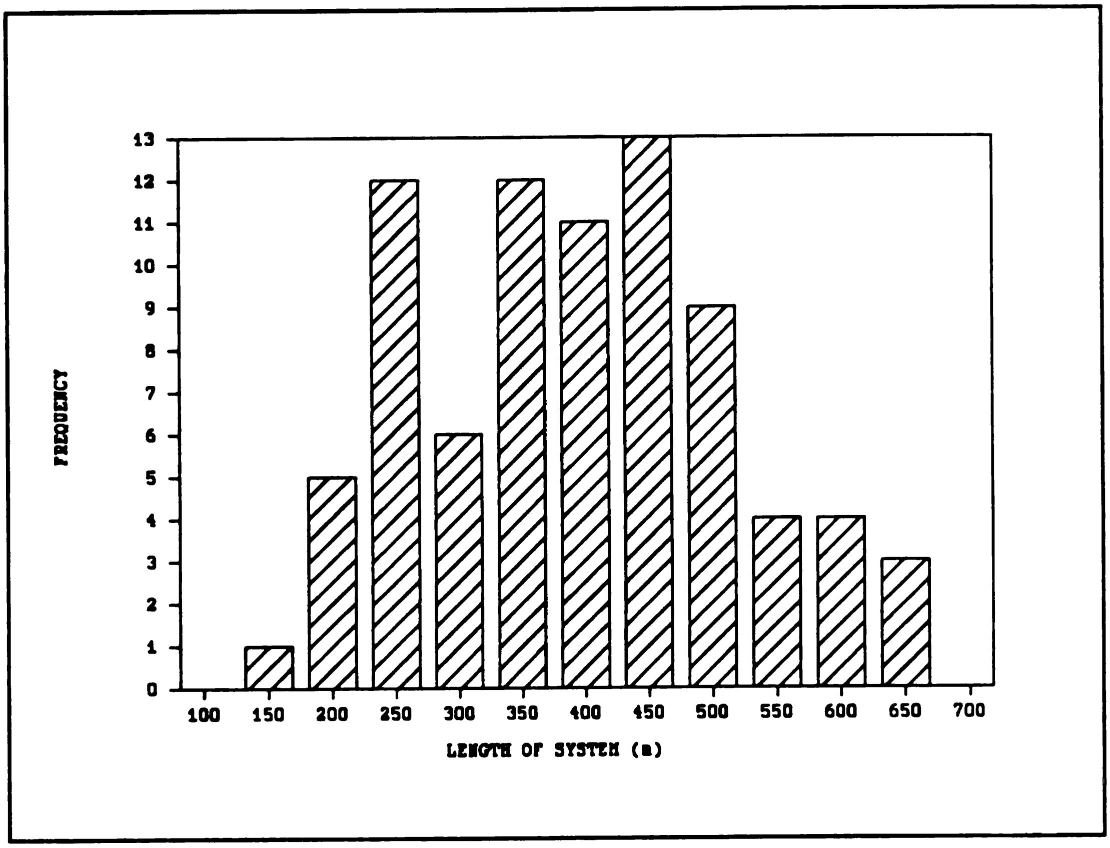

Figure 5. Length distribution of 80 irrigation systems.

During the assessment of uniformity, the average maximum application rate was measured by placing at least five covered catch cans about ten feet apart, in a line perpendicular to the system under the last span near the end tower. The center can was placed directly under the system water line. The covers were quickly removed and the time noted. When measurable amounts of water were caught in the cans, they were covered. The can with the most water was measured and the maximum rate determined using the elapsed time.

The maximum application rate measured on the eighty systems ranged from 12 to 99 mm/h, though 65 mm/h seemed more likely as an

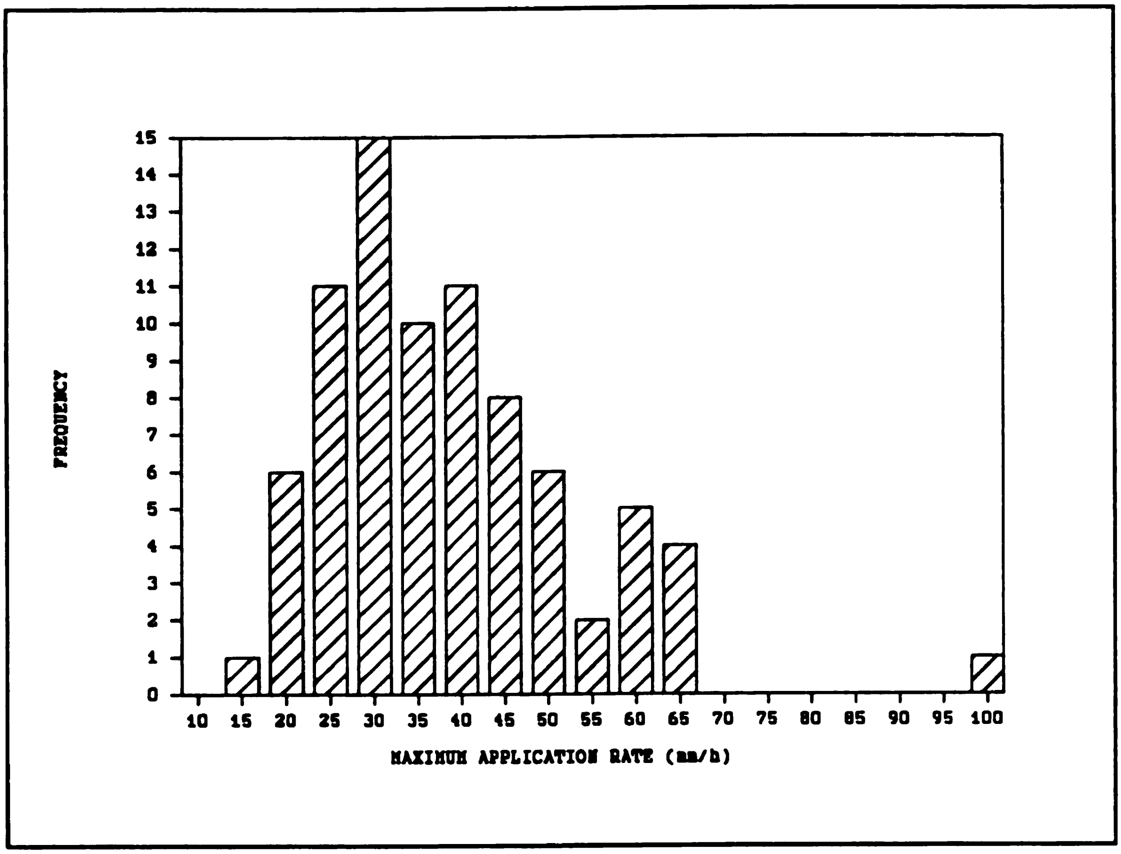

Figure 6. Maximum application rate frequency distribution of 80 irrigation systems.

upper limit, since there was only one system that was greater than 65 mm/h. Fifteen of the eighty were 30 mm/h, and the average maximum application rate was 36 mm/h.

The system pressure was measured at the pump, pivot, and end gun. The average pivot pressure was 450 Kpa (65 psi), the modal pressure was 340 kPa (50 psi), and the pivot pressures ranged from 206 to 861 kPa (30 - 124 psi).

One of the most commonly held beliefs reported in the literature is that low pressure systems have the highest maximum rates (Gilley and Mielke 1980; Lyle and Bordovsky 1981; Gilley 1984; Von Bernuth and

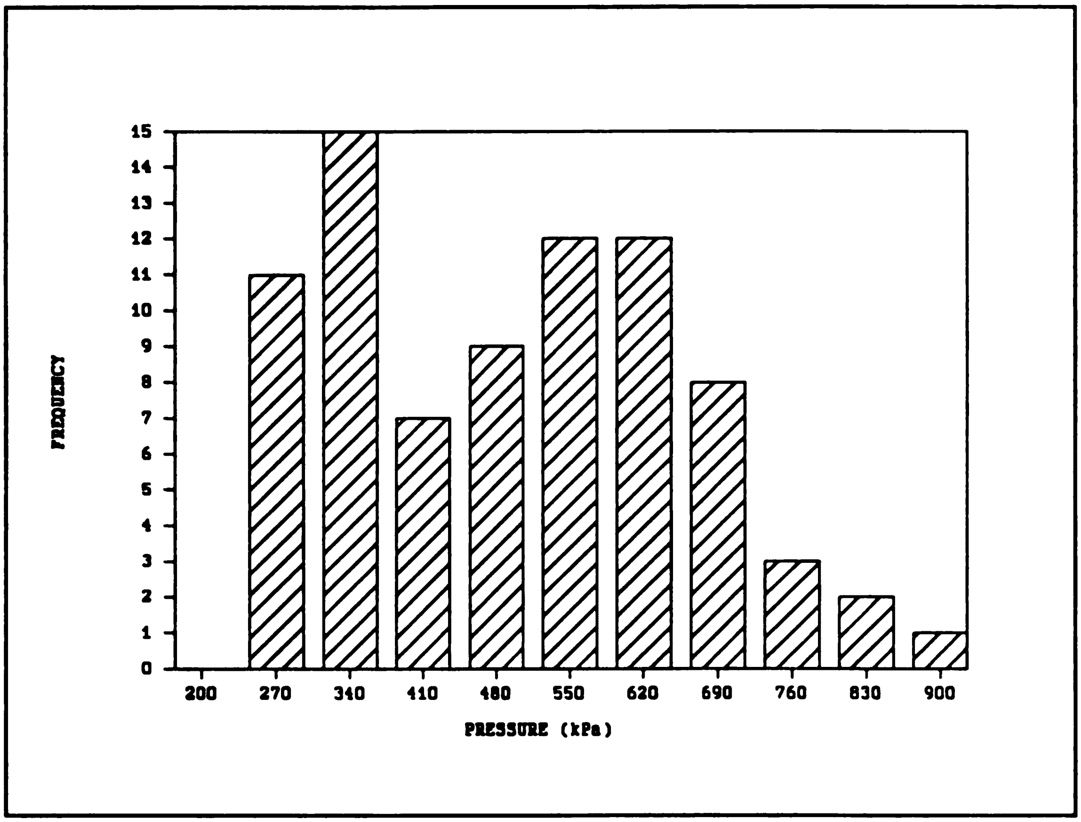

Figure 7. Pivot pressure frequency distribution of 80 irrigation systems.

Gilley 1985). No very low pressure systems (130 to 200 kPa [20-30 psi]) were evaluated in St. Joseph and Kalamazoo counties, but Figure 8 shows the relationship between system pressures and maximum application rates for 25 measured systems which have lengths between about 400 m and 500 m. It seems unlikely that poor measurement technique is responsible for the lack of any relationship between system pressure and maximum application rate.

If a like graph is constructed using other ranges of lengths, the results are similar to those above.

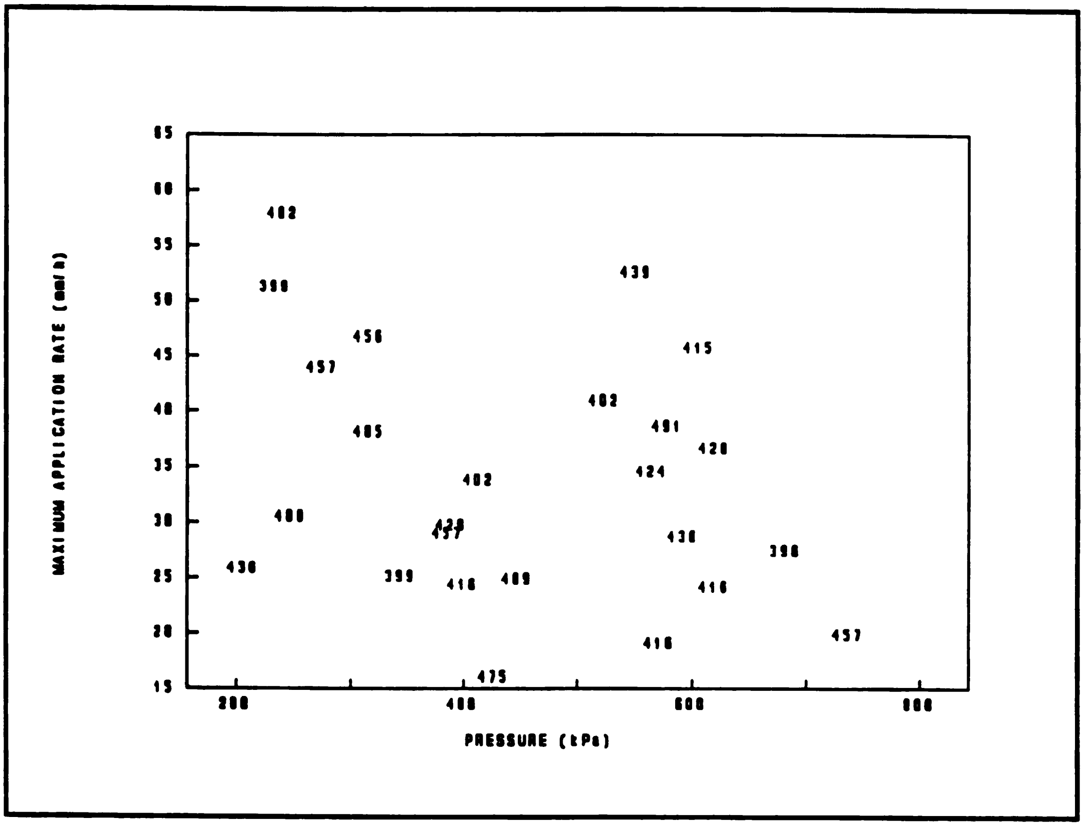

Figure 8. Pivot pressure vs. maximum application rates for 25 irrigation systems (labelled with length of system).

D. Summary

It is proposed that the parabola be used to describe the application pattern of a moving sprinkling irrigation system. The parabolic application pattern can be described by the maximum application rate and the period of application. While the maximum application rate should be considered to be a fixed characteristic of a particular system, the period of application is controlled by the system speed. The maximum application rate ranged from 12 to 99 mm/h for 80 measured systems, more generally, from 12 to 65 mm/h. No relation between maximum application rate and pivot pressure could be found.

IV. The sprinkling infiltrometer

This section describes the sprinkling infiltrometer, its design criteria, the procedure for its use, and the analysis of data.

A. Description

The sprinkling infiltrometer used in this study is a portable hybrid infiltrometer, combining the best qualities of the Tovey (Tovey 1962, Tovey and Pair 1966) and the Zegelin-White infiltrometers (Zegelin and White 1982). It was designed to satisfy the six desirable criteria for the design of a sprinkling rainfall simulator as proposed by Bubenzer (1979) with irrigation characteristics substituted for rainfall characteristics. The modified Bubenzer criteria are: 1) Drop size distribution similar to that of sprinkler irrigation; 2) drop velocity at impact near sprinkler irrigation drop velocity; 3) intensity corresponding to sprinkler irrigation; 4) uniform application and random drop size distribution; 5) total energy applied near that of sprinkler irrigation; and 6) reproducible patterns of application like sprinkler irrigation.

The infiltrometer consists of six non-overlapping spray nozzles mounted on a horizontal boom which is supported about 1 m above the soil surface. The boom is divided into two sections, each carrying three nozzles, 1.37 m (4.5 ft) apart. Each section is about 3.7 m (12 ft) long and made of square steel tubing connected by a quick-coupler. The boom is seated on two tripods and a center support which are adjustable so that the boom can be made parallel to the terrain. Appendix C contains the schematics for the entire operating system.

A schematic of the main components can be found in Figure 9. A 1230 L (325 gal) polypropylene tank supplies water to the system and the 4 kW gas generator supplies power to the pump and the timing circuit. A by-pass line and gate valve are used to control the nozzle pressure and two additional gate valves allow the tank to be filled from a nearby lake or stream. A 80 m (260 ft) hose extends the water supply to the spray boom, shown in Figure 9 with its supports, solenoids and spray nozzles. The boom, water tank, generator, pump, and control unit are transported on a 4.25 m (14 ft) trailer.

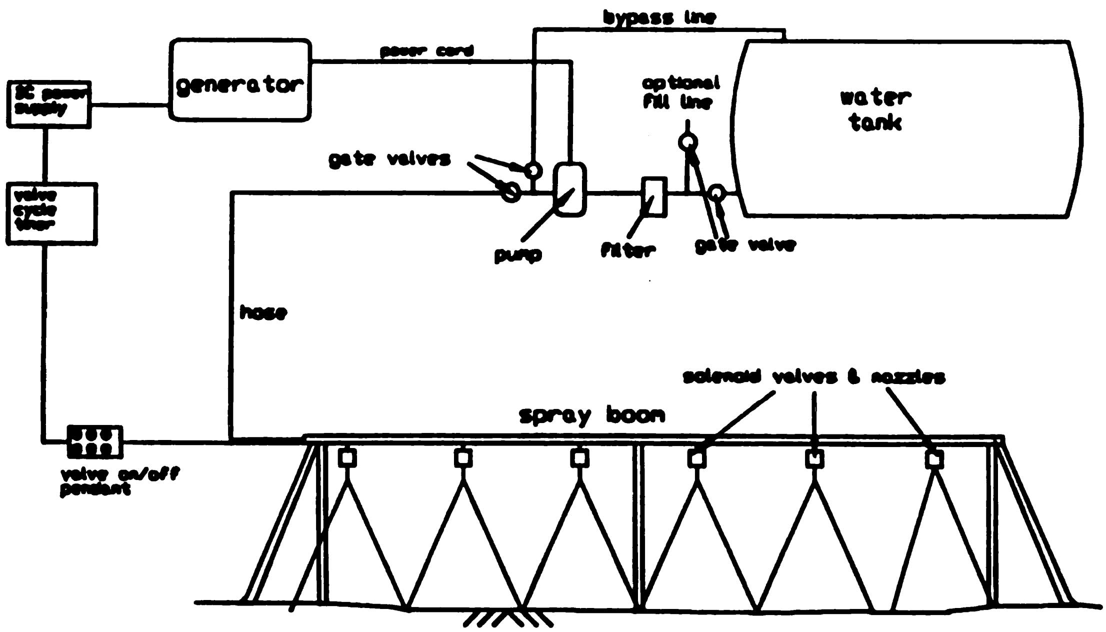

Figure 9. Schematic diagram of the infiltrometer showing the main components.

The six nozzles mounted on the boom are controlled by separate solenoid valves. Flexible gooseneck tubes between the nozzles and valves allow the spray patterns to be oriented perpendicularly to the soil surface and also protect the nozzles from becoming jammed with soil during transport. Two Full-Jet nozzles, Spraying Systems 1/4 HH 12W and 1/4 HH 10W, were selected for the infiltrometer. Both nozzles distribute medium to large sized droplets in a uniform circular pattern and finer control over low rates is achieved by using the smaller nozzle (10W), since the analog control-rate response is not linear. The mean droplet diameter generated by the nozzles was computed by Spraying Systems Co., using the procedures outlined by American Society for Testing Materials (Standard E799), to be about 1.6 mm at 82 kPa (12 psi) for both nozzles. The infiltrometer is started up each time from a static pressure of 82 kPa, controlled by the by-pass line and gate valve near the pump.

The rate of application is regulated by timers which control the solenoid valves on each nozzle. The rates used in the field tests ranged between 10 and 95 mm/h and were achieved by controlling the off time of the nozzle while the on time is held constant at about 0.6 s for each nozzle. The actual (constant) rate of application is determined after the test is completed by dividing the application depth (the volume of water in a container under the nozzle divided by the container catch area) by the total elapsed time. Not knowing the exact application rate helps to offset observer bias.

The pressure at the nozzles fluctuates slightly as the surrounding nozzles cycle on and off. Despite the changes in pressure, with the exception of the center of the impact area where a droplet is discharged every time the nozzle is turned on, the Christianson's coefficient of uniformity is greater than 85%. Delivery rates at a given analog setting at different times had a coefficient of variation of about 15%.

Wind protection is necessary when wind interferes with the spray pattern (at around 8-16 kph) and is accomplished by driving five steel fence posts into the soil upwind of the infiltrometer setup and attaching tarpaulins to the posts. The entire system cost $4200 to assemble and no operational problems were experienced during the entire 1988 and 1989 summer seasons.

B. Comparisons and design criteria

The infiltrometer is like the Tovey infiltrometer in that it allows one to simultaneously observe the application of constant sprinkling rates to multiple circular observation areas. It is like the Zegelin-White infiltrometer in that it uses solenoids to control the rate of application by the use of intermittent off periods and uses nozzles which deliver a uniform distribution of medium-large droplets over a circular observation area. Unlike the Tovey infiltrometer, however, each of the areas over which a constant rate is applied is independently controlled and the droplet size distributions from area to area are the same. It differs from the Zegelin-White infiltrometer in having six controllable areas simultaneously observable rather than one, and that initial static pressure is controlled with a by-pass line rather than by in-tank pressurization.

Most of the Bubenzer design criteria can be approximated for the infiltrometer. The drop size distribution for the Spraying Systems nozzles was calculated using the procedures outlined by ASTM (Standard E799), to be 0.76, 1.6, and 3.1 mm for the 10th, 50th and 90th percentile volume droplet diameters at 82 kPa (12 psi) for the 12W nozzle, and 0.73, 1.6, and 2.6 mm for the 10W nozzle.

Distributions for some irrigation spray nozzles have been collected by Solomon et al. (1985) and the average 10th, 50th, and 90th percentile diameters for the 44 nozzles tabulated by them are 0.62 mm, 1.12 mm and 1.70 mm. The droplet sizes reported by Kohl (1974) for medium pressure agricultural sprinklers ranged from about 0.3 mm to 5.0 mm, with the modes about 1.5 to 2.0 mm; whereas droplets from low pressure systems ranged from about 0.3 to 3.5 mm with modes between 1.0 and 1.5 mm (Kohl and DeBoer 1984). The mean volume diameter for both the 10W and 12W Spraying Systems nozzles is close to the modal range for both the medium and low pressure systems.

The terminal velocity for a 1.6 mm drop (the average 50th percentile volume droplet from the infiltrometer) is estimated to be about 5.7 m/s (14.4 ft/s) by Laws (as cited by Seginer 1965). The flow rate divided by the nozzle area yields an average exit velocity of about 11 m/s (36 ft/s) but the actual velocities of impact for infiltrometer droplets with the ground are unknown. Terminal velocities for irrigation- sized droplets between 1.25 and 6 mm are estimated to be between 4.85 and 9.3 m/s (15.9 - 30.5 ft/s), but impact velocities are unknown.

Uniform application rates of the infiltrometer range between about 10 and 95 mm/h (0.4 to 3.7 in./h). Although intensities approaching 115 mm/h (4.5 in./h) have been measured for reduced pressure sprinklers (DeBoer and Beck ASAE Paper 83-2024, 1983), the maximum application rate measured on eighty irrigation systems in St. Joseph and Kalamazoo Counties, Michigan, was 99 mm/h (3.9 in./h), on a 310 kPa (45 psi) system. The average of all maximum application rates on the eighty systems was about 36 mm/h (1.4 in./h). It is useful to remember that non-ponding infiltration rates for different soils and tillages may be less than the application rates. Good quality ponding functions can only be generated when the application range is appropriate for the soil and tillage types tested. The large area over which the application rate is uniform enables the operator to judge the average behavior of the entire area before making a time to ponding determination, thus lessening the effect of any local nonuniformity.

The total energy which is expended on the soil surface by the spray of the sprinkling infiltrometer is probably similar to that expended by irrigation sprinklers. However, better information on impact velocities for both the infiltrometer and irrigation nozzles in common use needs to be known before one can say with complete confidence that the energy criteria suggested by Bubenzer are fulfilled.

Reproducible irrigation pattern simulation is possible on this infiltrometer since the rate through any nozzle can be changed when desired. Further research using this capability to test the time to ponding predictions for complex rate application patterns is one of the more promising potential uses of the infiltrometer.

Improvements to the basic design could include better pressure control and a more lightweight construction. Better pressure control might be achieved by extending the ends of the boom vertically so as to obtain the effect of a surge tank and thus lessen the influence of the on/off effect of surrounding nozzles. The frame of the infiltrometer could be reconstructed using lighter materials, reducing the weight and increasing its portability.

C. Field procedure

An experimental site was chosen near a place where the trailer could be easily parked. At the site, any leaves and weeds that interfere with the discharge pattern of the nozzle are cut, but the residue is left in place. In a tall crop, such as corn late in the season, the end tripod and center supports are first set up in among the plants. Then the boom section is lifted over the plants and attached to the tripod and center support. The second tripod is placed at the end of the plot, and the second section installed. Circular observation areas are located side by side under the nozzle pattern and the boom height adjusted so that water from the nozzles does not overlap. Three cups are placed in a triangle within the observation area so that an average application rate can be obtained. Before the nozzles are turned on, the air from the hose and boom must be purged.

To avoid the possibility of all circular observation areas ponding immediately or not at all, only three nozzles are started at first: one at 65 mm/h (2.6 in./h), one at 45 mm/h (1.8 in./h), and one at 15 mm/h (0.59 in./h). After observing the effect of these for about 10 minutes, appropriate starting rates can then be selected for the remaining three.

Time to ponding is determined when ponding is observed in the vicinity of the cups. Ponding is defined to occur when a pond about 25 mm in diameter persists at the soil surface. In 1988 and 1989, ponding observations were made continuously rather than at regular intervals. However, when an observer is first starting out, it is suggested that observations be made at timed intervals of 1 to 2 minutes so that ponding decisions can then be based on the presence or absence of ponding rather than anguishing over the precise onset of ponding.

After the time to ponding is determined, the water is turned off and the final time noted. The volume in the cups is measured (to the nearest mm) and application rate and the depth infiltrated at ponding is calculated. After the circular observation area drains, i.e., all ponding disappears, another time to ponding (wet) observation can be started. Up to 20 constant sprinkled rate vs. time to ponding observation pairs in an hour can be made on a moldboard (MB) plowed site. On tillage practices which accept higher application rates, fewer observations are possible.

D. Data analysis

An example of a site that was properly managed with regard to rate selection can be seen in Table 6. Application rates for nozzles 2, 4 and 6 were initiated at 24.9, 50.1, and 97.4 mm/h, respectively. After the soil under sprinkler no. 6 ponded, rates were selected for nozzles 1, 3, and 5 that were between 15 and 50 mm, resulting in a dry set of data that was well spaced and exhibited both a vertical and horizontal component when graphed.

Table 6. Constant sprinkled rate vs. time to ponding (t_p) pairs for Montcalm loamy sand: paratilled non-wheel track (P=dry, ponded; S=wet, ponded; and SN=wet, not ponded).

label (P,PN,S,SN)	noz no.	t_p (min)	rate (mm/h)	depth (mm)	ln t_p	ln rate
P	1	41.83	15.87	11.06	3.73	2.76
P	2	17.00	24.93	7.06	2.83	3.22
P	3	26.83	22.85	10.22	3.29	3.13
P	4	5.50	50.14	4.60	1.70	3.91
P	5	6.83	48.97	5.57	1.92	3.89
P	6	1.83	97.42	2.97	0.60	4.58
S	2	4.17	26.26	1.83	1.43	3.27
S	2	6.00	22.46	2.25	1.79	3.11
S	2	5.83	21.09	2.05	1.76	3.05
S	2	4.67	19.97	1.55	1.54	2.99
S	3	6.67	23.06	2.56	1.90	3.14
S	4	1.83	53.00	1.62	0.60	3.97
S	4	2.33	50.72	1.97	0.85	3.93
S	4	3.50	33.43	1.95	1.25	3.51
S	4	6.17	23.64	2.43	1.82	3.16
S	4	9.50	20.50	3.25	2.25	3.02
S	5	2.50	51.09	2.13	0.92	3.93
S	5	3.00	40.59	2.03	1.10	3.70
S	5	4.83	29.58	2.38	1.57	3.39
S	6	0.67	85.96	0.96	-0.40	4.45
S	6	1.17	49.18	0.96	0.16	3.90
S	6	1.33	43.40	0.96	0.29	3.77
S	6	2.00	30.50	1.02	0.69	3.42
S	6	3.83	23.40	1.49	1.34	3.15
S	6	3.83	20.33	1.30	1.34	3.01
SN	1	18.17	17.61	5.33	2.90	2.87
SN	3	20.33	18.79	6.37	3.01	2.93
SN	5	12.50	19.48	4.06	2.53	2.97

After the circular observation areas drained, the wet observations were started and in an hour's time, a total of 26 constant sprinkled rate vs. time to ponding data pairs and three non-ponded pairs were collected. These pairs are graphed in Figure 10.

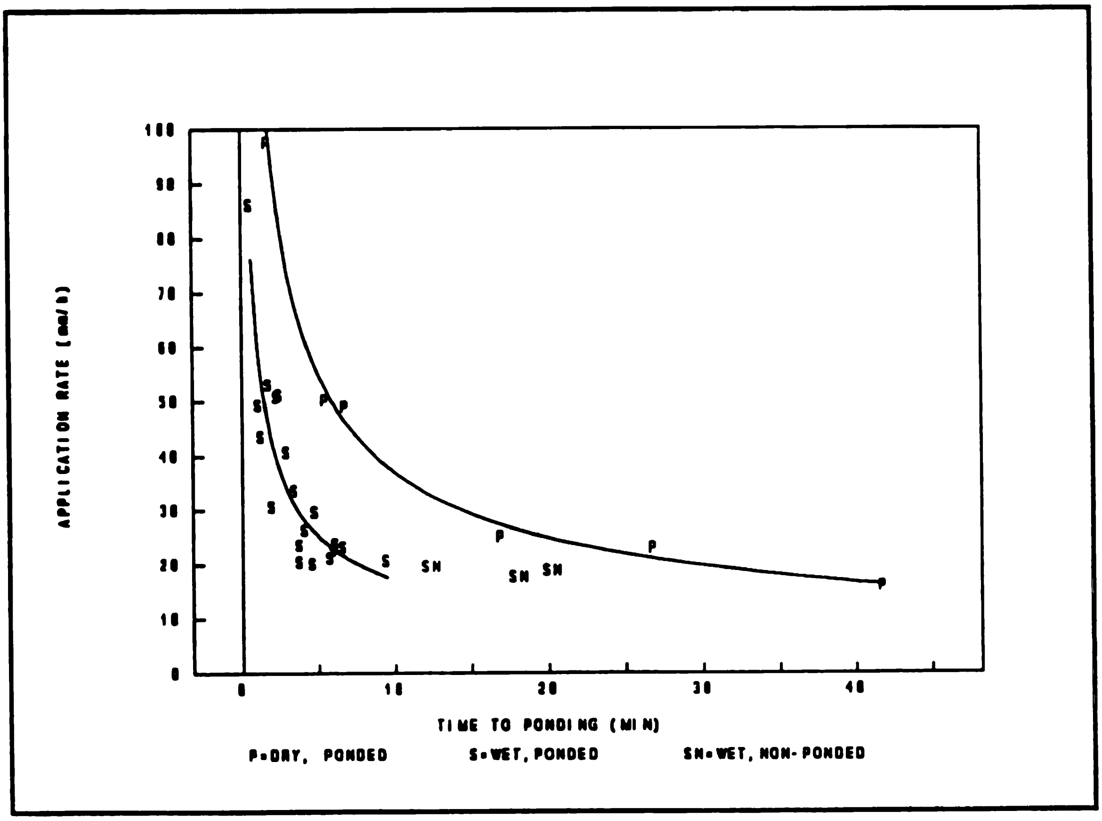

Figure 10. Data (letters) and regressions (lines) for application rates vs. times to ponding for paratilled non-wheel track, Montcalm loamy sand, in potatoes, Entrican MI; 26 July 1989; cumulative water additions to date: 103 mm.

A linear regression is calculated using the *natural logarithm of the application rate vs. the natural logarithm of the time to ponding*:

Dry data regression output:

Constant	4.926	$a=e^{4.926} = 137.8$
Std Err of Y Est	0.073	$b= -0.572$
R Squared	0.990	
No. of Observations	6.000	
Degrees of Freedom	4.000	

X Coefficient -0.572
Std Err of Coe 0.028

Wet data regression output:

Constant	4.112	$a=e^{4.112} = 61.1$
Std Err of Y Est	0.209	$b= -0.552$
R Squared	0.772	
No. of Observations	19.000	
Degrees of Freedom	17.000	

X Coefficient -0.552
Std Err of Coe 0.073

Once parameters a and b are determined (note that $a = e^{Constant}$), a time to ponding function in the Kostiakov form (1932) is used to estimate rates associated with longer times to ponding:

$$\text{application rate (mm/h)} = a * \text{time to ponding (min)}^{b}.$$

The resultant time to ponding functions which correspond to the dry (*) and wet conditions (+) can be seen passing through the data pairs used to calculate them in Figure 10.

In general, most of the data pair sets and associated functions had characteristic infiltration curve appearances, with short times to ponding for high rates, and long times for low rates. An average of 15 ponded observations could be made on moldboard plowed soils in an hour as compared to 9 for chisel plowed wheel tracks and 7 for chisel plowed (CP) non-wheel tracks and no-till. However, if all the nozzles were started at once, a situation like Figure 11, might occur. Figure 11 shows the results of an experiment which was conducted before a good measurement procedure had been developed.

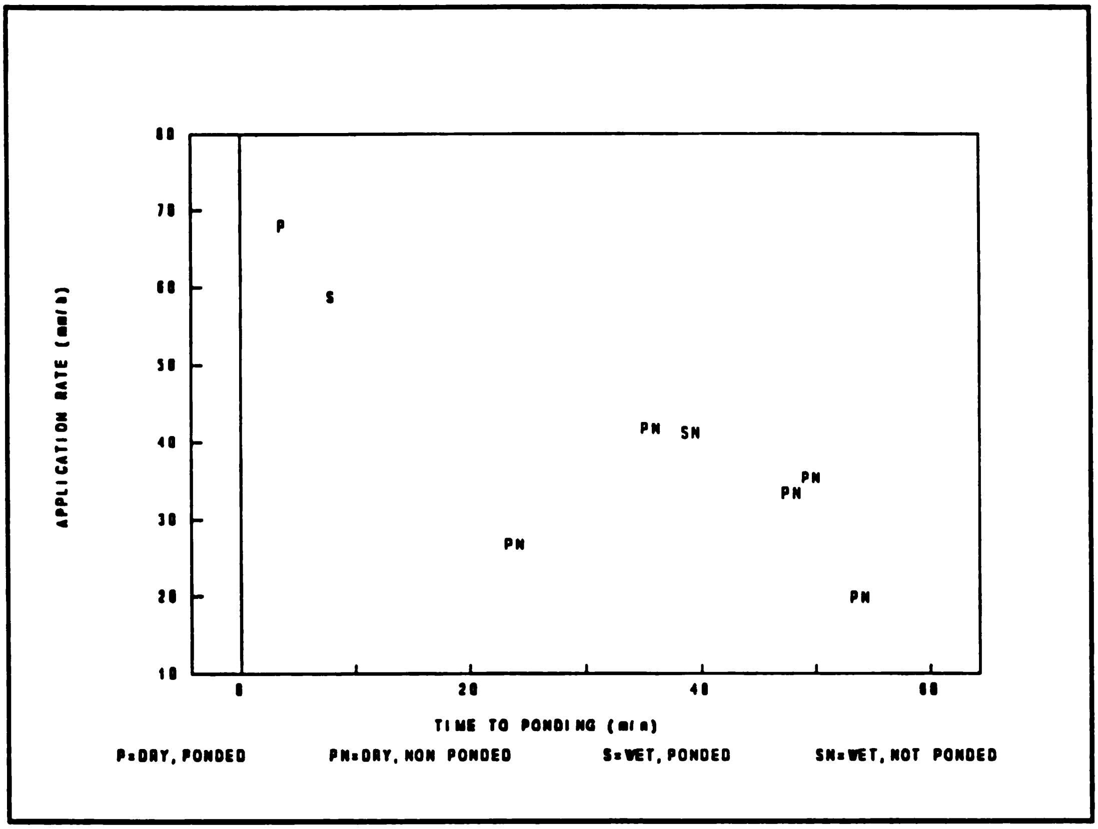

Figure 11. Oshtemo sandy loam: chisel plowed wheel track, 28 July 1988.

It is possible that ponding may not occur despite careful effort on the part of the operator, especially on no-till plots. Using larger nozzles will put the application rates out of range of those used in existing irrigation technology and thus serve no real purpose. Non-ponding data do contain information about ponding with respect to irrigation application rates and can be included in the derivation of the parameters a and b, but the r^2 derived from the relationship which includes the two kinds of data is not valid (personal communication Ted

Chester, statistician, UpJohn Co. Richland, Michigan). The collection and inclusion of such "censored" data (non-ponded) are useful in evaluating measured rates similar to those found in the field. Caution is urged in deciding to mix ponded and non-ponded data: An r^2 derived from ponded data alone is more valuable than from both. Non-ponded data should be included only when the ponded data are inadequate to determine a time to ponding function, as is the case for many CP and NT sites. Since some non-ponding data pairs are clearly unhelpful in determining time to ponding, as in the case of a sprinkler that is turned off arbitrarily, so as to conserve water or to end the experiment, some judgement in removing data points seems justified. However, the effect of such data points is considerably lessened when multiple site data are collectively used to determine a single time to ponding function and so removal is usually not necessary.

Another possible occurrence which is also out of the control of the operator is that the soil ponds very quickly no matter the rate. Almost all of the Montcalm sandy loams measured under moldboard and disk plow ponded after short times at both high and low rates. The best illustration of this can be seen when the data are presented in the rate as a function of depth form, as in Figure 12.

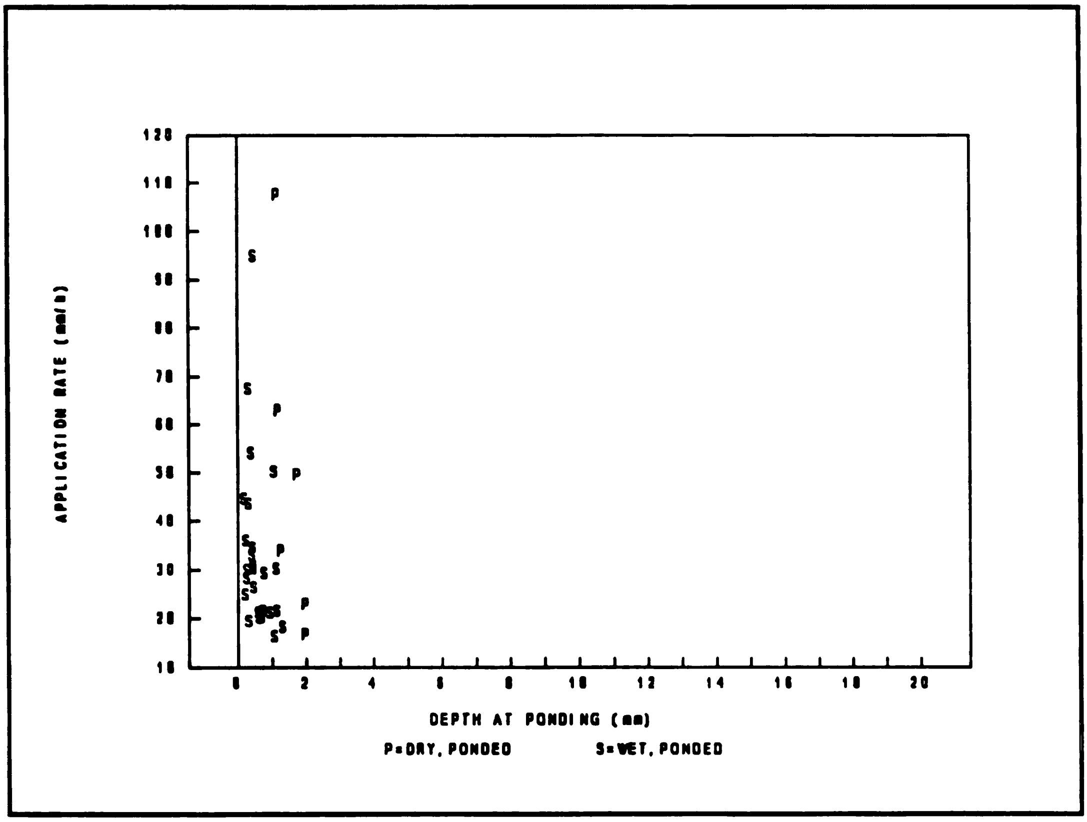

Figure 12. Montcalm sandy loam: disk plowed, non-wheel track,
28 July 1989.

E. Summary

The infiltrometer makes it easy to measure time to ponding for six application rates simultaneously with minimal disturbance to the soil surface conditions. The infiltrometer is easily transported and can use water from a variety of sources. Flow from each nozzle is separately controlled by a solenoid valve and delivers medium to large mean droplet sizes uniformly over an observation diameter of about one meter. In operation, a full tank of water will last four tests. When used with appropriate infiltration models, the infiltrometer provides information that can be used to design a comprehensive infiltration scheme.

V. Model development and use

This section shows how the assumptions of the general model were developed using Smith's work and then provides an example of how the model would consider a Michigan soil under a moving sprinkler application (parabolic) pattern.

A. Model development

1. Time to ponding

Smith (1972) solved the theoretical partial differential equation developed by Richards (1931) for unsaturated moisture flow with a versatile numerical scheme designed for accurate simulation of infiltration from various patterns of rainfall. Using known properties of six soils, ranging from sand to clay, he simulated the ponded function and 6 to 7 constant rate vs. time to ponding pairs for each soil. After examining the t_p for 21 simulated patterns of rainfall, Smith stated that a consistent and rather simple relationship exists to predict ponding times for complex storms: "As long as rainfall rate exceeds the saturated infiltration rate, ponding and subsequent decay of infiltration capacity occurs at very nearly the time when accumulated volume of infiltrated water reaches a constant *which is associated with the particular rate* of rainfall when ponding occurs" (emphasis added). In other words, the time to ponding is the time when the application rate and depth just begin to exceed the infiltration rate and depth. Smith also suggested that an infiltration function became "universal" when expressed in terms of rate as a function of accumulated depth, and one can use his simulated values to clearly demonstrate this. Finally, he showed that it was possible to use simple empirical functions to adequately represent the simulated output of the vastly more complex physical model. Using Smith's simulated values, I will: 1) show how a time to ponding function in the Kostiakov form describes Smith's constant application rate vs. time to ponding pairs: 2) demonstrate how the ponded function and the time to ponding function are nearly coincident when plotted as rate vs. cumulative depth; 3) show how the times associated with these functions differ; and 4) reproduce a typical set of four of his 21 rainfall patterns and times to ponding using only the time to ponding function.

The pattern of the rate vs. time to ponding pairs can be described by the time to ponding function which has the same form as the Kostiakov model:

$$r_{tp} = a*t_p^{\,b}, \tag{1}$$

where r_{tp} = (constant) rate associated with a time to ponding in cm/min, and
t_p = time to ponding in minutes, and
a,b = parameters.

The parameters a and b are obtained from the slope and intersect of the best fit line describing the natural logarithms of the constant application rates vs. the natural logarithms of their corresponding times to ponding. Smith's rates varied from 0.0635 to 0.931 cm/min, and his times to ponding varied from 0.59 to 35 minutes. The parameters a and b in Table 7 were calculated using Smith's reported rates and times to ponding. Table 7 also shows the regression coefficient for the comparison between the time to ponding function and Smith's simulated values for each soil type.

Table 7. The Smith time to ponding simulated values as represented by the time to ponding function.

SOIL TYPE	a	b	r^2
Poudre sand	0.871	-0.412	0.995
Nickel gr sandy loam	0.293	-0.481	1.000
Nibley silty clay loam	0.344	-0.483	1.000
Colby silt loam I	0.236	-0.510	0.999
Colby silt loam II	0.250	-0.502	0.999
Muren clay	0.347	-0.514	1.000
Average regression coefficient			0.999

Judging by the coefficients of regression, the time to ponding function in the Kostiakov form closely describes the rate vs. time to ponding pairs that Smith generated.

2. Coincident time to ponding and ponded functions

Two types of infiltration rate vs. time functions are needed to completely describe infiltration under irrigation for application patterns that produce ponding. The first is the time to ponding function as discussed above which describes the set of constant sprinkled rate vs. time to ponding pairs for a particular soil condition. The second is the ponded function which describes the intake rate of the same soil condition under a continuously ponded state from the time of ponding. The time to ponding function is needed to predict the time to ponding for any application pattern, and the ponded function is needed to predict infiltration after ponding. If only one of the functions is known, however, the other can be estimated, because when each is defined or graphed in terms of rate vs. cumulative depth, they are nearly coincident. The simulated values of Smith demonstrates this significant relationship. The Nibley silty clay loam exemplifies how each of the graphed rate vs. depth functions were generated. Smith's time to ponding values can be represented by the time to ponding function, Eq. (1) described above.

Since the measured application rate is constant when determining time to ponding, the accumulated application depth at time to ponding is:

$$D_{tp} = r_{tp} * t_p, \tag{2}$$

where D_{tp} = accumulated application depth at the time of ponding.

Substituting the parameters from Table 7 for the Nibley silty clay loam into Eq.'s (1) and (2) gives:

$$r_{tp} = 0.344 * t_p(\text{min})^{-0.483}, \text{ and}$$

$$D_{tp} = (0.344 * t_p^{-0.483}) * t.$$

Smith demonstrated how his generated ponded function could be adequately represented by:

$$r = ft^g + k, \tag{3}$$

where r = rate at some time after ponding, cm/min,
t = time after ponding, min, and
f,g,k = parameters.

Since the ponded rate is not constant, the depth of infiltration since ponding is the integration of the rate function used by Smith:

$$D = ft^{1+g}/(1+g) + kt, \tag{4}$$

where D = accumulated infiltration depth.

The parameters f, g, and k, were calculated and reported by Smith for the six soils in his work. Substituting Smith values for the Nibley silty clay loam into Eq.'s (3) and (4) gives:

$$r = 0.222*t^{-.555} + 0.0167, \text{ and}$$

$$D = 0.222t^{0.445}/0.445+0.0167t.$$

The values for r_{tp}, D_{tp}, r and D were calculated for 100 minutes of time for each soil. The r_{tp} was plotted against the D_{tp} for the time to ponding function, and the r was plotted against the D for the ponded function. The two functions for three other soils in Table 7 were produced in the same way. Figure 13 shows the Nibley silty clay loam and the Colby silt loam I, and Figure 14 shows the Poudre sand and Muren clay. The axes on Figure 14 are larger so as to accommodate the

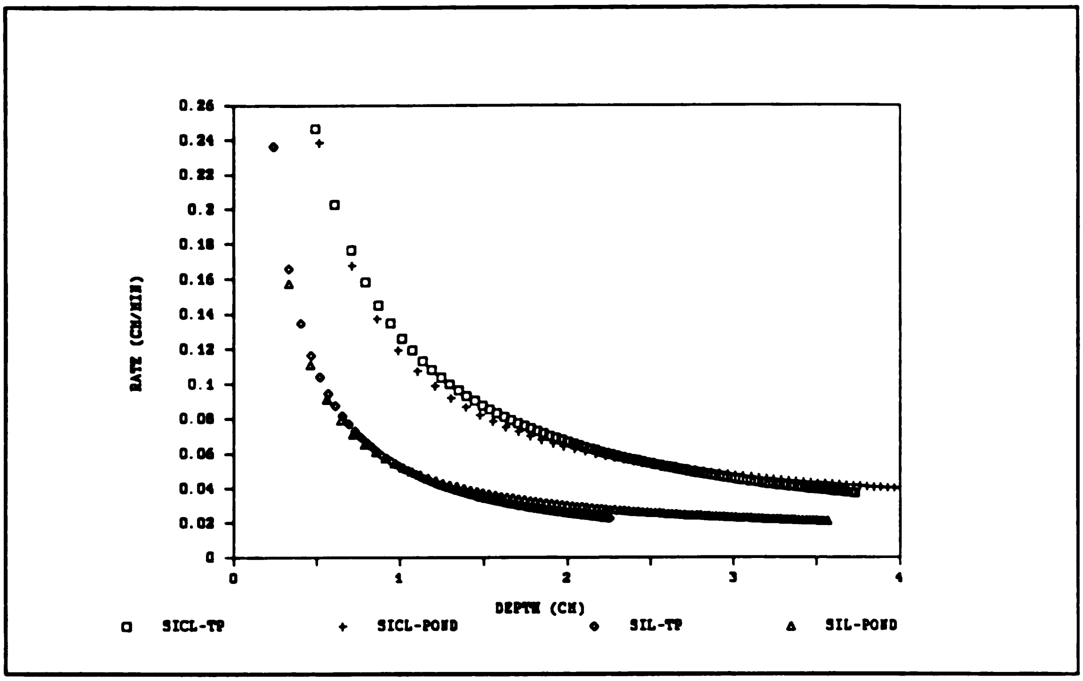

Figure 13. Time to ponding and ponded functions in terms of rate vs. cumulative depth for the Nibley silty clay loam and the Colby silt loam.

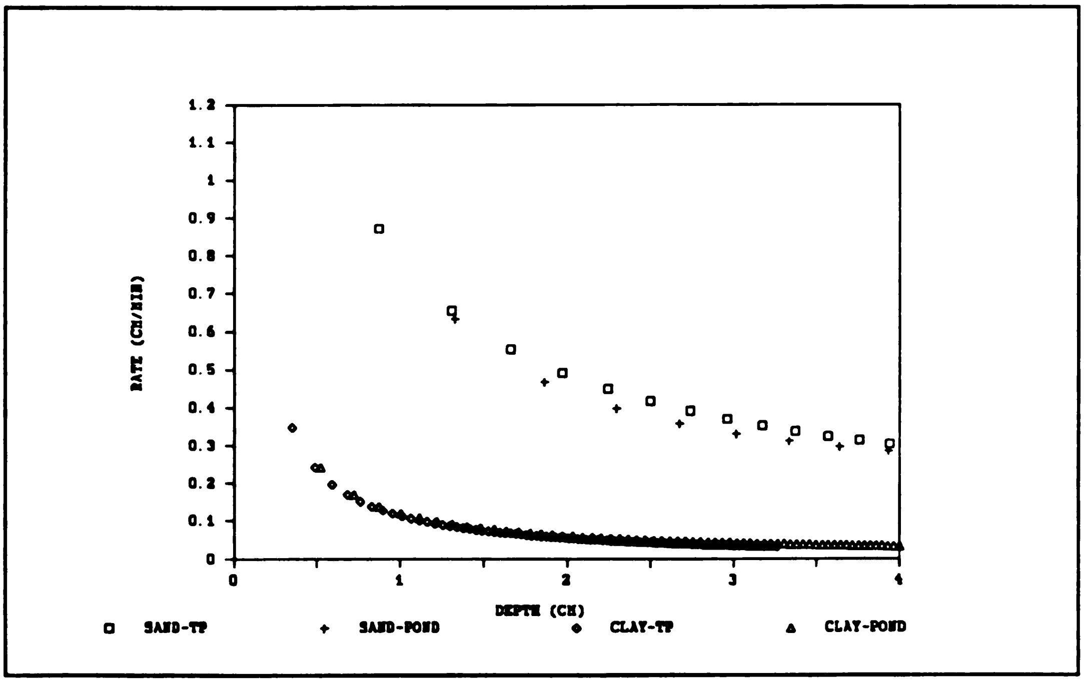

Figure 14. Time to ponding and ponded functions in terms of rate vs. cumulative depth for the Poudre sand and the Muren clay.

higher infiltrability of the sand. When graphed in terms of rate vs. depth, the two functions associated with each soil are nearly coincident. Therefore we can represent the rate as a function of depth relationship for any given soil condition with just one function.

3. The times associated with these functions are different

Figure 15 shows an enlarged view of the Poudre sand as seen in Figure 14. The time to ponding function is marked with a series of T's and the ponded function is marked with a series of P's. Numbers in the respective functions show the time in minutes. This is to stress an important point, which is, *the times from time 0 associated*

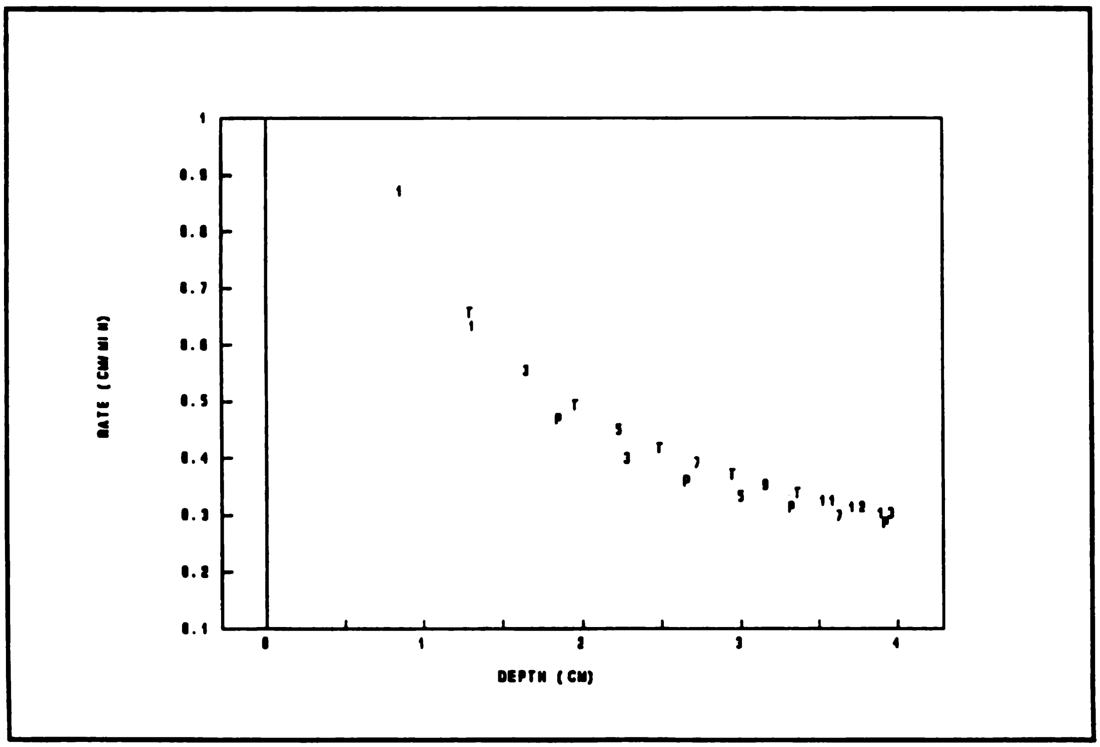

Figure 15. Times (minutes) associated with rate and depth for Poudre sand.

with a given rate and cumulative depth are different, depending on the type of function.

If the soil is ponded from the beginning, a greater depth of water will infiltrate in the same amount of time when compared to the time under sprinkling. This also explains why the *time associated with the ponded function* at the rate and depth associated with the time to ponding is less than the *time associated with the time to ponding function*. For example, in Figure 15, if the soil ponded when the rate was 0.3 cm/min and the depth was 3 cm, the time to ponding would be between 7 and 9 minutes. However, the ponded time equivalent to the same rate and depth would be 5 minutes. If one wished to continue to estimate the infiltration rate with time under ponded conditions, one could then use the ponded function, starting at the 5 minute time on the ponded function. In this model, the time associated with the time to ponding function and the application pattern is *real* time and denoted by alphabetical subscripts, such as t_p and t_e. Time associated with the ponded function is *virtual* time and denoted by using numerical subscripts, such as t_1, t_2, and t_3. These are introduced later. It is first necessary to understand how to calculate the time to ponding (t_p), rate at time to ponding (r_{tp}) and depth at time to ponding (D_{tp}) for any application pattern.

B. Model use

The relationships demonstrated above can be used to describe infiltration behavior from the beginning of the sprinkled application to the end of the ponded condition. The time to ponding function can be used to determine the time to ponding for any application pattern, and the coincidence of the time to ponding function and the ponded function makes it possible to estimate a ponded function which is properly defined for any time of ponding.

The general procedure for using this infiltration model is: 1) describe the application pattern function; 2) describe the soil time to ponding function; 3) calculate the time to ponding (t_p) and associated values: rate at time to ponding (r_{tp}) and depth at time to ponding (D_{tp}); 4) describe the ponded function by calculating the parameters: k, t_1 and f, and determine the summary variables and completion of ponding times, if desired. Four application patterns used by Smith will be used to demonstrate how the function works. The outcomes of this function will then be compared with his simulated values and model.

1. Simple application patterns

a. Describing the application pattern functions

Two application pattern functions are needed. The first describes the application rate at any time as a function of time, and the second describes the depth at any time as a function of time. Four of the application patterns used by Smith are described in Table 8. Pattern 1) and 3) are constant rate functions, and 2) and 4) are step variations of patterns 1) and 3).

Table 8. The Smith application pattern functions.

	Rate (r) (cm/min)	Duration (min)	Depth (D) (cm)
1)	0.1058	30	0.1058*t
2)	0.1693	1	0.1693*t when $0 \le t \le 1$;
	0.1058	20	0.1058*(t-1)+.1693 when $1 \le t \le 20$.
3)	0.1693	30	0.1693*t
4)	0.1058	2	0.1058*t when $0 \le t \le 2$;
	0.1693	15	0.1393*(t-2)+.2116 when $2 \le t \le 15$.

b. Describing the soil time to ponding function

After the application pattern functions are described, the soil time to ponding function must be written in terms of rate as a function of depth. Given Eq.'s (1) and (2), the time to ponding rate as a function of depth is:

$$r_{tp} = a(D_{tp}/r_{tp})^{b} = aD_{tp}^{b}/r_{tp}^{b}$$

$$r^{(1+b)} = aD_{tp}^{b} = a^{1/(1+b)}D_{tp}^{b/(1+b)}.$$

Therefore, $$r_{tp} = cD_{tp}^{d}, \tag{5}$$

where $$c = a^{1/(1+b)} \text{ and } d = b/(1+b). \tag{6,7}$$

For the Colby silt loam I, a = 0.236, and b = -0.51 (Table 7). Solving Eq's.(6) and (7) gives c = 0.052, and d = -1.041. Substituting these into Eq.(5) gives:

$$r_{tp} = 0.052*D_{tp}^{-1.041}.$$

c. Calculating the time to ponding and associated values

Ponding occurs when the application pattern function intersects the soil intake function. At that intersection, the application rate equals the infiltration rate and the application depth equals the infiltration depth. The time at which ponding occurs is dependent upon the application rate vs. time function. A particular set of r_{tp} and D_{tp} can be obtained from an infinite number of application patterns. Therefore, the same set of r_{tp} and D_{tp} can occur at an infinite number of times, each dependent upon the application pattern which produced it. In this next example, notice how application patterns 1) and 2) pond at different times even though their r_{tp}'s and D_{tp}'s are the same. The same observation is true for application patterns 3) and 4).

Again, the time to ponding is the time *associated* with the rate and depth of the intersection of the application pattern function and the unique soil rate vs. depth function, here represented by the time to ponding function. The intersection of the application pattern function and the soil time to ponding function can be solved by substituting the two application pattern functions into the rate vs. depth version of the time to ponding function [Eq.(5)]. The functions described in Table 8 for the four Smith application patterns are substituted into the Colby silt loam time to ponding function described above.

For application pattern 1):

$$0.1058 = 0.05251(0.1058t_p)^{-1.041}.$$

Therefore, $t_p = 4.82$ min, $D_{tp} = 0.510$ cm, and $r_{tp} = 0.1058$ cm/min.

Similarly, for application pattern 2):

$$0.1693 = c(0.1693t_p)^d.$$

t_p = 1.92 min. Note, however, by that time, the application rate is no longer 0.1693 cm/min, so that cannot be the correct t_p. Instead:

$$0.1058 = c(0.1058(t_p-1) + 0.1693)^d.$$

Therefore, t_p = 4.22 min, D_{tp} = 0.510 cm, and r_{tp} = 0.1058 cm/min. Application pattern 3) is solved in the same manner as 1): t_p is 1.92 min, D_{tp} is 0.325 cm, and r_{tp} is 0.1693 cm/min. Likewise, application pattern 4) is solved in the same manner as 2): t_p is 2.67 min, D_{tp} is 0.325 cm, and r_{tp} is 0.1693 cm/min. Smith observed that ponding occurs at very nearly the time when accumulated depth (he said volume) reaches a constant which is associated with the particular rate when ponding occurs. *This is why a function which describes a set of constant sprinkled rate vs. time to ponding pairs (such as that associated with the sprinkling infiltrometer) can be used to predict time to ponding for any application pattern.*

Table 9. Comparison between Smith's simulated values and values predicted using the time to ponding function (r_{tp}'s are identical).

	t_p (min)		D_{tp} (cm)	
	Smith	t_p function	Smith	t_p function
1)	4.83	4.82	0.510	0.510
2)	4.27	4.22	0.514	0.510
3)	1.89	1.92	0.320	0.325
4)	2.64	2.67	0.319	0.325

In every comparison in Table 9 for t_p and D_{tp}, the values derived by the time to ponding function differed less than 2 percent from the Smith simulated values.

d1. Describe the ponded function and calculate summary variables

The ponded function can be described by the Philip model. But even if the ponded function is known for the soil condition at the beginning of the rainfall or sprinkling event, it is undefined for the soil conditions at the time(s) of ponding, which are different for each pattern of application. If the ponded function is not known, however, it can be approximated from the time to ponding function since the two are coincident in the rate as a function of depth version. In this section, the Philip model is used to approximate the ponded function from the time to ponding function for the soil conditions at the onset of ponding.

The Philip model uses the same form as a Kostiakov model modified by the addition of an asymptotic variable:

$$r = f*t^g + k, \tag{3}$$

where the k would be a variant of saturated hydraulic conductivity, or constant infiltrability. The Philip model is:

$$r = S/2*t^{-\frac{1}{2}} + A,$$

so $f = S/2$,
$g = -0.5$, and
$k = A$.

Researchers (Philip 1957, Youngs 1968, Swartzendruber and Youngs 1974, Sharma et al. 1980, Whisler and Bouwer 1970, Brakensiek and Rawls ASAE Paper 81-2504, 1981) have used widely varying estimates of A, from $K_s/3$

to K_s. In situ measurements of K_{sat} using ponded infiltrometers on sites in close proximity to one another often result in a wide variety of values. Because the time to ponding function integrates the ponding observations over an entire circular observation area, it was decided that an estimate of the parameter k should be obtained from that function. Since the longest sprinkled irrigation application period is unlikely to exceed three hours, and the rate of decrease in the sprinkled application rate which is predicted to cause ponding at that time is very small, for the purposes of this dissertation, I decided to define the parameter k as that constant rate which is predicted to induce ponding after three hours (180 minutes), or:

$$k = a*180^b. \tag{8}$$

In Eq.(3), only the values for the ponded time equivalent of the time to ponding (t_1) and f are left undefined. These can be calculated, however, knowing the values associated with the time to ponding: t_p, r_{tp}, and D_{tp}:

$$r_{tp} = f*t_1^{-0.5} + k,$$

therefore $$f = (r_{tp} - k)/t_1^{-0.5}.$$

$$D_{tp} = f*t_1^{0.5}/0.5 + k*t_1,$$

therefore $$f = 0.5(D_{tp}-kt_1)/t_1^{0.5}.$$

So, if $$(r_{tp} - k)/t_1^{-0.5} = 0.5(D_{tp}-kt_1)/t_1^{0.5},$$

$$t_1 = 0.5D_{tp}/(r_{tp}-0.5k), \text{ and} \tag{9}$$

$$f = (r_{tp}-k)/t_1^{-0.5}. \tag{10}$$

Smith shows how the modified Kostiakov equation can be used to estimate the ponded function and gives values for f, g, and k for the t_p associated with every constant rate vs. time to ponding simulated pair. Using the simulated values he gives for the Colby silt loam as an example, the results of a Philip model derived from the time to ponding function can be compared with his estimates for ponded infiltration. A sample calculation demonstrating the Philip method will be done for Smith's first simulated pair for the Colby silt loam I (Table 10), at the rate of 0.0635 cm/min. Recall for Colby silt loam I, that a = 0.236 and

b = -0.510, therefore using Eq.'s (6) and (7), c = 0.0525 and d = -1.041. Substituting these into Eq.s (8), (5), (2), (9), and (10) gives:

$$k = 0.236 * 180^{-0.51} = 0.0167 \text{ cm/min.}$$

$$r_{tp} = c * D_{tp}^{d} = 0.0635 \text{ cm/min} = c(0.0635 * t_p)^{d},$$

making $t_p = 13.12$ min,

$$r_{tp} = 0.0635 \text{ cm/min, and}$$

$$D_{tp} = 0.833 \text{ cm.}$$

Therefore, $t_1 = 0.5 * D_{tp}/(r_{tp} - 0.5k) = 7.57$ min, and

$$f = (r_{tp} - k)/t_1^{-0.5} = 0.129.$$

If the total applied application depth (D_a) is 2.5 cm, at r = 0.0635 cm/min, the total application period (p) would be 39.4 min. Since the interval of time between the time to ponding and the end of the application is p minus t_p, the equivalent end of application in ponded time (t_2) is:

$$t_2 = t_1 + (p - t_p). \qquad (11)$$

The depth of water that has infiltrated between the time to ponding and the end of the application (D_p) is:

$$D_p = f(t_2^{0.5} - t_1^{0.5})/0.5 + k(t_2 - t_1). \qquad (12)$$

Here, D_p is 1.2 cm. The total depth of water infiltrated from the pre-ponded period to the end of application (D_{tot}) would be:

$$D_{tot} = D_{tp} + D_p. \tag{13}$$

Here, $D_{tot} = 2.1$ cm. The percentage of water that infiltrated of the total depth applied by the end of the application period ($\%D_a$) is:

$$\%D_a = D_{tot}/D_a * 100. \tag{14}$$

Here $\%D_a$ is 82%. Smith values are: $D_p = 1.1$ cm, $D_{tot} = 1.9$ cm, and $\%D_a$ = 76%. The next table, Table 10, shows the comparisons for all the Colby silt loam I t_p pairs.

Table 10. Ponded infiltration comparison between the Smith estimates (1) and the Philip model (2) derived from the time to ponding function determined for 2.54 cm added at a constant rate (cm/min).

Smith		(t_p)		(D_{tp})		(D_p)		($\%D_a$)	
rates	(f)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
0.0635	0.129	13.4	13.1	0.85	0.83	1.05	1.23	76	82
0.0847	0.138	7.6	7.5	0.64	0.63	1.18	1.22	73	74
0.1058	0.144	4.8	4.8	0.51	0.51	1.11	1.18	65	68
0.1270	0.148	3.3	3.4	0.42	0.43	1.12	1.14	62	63
0.1693	0.153	1.9	1.9	0.30	0.32	1.06	1.05	54	55
0.3175	0.161	0.6	0.6	0.19	0.17	0.73	0.84	37	41

The D_p values are within 7% of each other, and the $\%D_a$ values are within 4%. Table 10 also shows that the lower the rate of application, the higher the percent of the total applied ($\%D_a$) depth infiltrated by the time application ended. The values for f decrease as the depth of water that infiltrated before ponding increase. As f is roughly equivalent to S/2, this seems reasonable.

d2. After application ceases

Often, ponding continues after application has ceased. The ponded time associated with this condition (t_3) can be calculated by:

$$D_a - D_{tp} = f(t_3^{0.5} - t_1^{0.5})/0.5 + k(t_3 - t_1). \quad (15)$$

For $r_{tp} = 0.0635$ cm/min, and $D_a = 2.5$ cm; the t_3 is 44.2 min, or about 10.5 min. after application ceases. This time will be longer for higher rates at the same depth. The parameter, t_3, is defined here as a ponded (virtual) time, as are all times denoted by a t subscripted with a number. The real time when ponding ceases (te) is:

$$te = (t_p - t_1), \quad (16)$$

which here would be 49.7 min. If the application rate is parabolic, it is possible for those situations where time to ponding occurs very late that ponded water can disappear before the end of application.

2. Complex application patterns

The same model application process can be used to estimate infiltration of sprinkled water from a center pivot irrigation system into a Michigan agricultural soil. A parabolic application function can be used to represent the irrigation pattern, and measured constant sprinkled rate vs. time to ponding pairs can be used to derive the intake rate vs. cumulative depth function for the soil. The parabolic pattern is described earlier in this chapter in the section on application patterns, and a set of measured constant sprinkled rate vs. time to ponding pairs is converted into a time to ponding function for a given soil condition in the section on the sprinkling infiltrometer. As before, the process is the same: 1) describe the application pattern function; 2) describe the soil time to ponding function; 3) solve for the time to ponding (t_p) and associated values of application rate at time to ponding (r_{tp}) and application depth at time to ponding (D_{tp}); 4) solve for the constants associated with the ponded function: k, t_1 and f, and determine the summary variables and cessation of ponding after application ends.

a) Describing the application pattern functions

The general parabolic application pattern is described by:

$$D_a = 2hp/3.$$

(17)

where h = maximum application rate, in mm/h, and
p = application period, in h.

Therefore, a maximum application rate (h) of 16 mm/h and a period (p) of 2.38 hours will deliver a total application depth (D_a) of 25.4 mm. This pattern is typical of low maximum application rate center pivot systems existing in the field. The rate at any time for the parabolic application pattern can be described by:

$$r = 4ht/p - 4ht^2/p^2, \text{ or}$$

(18)

The application depth at any time can be described by:

$$D = 2ht^2/p - 4ht^3/3p^2, \text{ or} \qquad (19)$$

For this example, values for h and p are substituted into Eq.'s (18) and (19) to give:

$$r = 26.891*t - 11.299*t^2.$$

$$D = 13.445*t^2 - 3.766*t^3.$$

b) Describing the soil time to ponding function

This example uses the time to ponding function of the Montcalm loamy sand which was moldboard plowed. The test was done on a wheel track row, and the r^2 for the time to ponding function was 0.94, with a = 104.1, and b = -0.654. The suggested general time to ponding function is:

$$r_{tp} = c*D_{tp}^{d}.$$

(5)

Where r_{tp} = rate associated with the time to ponding in mm/h,
t_p = time to ponding in min, and
D_{tp} = depth at t_p in mm.

As a consequence of the difference in time units describing r_{tp} in mm/h and t_p in min, a correction factor needed to be added to the formula for calculating the parameter c:

$$c = a^{1/(1+b)}*60^{d},$$

where $$d = b/(1+b).$$

Therefore, c = 294 and d = -1.89. When these values are substituted into Eq.(5), the time to ponding function for the moldboard plowed wheel track row on the Montcalm loamy sand is:

$$r_{tp} = 294*D_{tp}^{-1.89}.$$

c) Calculating the time to ponding and associated values

When the application rate and depth [Eq.'s (18) and (19)] are substituted into Eq.(5), the Montcalm time to ponding function, the time to ponding (t_p) is that time (t) in Eq. 20 which makes the equation equal to zero:

$$0 = c(2ht^2/p - 4ht^3/3p2)^{d}-(4ht/p - 4ht^2/p^{2)} \qquad (20)$$

$$0 = 294\ (13.445*t_p^2 - 3.766*t_p^3)^{-1.89} - (26.891*t_p - 11.299*t_p^2).$$

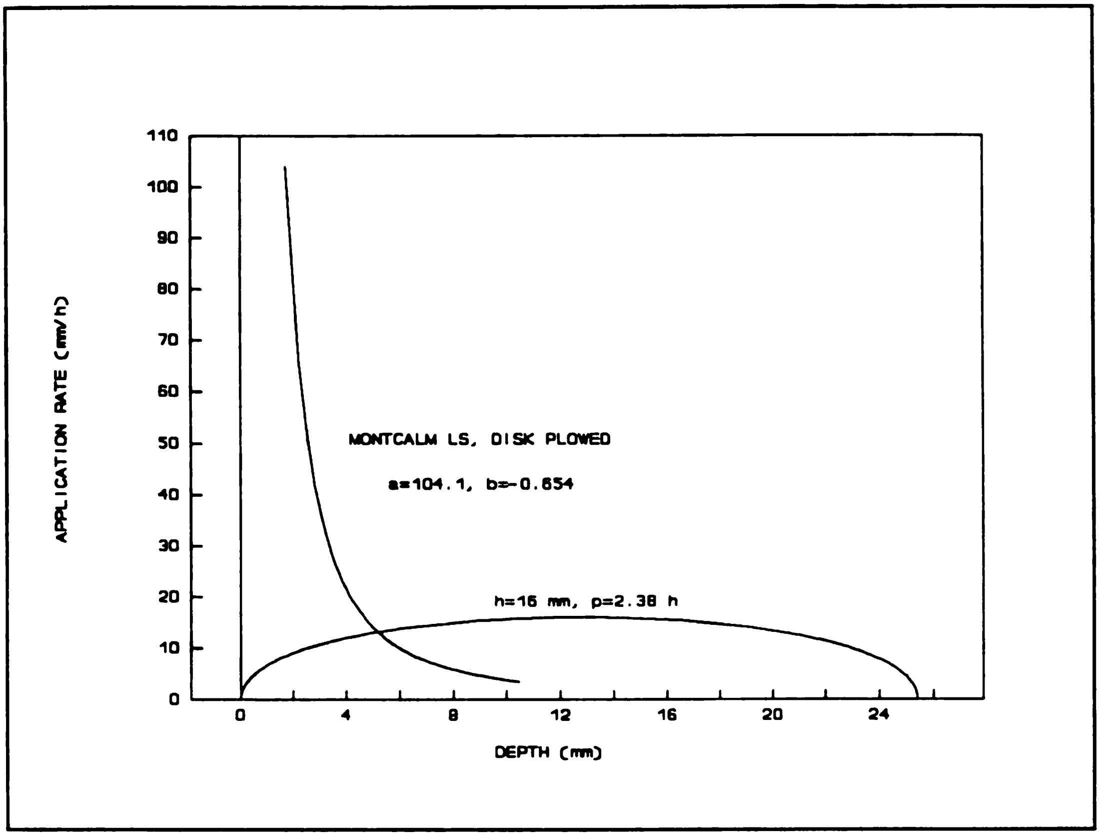

Figure 16. Intersection of rates and depths at the time of ponding.

Using a root solution method, that time (t_p), is computed to be 0.691 hours, or 41.4 min. Substituting t_p into Eq.'s (18) and (19) will give the application (and infiltration) rate at the time of ponding (r_{tp}) and the application (and infiltration) depth at the time of ponding (D_{tp}):

$$r_{tp} = 26.891*0.691 - 11.299*(0.691)^2 = 13.183 \text{ mm/h; and}$$

$$D_{tp} = 13.445*(0.691)^2 - 3.766*(0.691)^3 = 5.173 \text{ mm.}$$

d) Describe the ponded function and calculate summary variables

The parameters a and b are substituted into Eq.(8) to solve for k:

$$k = a*180^b = 3.5 \text{ mm/h, and}$$

the values for D_{tp}, r_{tp} and k are substituted into Eq.(9) to solve for t_1:

$$t_1 = 0.5*D_{tp}/(r_{tp}-0.5k) = 0.226 \text{ h or } 13.6 \text{ min.}$$

r_{tp}, k, and t_1 are substituted into Eq.(10) to solve for f:

$$f = (r_{tp}-k)/t_1^{-0.5} = 4.609, \text{ and}$$

t_1, p, and t_p are substituted into Eq.(11) to solve for t_2:

$$t_2 = t_1 + (p-t_p) = 1.915 \text{ h or } 114.9 \text{ min.}$$

Then, the rest of the summary variables are calculated, using Eq.'s (12) through (14).

$$D_{tp} = f(t_2^{0.5}-t_1^{0.5})/0.5 + k(t_2-t_1) = 12.264 \text{ mm.}$$

$$D_{tot} = D_{tp} + D_p = 19.437 \text{ mm,}$$

$$\text{and } \%D_a = D_{tot}/D_a*100 = 76.5\%.$$

t_3 can be found by determining the time that makes this equation equal to zero:

$$0 = f(t_3^{0.5}-t_1^{0.5})/0.5 + k(t_3-t_1) - (D_a-D_{tp}), \text{ or}$$

$$3.487t_3 + 9.218t_3^{0.5} - 25.397.$$

That time (t_3) = 2.833 h. $t_e = t_3 + (t_p-t_1) = 3.298$ h.

Summary: Given:		Calculated:
	h=16 mm/h	c=295
	p=2.38 h	d=-1.89
	a=104.1	k=3.5 mm/h
	b=-0.654	t_1=13.6 min.
		t_2=114.9 min.
		t_3=2.83 h.
		t_p=41.4 min.
		r_{tp}=13.2 mm/h.
		D_{tp}=5.2 mm.
		f=4.609
		D_p=14.3 mm.
		D_{tot}=19.4 mm.
		$\%D_a$=76.5%
		te=3.30 h.

This was an application pattern which had a relatively low maximum rate and is an example of a soil-tillage condition and application strategy combination that is somewhat successful. In the results section of this work, this combination will be compared with the same soil condition under a high maximum rate application pattern and low and high maximum rate systems that apply half the application depth.

In summary, this section showed that a time to ponding function in the form of a Kostiakov model could be used to predict the time to ponding successfully, not only in representing the field conditions, but when compared to output generated by a numerical solution of the Richards equation. Not only can the time to ponding function be used to predict the time to ponding for any application pattern, it can also be used to estimate the Philip ponded model and determine the proper sorptivities associated with any application pattern time to ponding starting with initially dry soil conditions.

VI. Field measurements

A. The tests

One hundred and three sprinkling infiltrometer tests were performed in two years on three soil series, under five tillage practices and two crops. With the exception of field #1 and the chisel plow tillage in field #2, ten tests were done on each soil/tillage/crop combination: half on wheel track furrows and half on non-wheel track furrows. A sprinkling infiltrometer test plot consisted of one target row section, about 10 m in length, and two adjacent row sections, used for access and observation. The procedure for conducting the time to ponding tests is described in detail in the methods section on the design of the sprinkling infiltrometer. In addition to measuring the volumes of sprinkled water and times to ponding, we also measured the depth to the B horizon and percent residue, using the Laflen (1981) line transect method (n=2). For each infiltrometer test we also noted the time and estimated air temperature, wind speed and direction, slope, presence or absence of crusting, and crust thickness. An average of two infiltrometer tests were performed per day. A different crop/tillage treatment was tested each day so as to get maximum variability in soil moisture over a season and similar average values between treatments.

The soil tests were done either in conjunction with the sprinkling infiltrometer tests on the same plots, or independently, on separate plots. The tests included:

1. Bulk density, θ_v, and θ_g, using the Grossman compliant cavity method, described in Appendix D. (n=2, one at each end)

2. Bulk density, θ_v, and θ_g, using the modified Grossman compliant cavity method, described in Appendix D. (n=2, one at each end)

3. Bulk density, θ_v, and θ_g, using the Madera sampler (tm) method, described in Appendix D. (n=10, at five regular intervals throughout the plot)

4. Saturated hydraulic conductivity, using the velocity head permeameter (Personal communication, Merva 1988). (n=2-12, equivalent to 30 minutes at each end)

In the second year, a textural analysis was added to the set of soil tests for each plot, using a composite from the soil samples gathered from the Madera sampler tests. The velocity head permeameter measurements were discontinued, and, after four weeks of doing three versions of the bulk density and soil moisture tests, the Grossman tests were abandoned because no significant differences were found between them and the Madera sampler tests, probably because of the relative lack of stones and gravel larger than 2 mm in the Montcalm soils.

We received help from the Soil Conservation Service and the Michigan State Cooperative Extension Service in locating fields where the tests could be conducted. After a location was approved by the landowner, either Dr. D.L. Mokma of the MSU Crop and Soil Science Department, or Greg Thoen, the SCS area soil scientist, inspected the potential field sites to verify the soil classification and to advise avoidance of unlike soil areas when making final siting decisions.

B. The fields

Field #1, Kalamazoo sandy loam (Typic Hapludalf, fine-loamy, mixed, mesic) is located SW1/4, NW1/4, Section 29, T4S, R4W of the Michigan meridian, south of Homer in Calhoun County. In 1988, it had three types of tillage plots: moldboard plowed (MB), chisel plowed (CP) and no-tilled (NT), and this was the third year of establishment for all of them. The moldboard and chisel plowing had been done in the Fall of

1987, and the secondary disking was done on 28 April. Corn was planted on all the plots on 29 April. One third of the furrows were wheel tracks. The plots were not irrigated. The depth to the B horizon ranged between 45-60 cm, and there was no crusting at the time of testing, which was in the early season between 24 May and 10 June. At this first field, which was primarily used to gain experience with the new infiltrometer, we did only four replicas per tillage and no wet tests (they hadn't been thought of yet). The amount of rainfall that fell on the plots between the time of disking and the dates of the tests was between 3.7 and 4.5 cm.

Field #2, Oshtemo sandy loam (Typic Hapludalf, coarse-loamy, mixed, mesic) is located SW1/4, SE1/4, NE1/4, Section 18, T2S, R9W of the Michigan meridian, northeast of Galesburg in Kalamazoo County. In 1988, it had the same three kinds of tillage plots as field #1. It was the fourth year for the NT, but the MB and CP tillages were newly established. The moldboard and chisel plowing was done on 21 April, and corn was planted on 5 May. One third of the furrows were wheel tracks. The field was irrigated by a center pivot system and applications were scheduled through the Michigan Energy Conservation Program. The depth to the B horizon ranged between 33-50 cm, when one could get through the rocks, and there was very little crusting at the soil surface. Rocks could be found throughout the profile, and 70 widely-scattered samples of the surface 5 cm revealed that the mass of the material larger than 2 mm ranged from 12-58 percent, averaging about 26 percent of the total mass.

The soil tests (bulk density, soil moisture, and saturated hydraulic conductivity) were done on a total of 30 MB sites during the early, mid, and late season (13-15 June; 5-8 July, and 12 July-8 August). The sprinkling infiltrometer tests were done during the late season only. On CP, both the soil tests and the sprinkling infiltrometer tests were done on a total of 20 CP sites during the mid and late season (24-30 June and 14 July-11 August). On NT, only the soil tests were done during the early season (11-17 June), but both the soil tests and the sprinkling infiltrometer tests were done during the late-season (14 July-11 August). The amounts of rain and irrigation water added to the field between tillage and the early season tests ranged from 8-9.3 cm; between tillage and the mid-season tests, 12.2-12.4 cm; and between tillage and the late season tests, 16.2-29.4 cm.

Field #3, Montcalm sandy loam (Eutric Glossoboralf, coarse-loamy, mixed) is located NE1/4, SW1/4, SW1/4, Section 18, T9N, R7W of the Michigan meridian, southeast of Greenville in Montcalm County. In 1989, it was agreed that MB and CP plots would be installed in this field that had been in corn and disked for three years, but the area set aside for the CP plots was instead disked by the implement operator, so we went ahead with disked plots instead of the CP as planned. I had also been looking for a Montcalm loamy sand for the 1989 tests and although the area soil scientist said it was a loamy sand, when tested it turned out to be a sandy loam. The disking was done on 1 May and the moldboard plowing was done on 8 May. The corn was planted on 9 May. One-half of the furrows were wheel tracks. The field was irrigated by a center pivot system and applications were scheduled through the Michigan Energy Conservation Program. The depth to the B horizon ranged from 28-38 cm and a few sites had some non-uniform crusting. The period of sprinkling infiltrometer and soil testing was between 28 June and 3 August, during which time 16.9-33.2 cm of water was added to the field since tillage.

Field #4, Montcalm loamy sand, is located about 200 m from field #3, in an alfalfa field which had been established for five years. The alfalfa in a small section was killed with 2,4 D and Roundup and it was planted with corn on 9 May. All of the corn received some damage from deer grazing. This "no-till" plot was installed because none other could be located in the county with the correct soil series and field access. These plots were irrigated by the same center pivot as in field #3, and one half of the furrows were wheel track furrows. The depth to the B horizon was over 60 cm and no crusting was observed. The period of sprinkling infiltrometer and soil testing was between 29 June and 2 August, during which time 16.9-33.2 cm of water was added to the field since planting.

Field #5, Montcalm loamy sand, is located NW1/4, SE1/4, SW1/4, Section 8, T11N, R7W of the Michigan meridian, west of Entrican in Montcalm County on the Michigan State University Potato Farm. A MB tillage plot area and a Paratill over MB (PT) tillage plot area were established in 1989 on a section which had been in soybeans the year before, with a fall rye cover crop plowed under on 1 May. The paratill operation was done on 18 May, as was the planting of the potatoes. On 8 June, the plots were hilled. These plots were irrigated by a fixed sprinkler irrigation set. One half the furrows were wheel tracks. The depth to the B horizon was between 22.8-38.1 cm, and very little crusting was recorded. The period of sprinkling infiltrometer and soil testing was between 30 June and 7 August, during which time 12.6 cm of water was added to the field since hilling.

VII. Combining field results with the model

A. Time to ponding function

After the data for each plot were compiled and the parameters a and b were defined (using the method described in the section on the sprinkling infiltrometer), the time to ponding function (as described in the section on model development and use) was used to predict time to ponding for different application patterns. Four parabolic application patterns were combined with the soil parameters for the dry and wet conditions. All four applied the same depth (D_a) but in

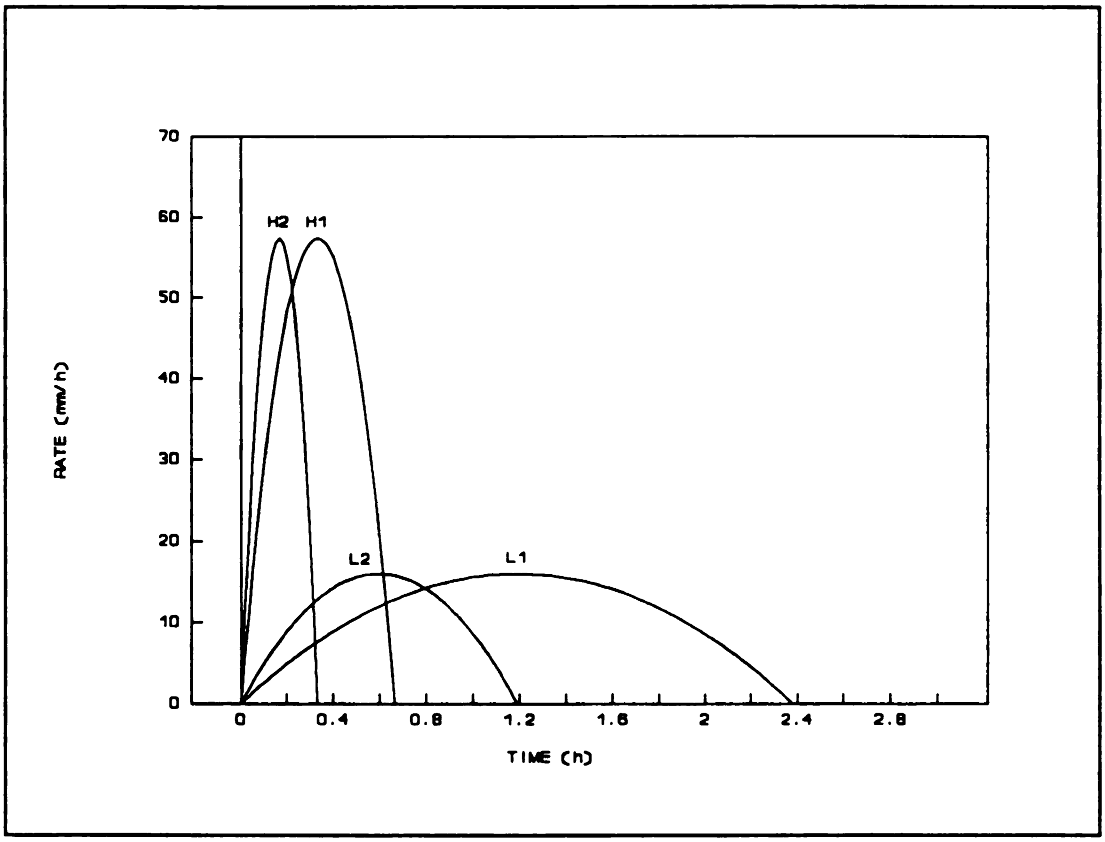

Figure 17. Four application scenarios in the rate vs. time form.

different ways: the first two patterns applied 25.4 mm of water at one time, 25.4 being a depth commonly applied in Michigan. One pattern had a long period (p) and a low maximum application rate (h), and the other had a short period and a high maximum application rate. In the first pattern, p was 2.38 hours and h was 16 mm/h. In the second pattern, p was 0.664 hours and h was 57.4 mm/h. These two patterns describe the minimum and maximum limits of the maximum application rates for 70 of the 80 field systems evaluated in the section on application patterns.

The last two application patterns applied a total cumulative depth of 25.4 mm, but in two applications of 12.7 mm. In each of these, the maximum application rate remained the same, but the period was shortened by one-half per application.

B. The ponded function

Using the rate (r_{tp}) and depth (D_{tp}) associated with the time to ponding (t_p), and the k derived from the soil parameters, the Philip model was used to estimate the infiltration under ponded conditions until the cessation of application (D_p). D_p was added to the depth of infiltration at the time of ponding (D_{tp}) to yield an estimate of total infiltration before the cessation of application (D_{tp}) and as a percentage of the applied depth ($\%D_a$). When ponding did not occur, this part of the model was not engaged. Also when ponding occurred late, or for a short time, the ponded function may have predicted a higher infiltrability than the application pattern delivered. In this case, the infiltration under ponded conditions was of course limited to the supply.

RESULTS AND ANALYSIS

This chapter is divided into four sections. The first section contains a summary of the range of observed application rates, depths, and times to ponding for each field site, tillage treatment, and soil surface texture. The second section contains a summary of the parameters, soil conditions (% residue, θ_i, bulk density), and cumulative water additions for all treatments. The third section contains comparisons of the treatments under the four application scenarios. The fourth section contains a simplified view of the different treatments and scenarios and shows how they can be evaluated if the random roughness and surface storage is known. The complete set of parameters, soil conditions and model output for each scenario and treatment is in Appendix E and the treatment acronyms are described after the list of symbols in the Preliminaries.

I. The range of observations

A summary of the observed application rates, depths, and times associated with the ponded and non-ponded data can be found in Table 11 for every field site, tillage treatment, and soil surface texture (if measured) for 1988 and 1989. The ranges of observation are helpful in evaluating the range of values for which the parameters were calculated.

The shortest t_p's were less than 30 seconds for the highest rates. In Table 11, the "longest t_p" is followed by the measured rate and depth for that particular observation. The longest t_{np} is the longest elapsed time that a particular rate was observed before being turned off. When two or more observations were made at the same t_p, the range of measurements of r_{tp}'s and D_{tp}'s are given, as in the Kalamazoo MB. The greatest depths that infiltrated without ponding for each class are shown at D_{tp} and D_{np}.

Usually the longest t_p or t_{np} is no longer than 60 minutes, as that was the standard length of the testing period. The testing period was extended, however, on two occasions to wait on application rates that seemed likely to pond. That is why two t_{np}'s are more than 60 minutes. In 1988, one of the six dry rates was usually set so that it might result in ponding during the second half of the testing period. In 1989, that strategy was changed to favor a slightly higher range of rates in the dry testing phase and to use lower rates in the wet phase. The range of rates that hovered between ponding and not ponding was usually small in MB, CP and DP, and usually large in the NT. This can be seen by looking at the rates associated with the longest t_p and the longest t_{np} for a given treatment. For example, in the Oshtemo MB, the longest t_p (40 min) is associated with a rate of 14 mm/h, and the longest t_{np} (60 min) is associated with a rate of 13 mm/h. The Montcalm NT, on the other hand, had a longest t_p (16 min) at 30 mm/h, and a longest t_{np} (53 min) at 44 mm/h. Both of these occurrences are frustrating to work with, since the first implies that a very slight adjustment in rate will have a big effect on t_p, and the second implies that the observer will have a hard time interpreting trends during the testing process.

The greatest depths (D_{tp} and D_{np}) that could be applied without ponding within the range of 8 to 83 mm/h seemed to be tillage-dependent within a soil type. For example, on the Oshtemo sl MB, the greatest D_{np} was 11 mm, whereas on the Oshtemo NT, the greatest observed D_{np} was 30 mm.

Table 11. Observed ranges for application rates (r_{tp}), depths (D_{tp}), and times to ponding (t_p) for ponded data and application rates (r_{np}), depths (D_{np}) and elapsed time (t_{np}) for non-ponded data from (n) data pairs. Rates are in mm/h, depths are in mm, and times are in minutes. Both dry and wet observations are included.

Kalamazoo sl.

Field #1.	MB	CP	NT
(n)	(5)	(4)	(4)
Range of r_{tp}	8.1-80	16-80	9.9-81
Greatest D_{tp}	15	22.4	30
Longest t_p, r_{tp}, D_{tp}	40,8.1-23,5.3-15	52,26,22	50,9.9-16,9.9-13
Range of r_{np}	3.8-8.6	9.9-22	8.9-41
Greatest D_{np}	8.6	22	33
Longest t_{np}, r_{np}, D_{np}	70,3.8,4.6	60,22,22	60,10,10

Oshtemo sl.

Field #2.	MB	CP	NT
(n)	(10)	(20)	(10)
Range of r_{tp}	8.4-80	12-91	18-83
Greatest D_{tp}	9.4	15	20
Longest t_p, r_{tp}, D_{tp}	40,14,9.4	56,16,15	27,26,12
Range of r_{np}	6.1-21	12-50	11-81
Greatest D_{np}	11	37	30
Longest t_{np}, r_{np}, D_{np}	60,13,13	74,15,19	60,12,12

Table 11 (cont'd).

Montcalm sl.

Field #3.	MB	DP
(n)	(10)	(10)
Range of r_{tp}	11-120	7.6-120
Greatest D_{tp}	16	3.5
Longest t_p, r_{tp}, D_{tp}	36,11,5.9	15,7.6,1.9
Range of r_{np}	10.5-130	8.4-120
Greatest D_{np}	4.4	1.7
Longest t_{np}, r_{np}, D_{np}	16,13,3.4	8.3,9.3,1.3

Montcalm ls.

Field #4.	NT	
	ls	s
(n)	(6)	(4)
Range of r_{tp}	17-120	17-140
Greatest D_{tp}	9.4	14
Longest t_p, r_{tp}, D_{tp}	16,30,7.9	16,56,14
Range of r_{np}	16-120	9.2-99
Greatest D_{np}	86	53
Longest t_{np}, r_{np}, D_{np}	53,44,39	52,26,22

Montcalm ls.

Field #5.	MB		PT	
	ls	s	ls	s
(n)	(9)	(1)	(7)	(3)
Range of r_{tp}	13-93	18-69	13-97	12-88
Greatest D_{tp}	16	6	11	52
Longest t_p, r_{tp}, D_{tp}	43,13,9.3	19,19,6	43,13,9.3	31,12,6.4
Range of r_{np}	13-22	14-24	13-20	16-19
Greatest D_{np}	17	17	15	3.7
Longest t_{np}, r_{np}, D_{np}	60,14,14	56,18,17	58,16,16	12,19,4

II. Field measurements results

Summaries of the average model parameters and plot characteristics for the treatments measured in 1988 and 1989 can be found in Tables 12, 13 and 14. Table 12 contains the mean SITE calculated DRY parameters, Table 13 contains the COLLECTIVELY calculated DRY parameters, and Table

14 contains the COLLECTIVELY calculated WET parameters. The complete set of parameters and plot characteristics from 1988 and 1989 for all sites and collective sets is in Appendix E. Table 12 contains the number of sites (N) used to determine the mean k (an estimate of conductivity in mm/h, equivalent to the Philip's A value) from parameters a and b calculated for each site. "a" and b are the parameters of the time to ponding function, r^2 is the regression coefficient indicating the goodness of fit of the time to ponding model to the data, and CUMWTR refers to the depth (cm) of water added since the last tillage, or as in the case of NT, since planting. The second N (as in the case of Oshtemo CPW1) indicates the number of tests used to determine the average plot characteristic values such as % residue (RES), θ_i, and bulk density (BD).

N ranges from 2 to 10. There were only 2-3 sites/treatment for the Kalamazoo sandy loam and 5 sites/treatment for all the others since the Kalamazoo field site was originally intended to be used as a testing ground for the sprinkling infiltrometer rather than for data collection.

Although the highest average r^2 (0.97) in Table 12 is associated with the Kalamazoo NTN, this is not typical, since the weighted average r^2 for NT is 0.63. The values for CP are slightly better than for NT, ranging at the site level from 0.46 to 1.00, averaging 0.74. The overall average r^2 for the 80 data sets summarized in Table 12 is 0.86. This high r^2 reflects the greater influence of the tillages which were quicker to pond and which were more aptly fit by the time to ponding function. While it is unfortunate that all the tillages are not as well described as MB, DP, and PT by the model,

Table 12. Means of SITE calculated dry parameters, soil conditions, and applied water.

TREATMENTS	N	r^2	k (mm/h)	% RES	θ_i	BD	CUMWTR (cm)
#1.Kalamazoo sl.							
MBW	2	0.93	2.7	3	14.7	1.38	4.1
MBN	3	0.91	3.8	6	9.1	1.03	3.9
MB	5	0.92	3.2	4	11.9	1.20	4.0
CPW	2	0.83	6.9	17	14.5	1.40	4.1
CPN	2	0.65	11.3	19	6.4	1.02	4.1
CP	4	0.74	9.1	18	10.5	1.21	4.1
NTW	1,2	0.53	14.8	100	23.6	1.42	4.1
NTN	2	0.97	12.0	100	20.8	1.32	4.4
NT	3,4	0.75	13.4	100	22.2	1.37	4.3
#2. Oshtemo sl.							
MBW	5	0.92	3.6	4	11.9	1.40	21.6
MBN	5	0.89	4.3	6	12.6	1.23	21.6
MB	10	0.91	4.0	5	12.3	1.31	21.6
CPW1	3,5	0.76	6.5	65	13.7	1.15	12.2
CPN1	5	0.88	10.2	62	7.7	1.19	12.2
CP1	8,10	0.82	8.2	63	10.7	1.17	12.2
CPW2	4,5	0.66	4.7	60	14.9	1.22	22.4
CPN2	5	0.68	13.1	68	12.4	1.07	22.1
CP2	9,10	0.67	9.8	64	13.7	1.15	22.3
NTW	5	0.59	10.4	92	15.4	1.41	22.4
NTN	5	0.59	9.4	97	17.1	1.35	21.8
NT	10	0.59	9.9	94	16.2	1.38	22.1
#3. Montcalm sl.							
MBW	4,5	0.86	2.2	1	7.7	1.48	26.8
MBN	5	0.95	3.0	2	6.4	1.35	26.8
MB	9,10	0.90	2.6	1	7.1	1.41	26.8
DPW	4,5	0.90	2.4	1	11.5	1.54	26.9
DPN	5	0.94	2.1	7	11.1	1.38	26.2
DP	9,10	0.92	2.3	4	11.3	1.46	26.6
#4. Montcalm ls.							
NTW	4,5		27.3	78	8.7	1.42	26.7
NTN	5		25.0	74	10.5	1.44	26.9
NT	9,10		26.2	76	9.6	1.43	26.8
#5. Montcalm ls.							
PMBW	5	0.92	6.0	8	12.7	1.55	12.5
PMBN	5	0.93	4.6	6	10.9	1.32	12.5
PMB	10	0.93	5.3	7	11.8	1.44	12.5
PPTW	5	0.85	5.1	10	13.0	1.59	12.6
PPTN	5	0.92	6.3	11	10.8	1.32	12.6
PPT	10	0.89	5.7	10	11.9	1.46	12.6

since MB and DP are the most widespread of the tillage practices in Michigan, it is fortunate that the model fits them well, with an average r^2 always greater than 0.85.

The k value is used in the ponded portion of the infiltration model and represents the sprinkled rate which is predicted to cause ponding after 180 minutes, using parameters a and b as input to the time to ponding function. Parameters a and b were estimated from both ponded and unponded pairs, and so k, too, is a product of ponded and unponded information. "k" can be used to summarize the effect of both parameters and to give a sense of relative infiltrability.

Disregarding soil types, it is interesting to see the order of tillages associated with the different k values in Table 12. The absolute lowest estimates of k are associated with the disk plow, at only 2.1 to 2.4 mm/h. The next lowest estimates are the (P)MB and the PPT, with averages between 2.2 and 6.3 mm/h. The highest are the NT and CPN, with averages between 9.4-to 27.3 mm/h.

There are six natural intervals into which the estimates of percent residue fall. These are: 1-7% for MB and DP; 6-11% for PPT and PMB; 17-19% for the Kalamazoo sl CP; 60-68% for Oshtemo sl CP; 74-78% for NT in the Montcalm alfalfa field; and 92-100 for NT established in corn residue. The higher values for the potato crop came about because at one point in the season, many leaves fell off the plants, leaving a temporarily increased residue level. The difference in the % of residue between the two CP's may have been because the Kalamazoo field site was fall plowed, and the Oshtemo field site was not only spring plowed, but converted from NT. If all the treatment k's (N=99) are regressed

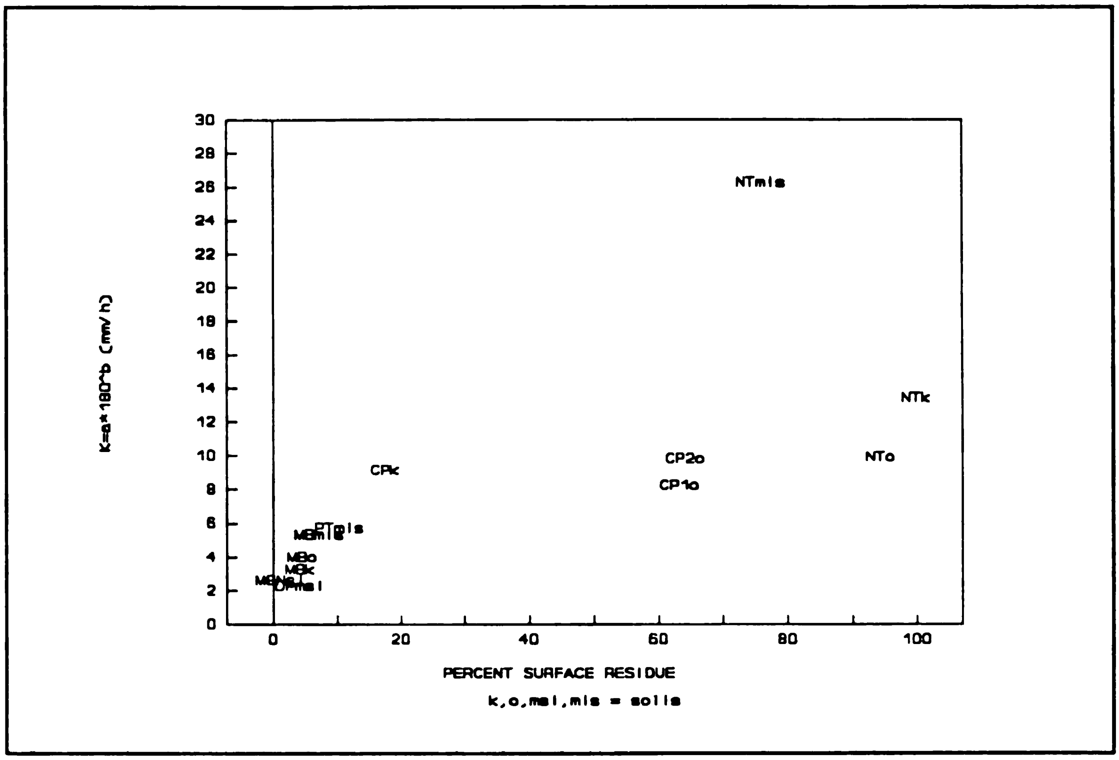

Figure 18. Percent surface residue vs. k.

all the average k's are linearly regressed against the average % residue values, the regression coefficient is 0.497. Figure 18 shows the mean site treatment k plotted against % residue. The r^2 for all the treatments shown in the figure is 0.449. The average r^2 within a soil type is 0.338 and is greatest when the soil included no-tillage, but decreases to an average of 0.099 within tillage types. It is clear that some relationship between residue levels and pre-ponded infiltration exists, but it is not clear how it can be included as an explicit part of the model until it is measured experimentally under controlled conditions. As it is now, the values for the parameters a and b intrinsically adjust for the residue status.

The highest average values for percent soil moisture by volume at soil surface (21-24%) were found in the Oshtemo NT even though it was during the driest year in recent history and had received only an average of 4.1 cm of water since tillage. This NT was on a sandy loam and had been established for four years. High θ_i is generally associated with high bulk density and high percentages of residue. A different tillage treatment was measured every working day in a cyclical rotation so that the soil moistures would be as variable as possible within any replicated set of conditions and the average moistures as similar as possible between treatments over a season.

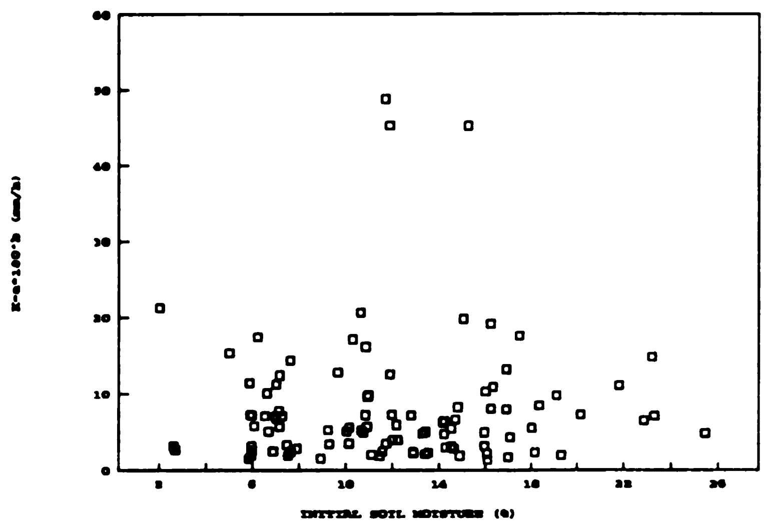

Figure 19. Initial soil volumetric soil moisture vs. k, all sites measured.

When all treatment k's were regressed against all θ_i values, the r^2 was 0.000. (See Figure 19). The average within soils (all sites) was 0.016 and the average r^2 within tillages was 0.165. The coefficients of variation of θ_i (Appendix E) for all the treatments varied from 2 to 54, with 12 of the 24 treatments falling between 22 and 32 CV. Three of the treatments had a coefficient of variation of 29: CPN2, DPW, and PMBN. These were closely examined to see if θ_i was correlated with k. The r^2's were 0.124, 0.612, and 0.485, respectively.

The average bulk de121nsities of the treatments in which infiltrometer tests were also made ranged from 1.02 to 1.59. Ten out of the 24 replicated treatments averaged 1.40 or greater. All except one of these was a wheel track, and that was a NT. The treatments with averages over 1.50 were not NT, but MB, DP, and PT wheel tracks. NT averages ranged from 1.32 to 1.48. Some of the highest and some of the lowest mean values for k are associated with those treatments with average bulk densities over 1.40. For example, the Montcalm ls NTW had a k of 27.5 mm/h and a bulk density of 1.42, while the Montcalm sl MBW and DPW had k's of 2.2 and 2.4 mm/h and bulk densities of 1.48 and 1.54.

When all site k's and BD's were regressed, the r^2 was 0.000. When all sites within tillages were regressed, the average r^2 was 0.130, and when all sites within soils were regressed, the average r^2 was 0.041. This would indicate that BD and infiltrability are poorly correlated in general.

Three treatments, Montcalm ls NTW, Oshtemo CPW1, and Montcalm sl DPN, were selected for closer analysis of within-set relationships between bulk density and k. The NTW set was chosen because it represented the highest value of k, the DPN the lowest k, and CPW1, a set with a mid-value of k. The r^2 for NTW was 0.511, for CPW1, 0.54, and for DPN, 0.151. The correlation for NTW and DPN was positive, indicating higher values of k with higher values of BD!

During the 1988 season, much time was spent characterizing the changes in BD for the Oshtemo MB and CP tillages. Although BD did not turn out to be important in predicting time to ponding, the results of the BD measurements were interesting. Each tillage/furrow set measured by the modified Grossman method was compared to the others using the t-test with alpha equal to 0.05 (USDA 1962). Treatments proven to be significantly different from others are indicated in the following list of statements about BD over the season as inequalities. Those with insignificant differences are indicated as equalities and were later grouped with other treatments into larger sets and compared.

General statements about the Oshtemo ls tillage/furrow BD's:

1. MBW > MBN at any time during the season.
2. MBW did not change from the beginning of the season to the end.
3. Early MBN < late MBN, but it changed so gradually as to not be significantly different from early to mid-season or from mid-season to late season.
4. In mid-season CPW = CPN. Mid-CPN > late CPN, and in the late season, CPW > CPN because of the CPN decrease in density.
5. At any time during the season, NTW = NTN. Early NT = late NT.
6. MBW at any time = NT.

7. MBW > CPW at any time.

8. It follows that CPW < NTW at any time.

9. MBN < NTN at any time.

10. All CP < all NT during the mid season.

Grouped values of BD for the Oshtemo ls (g/cm^3):

Mid and early season			Late season		
Group	Mean	Range (95% c.l.)	Group	Mean	Range (95% c.l.)
NT-MBW	1.37	1.32-1.42	NT-MBW	1.32	1.25-1.39
CP-MBN	1.11	0.90-1.32	CPW-MBN	1.22	1.15-1.29
			CPN	1.07	1.03-1.11

CUMWTR varied from 3.9 to 26.9 cm. With the exception of the Kalamazoo tests, most of the treatments averaged between 12.2 and 26.9 cm of water added by rainfall and irrigation.

Because no or only weak correlations existed between k and bd, θ_i, and % res on a mean site basis, data pairs from every site were pooled together (total pairs = n) to calculate collective parameters a,b and k. See Table 13. Since both non-ponded and ponded data pairs were included in the determination of a single a, b and k per treatment, the r^2 shown in Table 13 do not represent the variation of the ponded data, but are included to give the reader a sense of the goodness of fit between the model and the entire set of data pairs used. The average soil conditions for each treatment in the two tables are the same.

The error in the prediction of the rate at the time to ponding by the model is indicated by the values of SEln(r). These values are added to or subtracted from the predicted natural log of the rate

Table 13. Summary of plot characteristics, tp parameters and predicted values for COLLECTIVE DRY data pairs (n).

	% RES	θ_i	BD	a	b	r2	SEln(r)	n	k
#1. Kalamazoo sl.									
MBW	3	14.7	1.38	84.2	-0.652	0.92	0.166	12	2.9
MBN	6	9.1	1.03	292.5	-0.838	0.76	0.391	12	3.8
MB	4	11.9	1.20	117.3	-0.649	0.57	0.468	24	4.0
CPW	17	14.5	1.40	84.3	-0.508	0.80	0.161	12	6.0
CPN	19	6.4	1.02	98.9	-0.398	0.71	0.254	12	12.5
CP	18	10.5	1.21	76.3	-0.387	0.56	0.136	24	10.2
NTW	100	23.6	1.42	376.6	-0.844	0.56	0.444	12	4.7
NTN	100	20.8	1.32	104.4	-0.397	0.32	0.449	12	13.3
NT	100	22.2	1.37	189.6	-0.620	0.45	0.466	24	7.6
#2. Oshtemo sl.									
MBW	4	11.9	1.40	87.8	-0.588	0.85	0.198	30	4.1
MBN	6	12.6	1.23	99.2	-0.557	0.87	0.197	29	5.5
MB	5	12.3	1.31	91.5	-0.562	0.83	0.214	59	4.9
CPW1	65	13.7	1.15	99.2	-0.496	0.72	0.294	29	7.5
CPN1	62	7.7	1.19	98.8	-0.402	0.66	0.664	28	12.3
CP1	62	12.1	1.18	94.9	-0.430	0.65	0.322	57	10.2
CPW2	60	14.9	1.22	77.9	-0.441	0.74	0.293	26	7.9
CPN2	68	12.4	1.07	82.7	-0.362	0.66	0.34	29	12.6
CP2	63	11.8	1.17	75.9	-0.370	0.66	0.334	56	11.1
NTW	92	15.4	1.41	116.6	-0.460	0.74	0.279	26	10.7
NTN	97	17.1	1.35	118.7	-0.411	0.69	0.32	26	14.0
NT	94	16.2	1.38	116.0	-0.414	0.67	0.315	52	13.5
#3. Montcalm sl.									
MBW	1	7.7	1.48	104.7	-0.703	0.84	0.246	24	2.7
MBN	2	6.4	1.35	115.2	-0.680	0.92	0.196	30	3.4
MB	1	7.1	1.41	109.9	-0.686	0.88	0.225	54	3.1
DPW	1	11.5	1.54	107.8	-0.817	0.88	0.237	30	1.5
DPN	7	11.1	1.38	79.5	-0.680	0.91	0.18	30	2.3
DP	4	11.3	1.46	89.9	-0.730	0.87	0.226	60	2.0
#4. Montcalm ls.									
NTW	78	8.7	1.42	101.4	-0.296	0.39	0.395	22	21.8
NTN	74	10.5	1.44	101.1	-0.263	0.56	0.284	22	25.8
NT	76	9.6	1.43	102.5	-0.286	0.51	0.339	44	23.2
#5. Montcalm ls.									
PMBW	8	12.7	1.55	73.0	-0.444	0.83	0.21	30	7.3
PMBN	6	10.9	1.32	100.2	-0.552	0.78	0.276	29	5.7
PMB	7	11.8	1.44	84.4	-0.491	0.79	0.251	59	6.6
PPTW	10	13.0	1.59	80.9	-0.512	0.74	0.289	30	5.7
PPTN	11	10.8	1.32	89.7	-0.494	0.83	0.21	30	6.9
PPT	10	11.9	1.46	85.4	-0.504	0.77	0.257	60	6.2

because ln r was regressed against ln t. To get the error of a predicted rate, such as k for example, one needs to multiply or divide the predicted rate by e to the SEln(r). For example, for the Kalamazoo MBW, the predicted k, or rate at 180 minutes, is 2.9 mm/h. The lower limit of the error is $2.9/(e^{0.166})$, or 2.4, and the upper limit would be 3.4. Likewise, the upper and lower limits of the Kalamazoo MBN k (3.8) would be 5.6 and 2.5. Figure 20 shows the standard error of the estimated rate of a treatment with a relatively small error (0.226) and Figure 21 shows a treatment with a large error (0.334).

Twenty six of the 36 k values increased when the data were evaluated collectively. The collective parameters are presented in combination with the four application scenarios in Appendix E, Tables

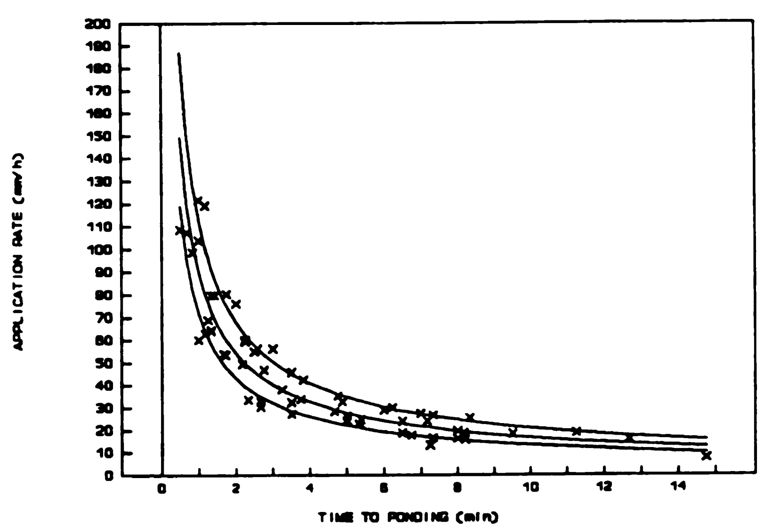

Figure 20. Upper and lower limits of a disk plowed time to ponding curve.

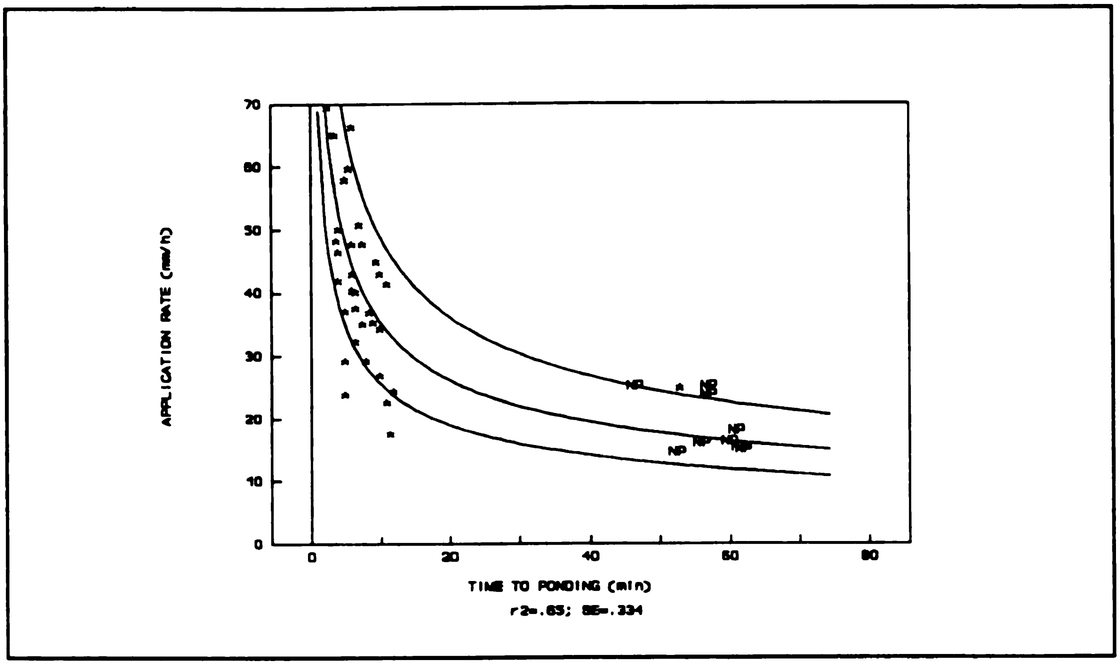

Figure 21. Upper and lower limits of a chisel-plowed Oshtemo
time to ponding function.

5-8. The collective parameters in Table 13 are used to make general statements about the soils and tillages for the purposes of evaluating the current recommendation strategies and proposing guidelines based upon the measured data.

Table 14 is included as a parallel to Table 13. Before the adaptation of the rate vs. cumulative depth idea, the wet data pairs were thought to be similar to one another in the sense that they had the same initial moisture conditions (near saturation) and could be used collectively. In light of the model used here, their previous infiltration history IS important, so the reader is cautioned against employing the table except to notice that the parameter a is generally much lower than the parameter a in Table 13.

Table 14. Summary of collective wet data and t_p parameters.

Kalamazoo sl.

Field #1. Wet testing not done.

Oshtemo sl.

Field #2.

	a	b	r^2	k (mm/h)	% RES	BD	CUMWTR (cm)
MBW	46.33	-0.520	0.70	3.1	4	1.40	21.6
MBN	47.74	-0.550	0.73	2.7	6	1.23	21.6
CPW1	81.84	-0.629	0.44	3.1	65	1.15	12.2
CPW2	50.14	-0.469	0.40	4.4	60	1.22	22.4
CPN1	56.53	-0.226	0.30	17.5	62	1.19	12.2
CPN2	55.97	-0.274	0.41	13.5	68	1.07	22.1
NTW	60.87	-0.390	0.51	8.0	92	1.41	22.4
NTN	60.27	-0.240	0.20	17.3	97	1.35	21.8

Montcalm sl.

Field #3.

	a	b	r^2	k (mm/h)	% RES	BD	CUMWTR (cm)
MBW	36.7	-0.601	0.61	1.6	1	1.48	26.8
MBN	44.2	-0.563	0.57	2.4	2	1.35	26.8
DPW	41.8	-0.722	0.75	1.0	1	1.54	26.9
DPN	33.2	-0.577	0.70	1.7	7	1.38	26.2

Montcalm ls.

Field #4.

	a	b	r^2	k (mm/h)	% RES	BD	CUMWTR (cm)
NTW	94.1	-0.249	0.13	25.8	78	1.42	26.7
NTN	81.6	-0.420	0.48	9.2	74	1.44	26.9

Field #5.

	a	b	r^2	k (mm/h)	% RES	BD	CUMWTR (cm)
PMBW	48.8	-0.561	0.74	2.7	8	1.55	125
PMBN	46.4	-0.503	0.76	3.4	6	1.32	125
PPTW	40.1	-0.543	0.69	2.4	10	1.59	126
PPTN	46.1	-0.493	0.70	3.6	11	1.32	126

III. Treatment comparisons

This next section describes the collective tp functions plotted first by soil type and then by tillage. The collective functions represent the parameters a and b in Table 13 which describe entire sets of data pairs for a particular treatment. Because the error of the predicted time to ponding associated with the tp root equation (Eq 19) is so difficult to solve, differences between treatments in the following sections are described in terms of the significance between parallel sets of site predictions of %Dtp and %Dtot. For example, the set of predicted %Dtp for Kalamazoo MBN (n=5) is compared to the set of predicted %Dtp for Kalamazoo CPN for all four scenarios. Every soil-tillage treatment is therefore tested in 16 comparisons, (2 wheel track conditions, 2 predicted values, and 4 application scenarios) each found significant or non-significant in t-tests with alpha equal to at least 0.1. When a wheel track set is compared to a non-wheel track set, there are only 8 comparisons (2 predicted values and 4 scenarios). For the sake of brevity, if a particular comparison is significant more than half the time, it will be referred to as strongly significant; more than one quarter to one-half of the time, fairly significant. Because the site t-tests did not allow comparison of tillages without regard to wheel track condition, they are similar, but not identical, to the collective soil-tillage functions.

A. Comparing tillages on the same soil.

This next section describes the Figures 22 through 25, where the collective tillage functions are plotted for each of the four soils studied.

a) Kalamazoo sandy loam.

Figure 22 shows three tillages on the Kalamazoo sandy loam: NT, CP and MB. The times to ponding for a particular application rate are longest for NT and shortest for MB. The site t-tests show that differences in cumulative infiltrated depth at time to ponding and at the end of the application are fairly significant between MB and CP and between MB and NT. The collective functions in Figure 22 show the most difference between time to ponding for MB and CP at lower rates, the most difference between CP and NT at higher rates, and a difference between MB and NT at all rates.

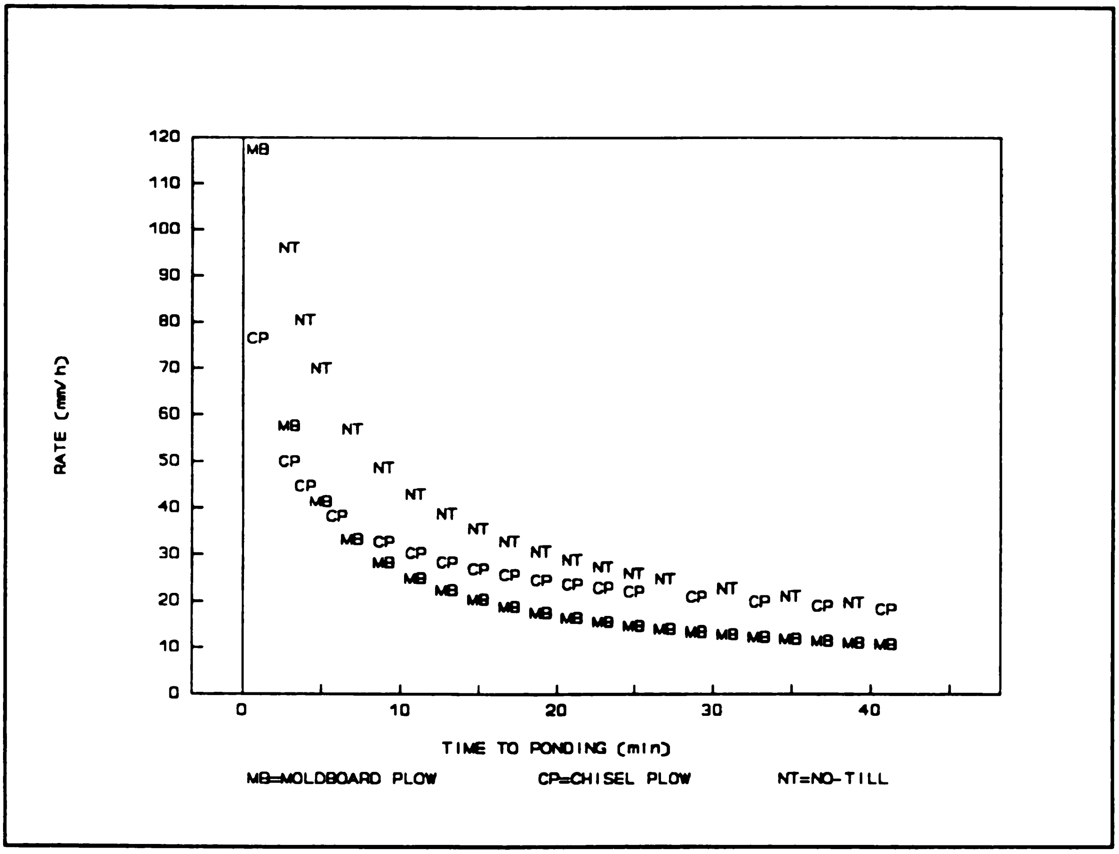

Figure 22. Time to ponding curves for three tillages on the Kalamazoo sandy loam.

b) Oshtemo sandy loam.

Figure 23 shows the same three tillages on the Oshtemo sandy loam, in the same order as on the Kalamazoo soil. The t-tests for this soil reveal much the same level of significance in cumulative infiltrated depths between MB and CP as on the Kalamazoo, but strong significant differences between MB and NT. The collective function shows large differences in CP and NT for all rates.

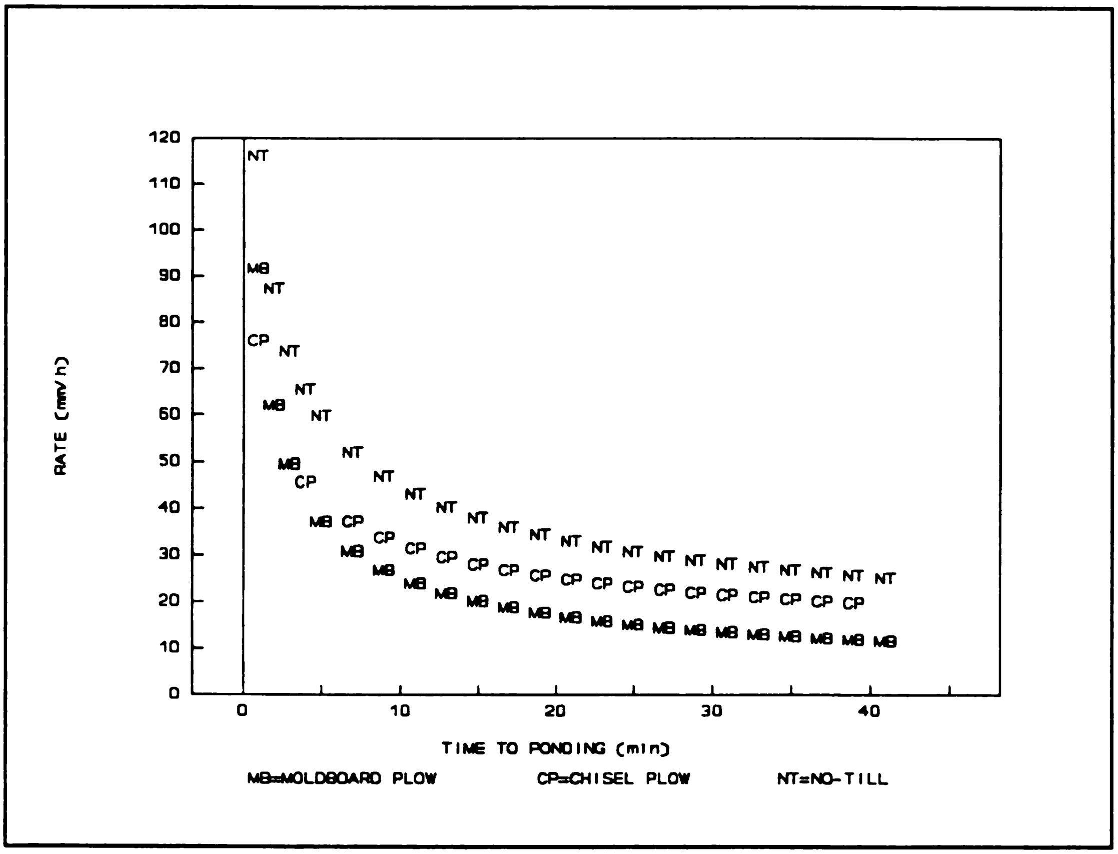

Figure 23. Time to ponding curves for three tillages on the Oshtemo sandy loam.

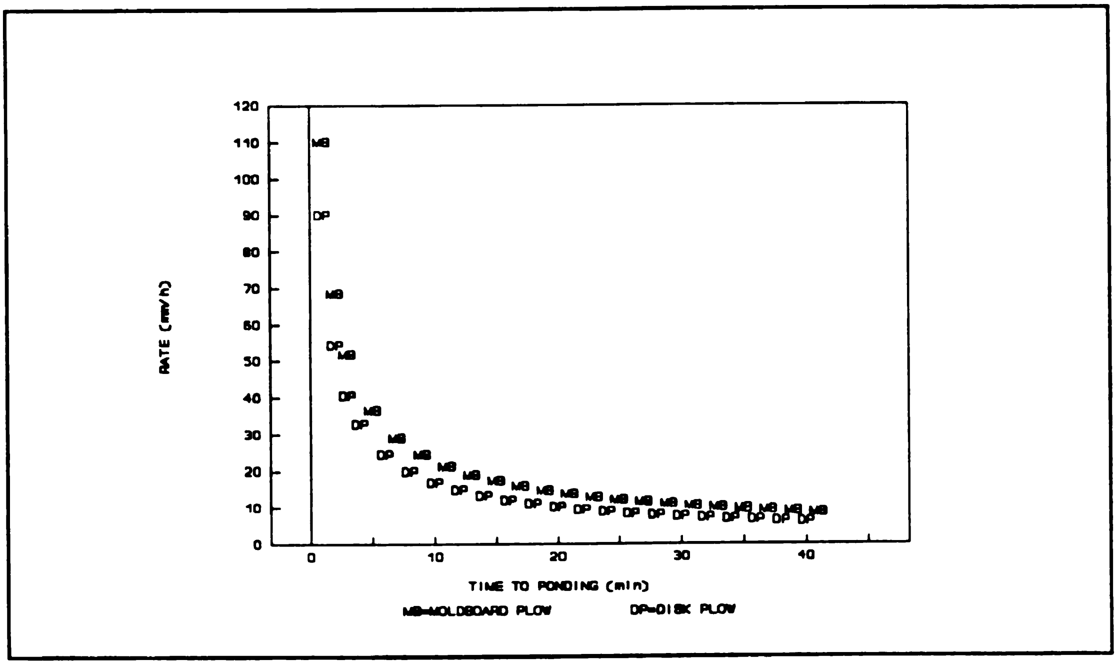

Figure 24. Time to ponding curves for two tillages on the Montcalm sandy loam.

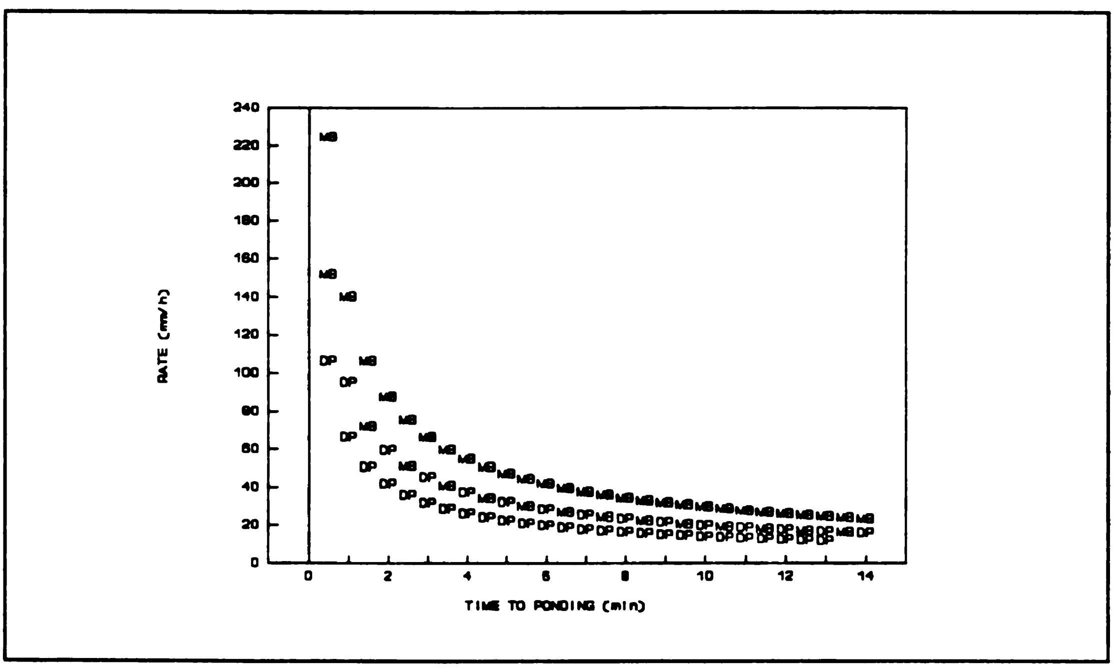

Figure 25. Time to ponding curves for moldboard and disk plow on non-wheel tracks, Montcalm sandy loam.

c) Montcalm sandy loam.

DP was mistakenly installed into the plot area set aside for CP on the Montcalm sandy loam. Though it kept us from maintaining a consistent set of tillages across soils, it was useful to compare with the MB because it is "the conventional tillage" in some parts of Michigan. Figure 24 shows the MB and DP tillages on the Montcalm sandy loam, with MB times to ponding greater than DP times to ponding for all rates. The t-tests for this soil reveal a strong level of significance in cumulative infiltrated depths between the two tillages, due mostly to the differences in the infiltrabilities of the non-wheel track treatments. Figure 25 illustrates how the lower limit of the error of the predicted rates for the MBN lies on the upper limit of the error of the predicted rates for the DPN. The significance of the difference between these two treatments is mostly a function of the small error associated with each treatment. It is worthwhile to remember here that the MB field site had been previously disked for three years.

d) Montcalm loamy sand.

Figure 26 shows three tillages measured on the Montcalm loamy sand: NT, MB and PT. Paratilling (PT) is a type of deep tillage where long shanks are pulled through the soil at 28" intervals, creating planar voids under the rows. Neither the collective function nor the site t-tests reveal differences between the MB and PT tillages. On the other hand, the collective function shows the expected times to ponding to be greater for the NT tillage than for either the MB or the PT. The site t-tests show strong significant differences in the

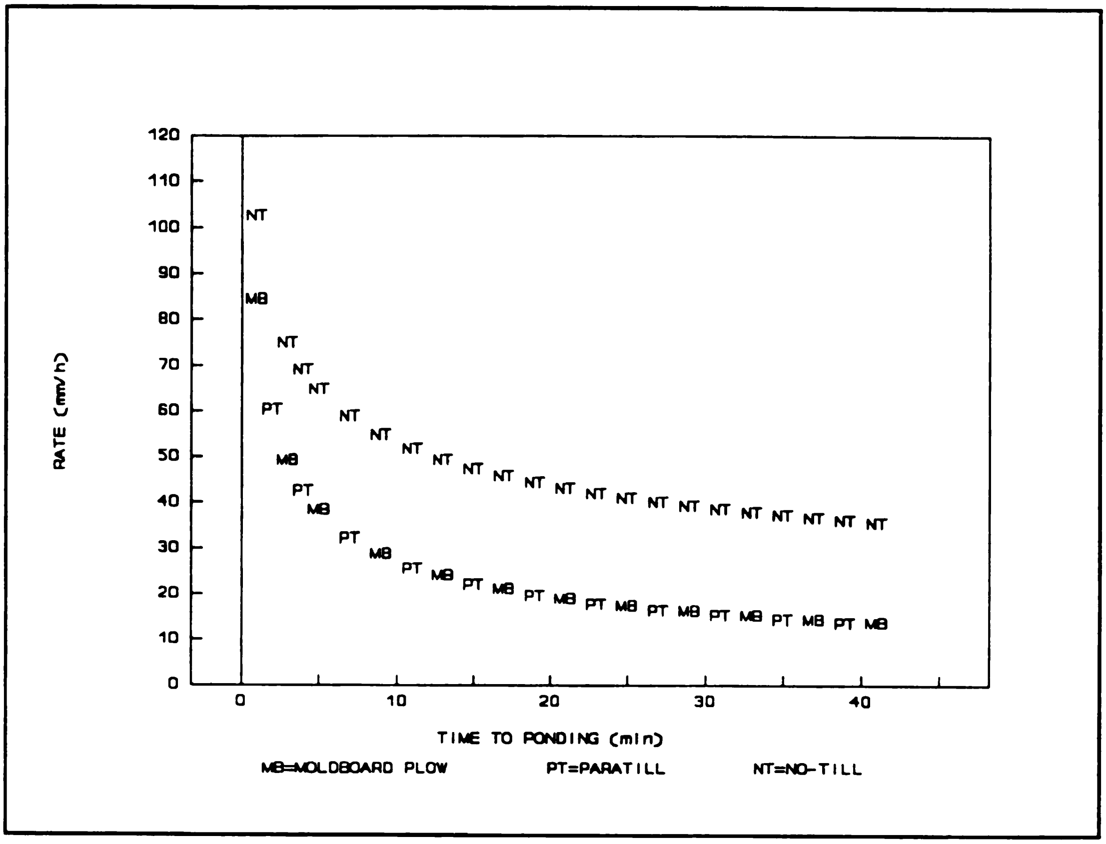

Figure 26. Time to ponding curves for three tillages on the Montcalm loamy sand.

cumulative depths at ponding and at the end of the application period between NT and the MB and PT tillages.

B. Comparing a particular tillage across soils.

Figures 27-29 show the tillage collective functions for every soil on which it was studied. These figures are rearrangements of Figures 22-25, with the underlying parameters a and b found in Table 13.

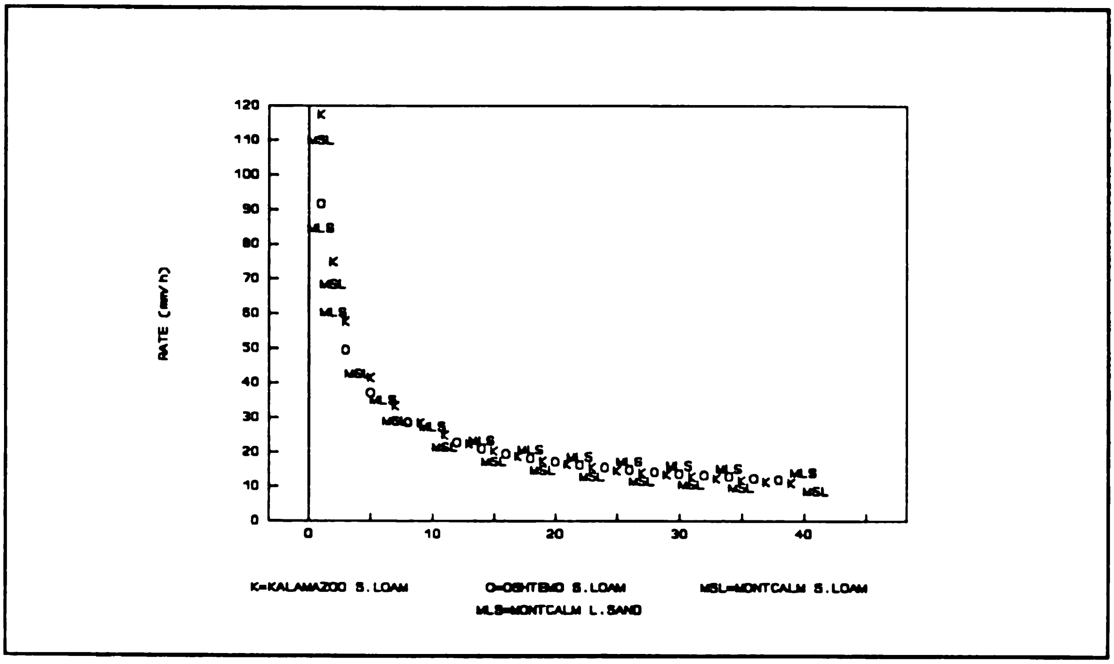

Figure 27. Time to ponding curves for moldboard plow on four soils.

a) Moldboard plow

Figure 27 shows the MB tillage functions for the four soils in close proximity to one another, with Montcalm sandy loam (MSL) on the bottom and Montcalm loamy sand (MLS) at the top. Because of the small variance associated with the MB tillage, a fair level of significant difference can be found between MSL and MLS depths.

b) Chisel plow

Figure 28 shows the chisel tillage collective functions for Kalamazoo and Oshtemo soils to be the same. The site t-tests show no significant differences between soils.

c) No-till

Figure 29 shows the no-till collective functions for Kalamazoo and Oshtemo sandy loams and Montcalm loamy sand.

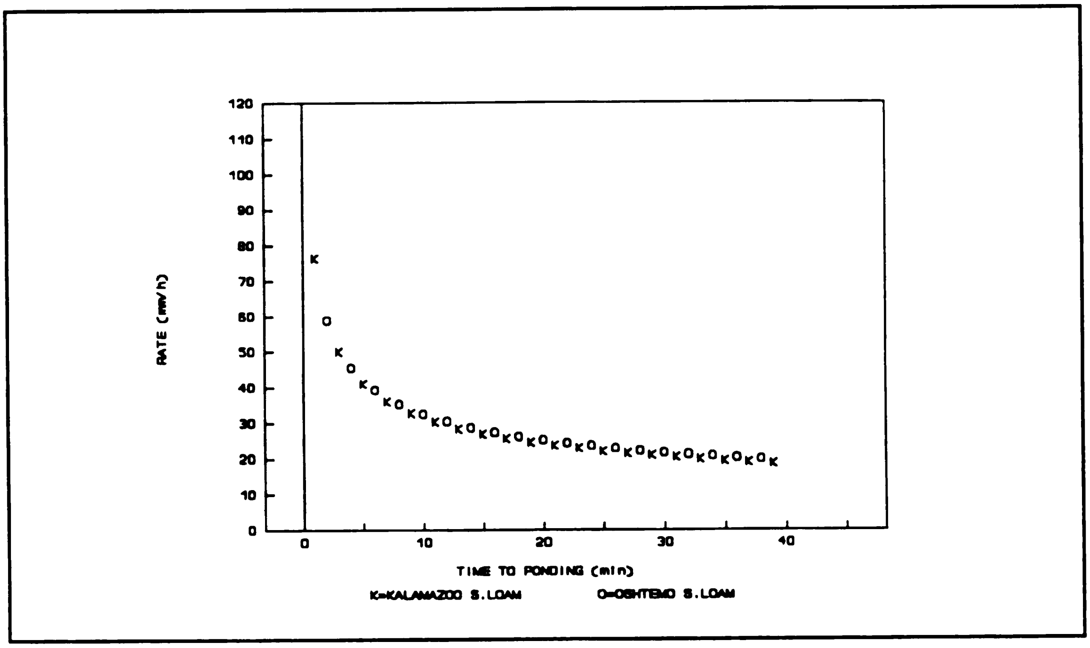

Figure 28. Time to ponding curves for chisel plow on two soils.

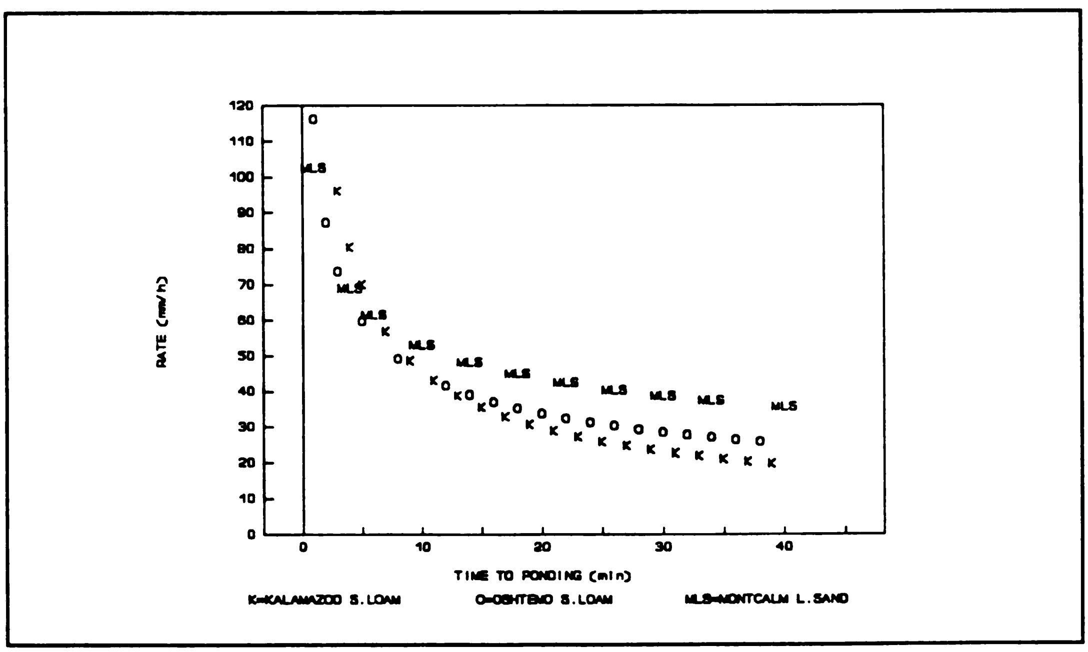

Figure 29. Time to ponding curves for no-till on three soils.

Although the sandy loams seem distinctly different from the loamy sand in the collective time to ponding functions, the large variance associated with NT makes the site differences generally insignificant, with the exception of a fair level of significance between the wheel track on Oshtemo and Montcalm loamy sands.

C. Mid vs late season infiltration

The 1988 Oshtemo sl field site was the only field site where both mid and late season infiltration experiments were conducted. The mid season tests were done between 24-30 June, and the late season tests were done between 15 July and 11 August. The cumulative water additions in the mid season period ranged between 12.2 to 12.4 cm, and in the second period, between 16.2 and 29.4 cm.

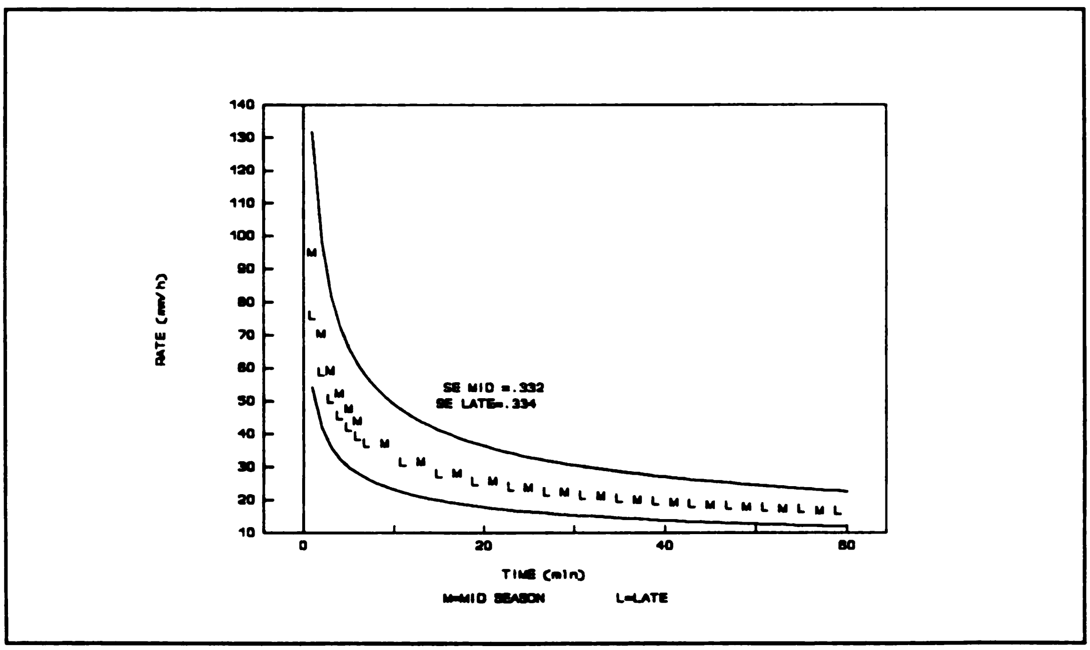

Figure 30. Mid vs. late season time to ponding curves for chisel plow on Oshtemo sandy loam.

Figure 30 shows the collective time to ponding functions for the mid and late season CP measurements. The expected times to ponding for both were about the same, with the same predicted error (SE) for both. Likewise, the site comparisons of predicted cumulative depth at time to ponding and at the end of application revealed no significant differences.

In addition to the CP comparison, several sets of soil/tillage/wheel track combinations containing five replicates each were sorted within the set according to date to see if there was any trend to be found with regard to t_p, θ_i, BD, crusting, and cumulative water added since last tillage. The Montcalm sl MBN, Oshtemo sl MBN, and Montcalm ls MBN were each sorted by date and examined, but no general trends were observed.

D. Wheel track vs non-wheel track.

Site comparisons were made between wheel track and non-wheel track sets of predictions for cumulative depth at the time of ponding and at the end of the application period. Strong differences were found for DP on Montcalm sandy loam and fair differences for the MB and CP on the sandy loams. Negligible differences between wheel track and non-wheel track were found for MB and PT on loamy sands and all NT.

IV. Linking with surface storage

Table 15 gives a simplified view of the model predictions for all soil treatments under each application scenario by showing four levels of ponding: A) no ponding at any time, B) some ponding during the application period, C) less than or equal to 2 mm of ponding depth at the end of the application period, and ---), more than 2 mm of ponding at the end of the application period.

Recall that Lindstrom and Onstad (1984) estimated the average random roughness on planted fields in the Corn Belt to be about 10 mm. Lindstrom in his Ph.D. dissertation (1979, as cited by Linden and Van Doren 1986) predicts 2.0 mm of surface storage at 2% slope for a random roughness of 10 mm, and 0.6 mm of surface storage at 6%. Remember that the model prediction are based on mean treatment functions. Thus even the A level of ponding still implies some ponding over 50% of the area. An example of how the model can be used to make decisions can be illustrated by using the Lindstrom and Onstad average random roughness estimate and the Lindstrom random roughness-surface storage relationship in Table 16.

Table 15. Summary of ponding during and at the end of the sprinkled application period.

	H1	H2	L1	L2
KALAMAZOO S.LOAM				
MB	---	---	---	B
CP	---	---	B	A
NT	---	B	B	A
OSHTEMO S.LOAM				
MB	---	---	---	B
CP	---	---	A	A
NT	---	B	A	A
MONTCALM S.LOAM				
MB	---	---	---	C
DP	---	---	---	---
MONTCALM L.SAND				
MB	---	---	B	B
PT	---	---	C	B
NT	---	B	A	A

A = NO PONDING THROUGHOUT APPLICATION PERIOD
B = NO PONDING AT THE END OF THE APPLICATION PERIOD
C = 2 mm or LESS PONDING DEPTH AT THE END OF THE APPLICATION PERIOD.
H1 = 57.4mm/h MAX RATE,1x25.4mm AMOUNT;
H2 = 57.4mm/h, 2x12.7mm;
L1 = 16 mm/h,1x25.4mm;
L2 = 16mm/h,2x12.7mm

Table 16. Ponding levels, surface storage and slope for surface with a random roughness of 10 mm.

SLOPE (%)	SURFACE STORAGE (mm)	ASSIGNED PONDING LEVEL
0-2	2.0-2.3	C
2-6	0.6-2.0	B
>6	<0.6	A

Two decision table were constructed to detail the alternatives intrinsic to Tables 15 and 16. The first table assumed a soil, range of slopes, and tillage system, and selected the appropriate irrigation strategy and rate. The second assumed a soil, range of slopes, and irrigation rate, and selected the appropriate irrigation strategy and tillage system. The following is a summary of the outcomes of the two decision tables based on the measurements and model.

1. Disk plowing on the Montcalm sandy loam is incompatible with sprinkler irrigation.

2. Moldboard plowing on the Montcalm sandy loam following disking should only be practiced on slopes no greater than 2% in combination with a low rate and an application depth of 12.7 mm.

3. High rate irrigation systems should only be used with no-tillage systems on slopes no greater than 6% and an application depth of 12.7 mm.

4. Moldboard plowing on soils other than the Montcalm sl should be restricted to slopes less than 6% and be used in combination with low rate systems, applying only 12.7 mm at a time on sandy loams.

5. On slopes greater than 6%, no-tillage in combination with a low rate system and applying 12.7 mm at a time is acceptable for all soils where NT was measured.

6. For slopes greater than 6% on the Montcalm loamy sand, 25.4 mm at a time can be applied in combination with NT. On the Oshtemo, either depth can be applied to CP and NT at low rates. On the Kalamazoo, 12.7 mm can be applied to CP and NT at low rates.

7. For slopes between 2% and 6% on any soil, if a high rate system must be used, it should be used in conjunction with no-till and at

depths of 12.7 mm. If a depth of 25.4 mm is necessary, for sandy loams, a low rate applied onto no-till or chisel plowed soil is acceptable. For loamy sands, a low rate on either NT or MB is acceptable. If a low rate system is used at a depth of 12.7 mm, any tillage system except DP is acceptable.

If better information concerning random roughness and surface storage is obtained, Level C can be easily reinterpreted by looking at Appendix E, Tables 5-8 to create a more appropriate set of tables like 15 and 16 from which decision tables can be constructed and summarized. For a more precise understanding of the rates which result in level A ponding, review the section on the current recommendations in the Methods chapter.

DISCUSSION

This chapter will address the merits of the work and discuss some of its limitations. A few ideas for future research will be presented.

I. Discussion of the work itself

A. Major contributions

1. The time to ponding function

The most notable difference between this work and others is the use of a field-measured time to ponding (t_p) function as input to an infiltration model. This function is a high quality representation of field conditions important to preponded sprinkler infiltrability and can be obtained in a variety of ways. The function represents the dominant tillages on the dominant irrigated soil series very well. It automatically incorporates the effect of residue and tillage. It obviates the need for measurements of saturated hydraulic conductivity, sorptivity, suction behind the wetting front, initial volumetric soil surface moisture, saturated volumetric soil moisture and a number of ever-increasing variables required by complex physical models, whose determinations are often doubtful, whose meanings are often difficult to explain, and whose predictive values are unmeasured. Estimates of sorptivity and hydraulic conductivity can be calculated from the function if desired, and those estimates will be based on several observations. The determination of the t_p function is relatively easy and requires no laboratory measurements or equipment. At this point in our understanding of infiltration under sprinkling, an hour spent measuring this function will be better spent than an hour spent conjecturing it from estimated soil properties, if the result is to be used for real application purposes, such as selecting an irrigation system or evaluating alternatives for improvement of infiltrability. Records of this function for the Michigan soil conditions tested will be invaluable in the future as ground truth for testing promising physical models as they become available.

2. Determining the t_p function

The controllable sprinkling infiltrometer evolved during this study is inexpensive, reliable, fast, and easy to use. It has the potential for not only obtaining basic measurements for the soil t_p function, but also for testing assumptions used in infiltration models, like the assumptions involved with predicting the time to ponding for a variable application rate pattern.

Irrigation companies could use the infiltrometer to measure a field t_p function before designing a system. Records of the functions for different soils and tillages could be compiled until a comprehensive predictive model was developed that could duplicate the information value by simpler means.

Irrigation system evaluators could use the installed irrigation system operating in a stationary position to determine the time to ponding function and the application pattern. This method would suffer from the same basic disadvantages of the Tovey infiltrometer: 1) lack of droplet size control across all the circular observation areas, 2) runoff from one area affecting another, and 3) the observer would have to get wet. Walking on a very wet soil might be difficult, as in the case of the Kalamazoo series, and the amount of soil puddling resulting from foot traffic might be undesirable. Nevertheless, the stationary method provides a means of measurement when no other exists and an additional benefit: a sample of the wetted application cross-section. This sample pattern could be used to modify the model, prove the utility of the parabolic application pattern assumption, and be useful to the owner at the time of system resale.

Where connections are available, a simple sprinkler head attached to a hose could be used to determine the t_p function, again with the same drawbacks of the Tovey infiltrometer.

3. Using the model

The infiltration model introduced in this study is appropriate, uses assumptions common to other accepted models, and can be easily understood. Understanding is essential to acceptance. If irrigators can visualize the infiltration problems associated with their own systems and soil conditions, they are more likely to be motivated to improve when the opportunity for change presents itself. This model facilitates understanding by its easy reduction into meaningful components: "This is your soil, this is your system, these are your alternatives." Not only irrigators, but irrigation salespeople, if convinced, can be influential agents of change favoring environmental protection.

4. Implications of the work

If the underlying model assumptions are valid, irrigation application patterns, tillage, and irrigation management strategies can be realistically assessed and implemented. Under some circumstances, proper irrigation system design alone will circumvent ponding during sprinkler irrigation, thus avoiding its chronic and controllable negative effects. However, under other circumstances, such as the disked Montcalm sandy loam measured in 1989, even if an application pattern could be designed to completely mimic the soil intake function, the application period needed to apply a small application depth would be unreasonably long, making it impossible to rely on system design only. Changes in irrigation strategy alone may increase preponding infiltration sufficiently. But for some systems and soils, changing tillage practices, starting with a reduction in field traffic, may be the only effective way to significantly reduce ponding. One advantage of converting to a tillage practice that ponds later is that the practice may also improve infiltrability under rainfall applications. If preponded infiltration can be improved by using the model, a number of benefits accrue: an increase in soil water uniformity (after application), improved initial chemical (via chemigation) placement, a decrease in potential runoff and erosion, better delivery of water to the root zone, improved control of agrichemicals, and a reduction in pollution rates to the ground and surface waters. The decision of buyers in selecting low rate delivery systems over high rate delivery systems will affect the irrigation industry's research and development and improve the quality of irrigation systems available for purchase over the next several decades.

B. Theoretical and analytical questions

The research process is a non-linear one, with advances in theory, analytic capability and means of measurement each surging forward independently. The discord brought about by the lack of consistency may be the fuel of the investigation process, but it is also the frustration of the summary process. At the time that this is being written, several main ideas are under evaluation: the rate as a function of depth concept, the model output based on mean input, the value of the wet data pairs, and using non-ponded data.

1. The rate as a function of depth concept

One of the underlying assumptions of the time to ponding part of the model is that the time to ponding occurs when the application rate vs. depth function intersects the soil intake rate vs. depth function for the first time. This assumes that there is a unique soil intake rate vs. depth function which can be defined for the range of pre-irrigation soil surface moistures and that the time associated with the intersection rate/depth set is solely dependent upon the application pattern.

Paradoxically, time is important in defining the soil intake rate vs. depth function itself. The soil intake rate vs. depth function is a modified descriptor of the set of constant rate vs. time to ponding pairs. While the modified function describes the rate at ponding (r_{tp}) vs. the depth at ponding (D_{tp}) version of the data with an r^2 equal to the unmodified t_p function, it is not possible to obtain a good fit so easily with the modified version of the data. Perhaps this is because the range of times to ponding measured is much wider than the range of depths at ponding and may permit an improved discernment of the typical pattern.

Model predictions of r_{tp} and D_{tp} have generally been within the ranges of observed r_{tp}'s and D_{tp}'s. According to the model assumptions, the time it takes a particular pair of r_{tp} vs. D_{tp} to develop is irrelevant and thus, theoretically, the predicted times to ponding do not have to be in the range of observed t_p's. I imagine that there is some implicit time limitation to this assumption, but I also assume it to be longer than a realistic period of irrigation. It would, of course, be much better to have confidence that the assumption is valid in the first place.

2. Evaluating the output of a model that uses mean value input

At this time, the input to the model is in the form of mean values for the parameters a and b for a particular soil condition. Just looking at the outcomes of the model given those parameter values under the four imposed scenarios (Table 15), one can see that some treatments produce similar outcomes as others. During the analysis, it was found that a high maximum application rate minimized the differences between soil treatments and a low maximum rate and more frequent, less depth scenarios accentuated the differences between soil treatments.

This is a worthwhile observation to make at this time because it colors one's desire to discriminate between alternatives. If a particular scenario is unlikely to be tried, or if the difference in means is presently so small that it hardly makes a difference in outcome, the significance of that difference is hardly worth ascertaining.

Though a single infiltration test does not take long to carry out, ancillary measurements and travel time (incidently increased so as to deliberately maximize the measured variability in θ_i) all add up to only a taste of what is out there. On the other hand, it is now possible to begin to perceive differences in population variance and plan for fewer or greater numbers of observations as they are called for by an in-depth statistical analysis performed at this time. An accurate depiction of the main soils and tillages will continue to unfold as the investigation continues after the analysis. For example, moldboard plow tillage usually has the least variance, while chisel plow and no-till have greater variance, possibly due to differences in amounts and distribution of residue. It is possible that some of these questions are close to resolution.

3. The wet data

Originally I thought that the soil intake function was a family of functions, dependent upon the initial soil moisture, and that the wet data represented data obtained under identical conditions and that collecting it and combining it would make it possible to estimate the most restrictive soil intake function. After observing the frustration of a manager who committed to the application of nitrogen to his crop through his irrigation system during a particularly rainy growing season, I hoped that I would be able to devise some recommendation for that condition if I was going to make any effort to promote chemigation as an environmentally superior method of applying agrichemicals.

Although the combined wet data resulted in a reasonable r^2 for many soil treatments, it is theoretically incorrect in the context of this model to combine the data in the manner that it is now. Instead, the data collection should be modified so that data points can be used to add information to the soil intake rate vs. depth function. Although times were measured in real time over the hour testing period, and the correct application rates and depths could be reconstructed from the existing field records, unfortunately, water was consistently over-applied past the time of ponding which caused runoff to be subsequently bailed off the observation area and onto another furrow. Improved collection of wet data can also be used to test the model assumptions, since a complex record of rates and depths applied over time will be known for every observation area.

4. Using non-ponded data.

Non-ponded data has information value. Statisticians call this kind of data "censored" data and it is used to construct models in epidemiological studies. For example, participants in a cancer treatment comparison are followed until their death, then the no. of years to death is recorded. If one of the participants moves away to another city, or fails to die within the time frame of the study, the information gained from him or her is not equivalent to one whose time of death is known, but nevertheless useful information is gained. These censored data are used to determine model parameters, but not the variance. This technique could be applied to this situation but not all non-ponded data pairs should be included, since some can be well estimated by looking at other data. Instead, only the pairs whose rates or times are not already well represented should be included.

One last thing that would keep the model from underestimating the infiltrability of a particular soil treatment would be to figure out how to calculate the time of cessation of ponding <u>during</u> application. One can already calculate the depth of ponding at the end of the application and how long it would take that same depth of water to infiltrate. For some soil treatments, there is always ponded water predicted at the end of application. However, for others like chisel plow and no-till, not only is there no ponding at the end of the application time, ponding ended not long after it started, resulting in a much larger portion of non-ponded infiltration occurring than is actually calculated. This is not a straightforward problem because the cessation of ponding before the end of application is not the second intersection of the soil intake vs. application function as is often proposed, especially on sloping land, and the problem would probably need to be solved as a time-based water balance problem, which is a lot of work.

5. Should measurements of θ_i and BD be dropped?

Despite the lack of relationship measured between initial volumetric soil surface moisture and the function parameters, it is hard to let go of the intuitive desire to incorporate θi. Looking at the dry vs. wet model predictions, there's obviously a difference between wet and dry functions, but how often would an irrigation manager be forced to chemigate when the soil is close to saturation? Perhaps infiltration is not that sensitive within the typical range of pre-irrigation values:

The lowest measured θ_i at an observation area was 2.0 (θg=1.4), and the highest was 25.5% (θg=19.3), but the average lowest value is 6.5

and the average highest value is 16.5. Largest range in θ_i over one set of soil treatments data (n=5) was 15.4 (θv=10.7), and the smallest range was 5.2 (θg=3.4). The average range was only 10% (θg=7.4), despite an extraordinary effort to maximize the range.

Determination of θ_i and BD is a time consuming task, especially if one must use the Grossman compliant cavity method for the whole season. The transportation, weighing, drying, and sifting of samples takes up 2-3 times longer than the infiltration test itself per site. Also laboratory space has to be arranged to handle the oven and storage of containers.

Some people have found the available pore space (θ_0-θ_i) to be more related to infiltrability, but I'm not sure if this observation was based on model output or based on measurements. It's not much more work to add θ_0 on to the list of ancillary measurements, but the question remains whether or not it's worth the effort. I found it interesting that Smith (1972) did not find θ_i useful in predicting his transformed (dimensionless) estimates of t_p, but I did not find the dimensionless estimation method very helpful either.

C. Limitations to irrigation application

This study did not estimate the effects of crop canopy or surface storage. Despite the desirability of attaining pond-free irrigation, this may not be possible for all soils or situations. An understanding of crop canopy and surface storage would make it possible to set a more modest goal: limiting ponding depth to a depth that does not run off.

Irrigated soils are most vulnerable to droplet impact energy before cover is established. If significant rainfall is not received early in the season, irrigation will be started before the canopy is complete. While the cover breaks the impact energy of the droplets, by the time the canopy is established, a crust has probably been formed in the soils prone to crusting. The presence of a canopy changes the application micropattern, with some parts of the canopy blocking water to the soil and others concentrating flows, as in stemflow. Interception of water by the canopy affects the evapotranspiration process. All in all, this unpredictable effect of canopy is a challenge to consider.

Problems in evaluation of surface storage are similarly complex. Hopefully some level of standardization such as use of Colvin's (1984) index will be linked to estimates of surface storage values so that field personnel will have some quantitative measure of observed field conditions with which to assess storage values. Residue and non-random roughness should also be incorporated into the estimation process.

II. Ideas for further research:

As the work progresses and more insight is developed, the questions get more interesting. Here are a few ideas that are waiting for time and energy; some are for the mid-term (the next field season) and some are for the long-term (new funding).

A. Mid term, in context of another field season

Improve the collection of wet data so that 1) the Smith rate/depth ponding assumption can be tested and 2) the rate vs. depth soil intake function can be strengthened and/or extended. Improvement of data collection involves turning off sprinklers as soon as ponding occurs and using a smaller graduated cylinder to measure the smaller volumes. The sprinkling infiltrometer could be used to test the first assumption by using the addition of the wet tests as complex application events: e.g. 5 min of x mm/h, 3 min of 0 mm/h and 10 min of y mm/h. The wet data depths and rates could be added to the dry rate vs. depth function.

The second assumption that implies that the time to ponding function and the ponded function are coincident when plotted as rate vs. depth is more difficult to directly prove in the field. It is however, indirectly proven by examining the output of complex physical models, as I did in the model development section. In the field, the measurement of the ponded function seems to be a great deal more variable than the time to ponding function, since it is susceptible to so many more measurement errors. I am interested in formally comparing the time to ponding function obtained with the sprinkling infiltrometer to a set of two ponded functions started at the same θ_i measured with the disc permeameter with the surface head fixed at a minimal value (< 2cm) on a Spinks MB for both wheel track and non-wheel track.

Go back to setting one of the dry rates so that it will pond late in the observation period. Take care not to set rate too low (if used as "censored" input, will affect function).

B. Long term, spin-off investigations:

What do real irrigation application patterns look like? Are there typical ones? How can they best be approximated? Parabola, rectangle, trapezoid? Look at the difference in pattern as measured by a tipping bucket and a stationary system method. What are the implications?

Investigate the role of residue more closely. Consider undertaking controlled tests using infiltrometer with different types of residue at different moistures placed on an impervious surface and measuring runoff. Determine t_p functions as for a soil. Estimate the sorptivity and Ks of different kinds and conditions of residue. Investigate the soil moisture transport mechanisms between residue and the soil surface and consider albedo and the effect of residue on evapotranspiration.

Compare the range of irrigation events within the context of rainfall. Consider intensity and duration patterns and impact energy. Estimate the range of effects of irrigation compared to rainfall within a season for the average and extreme years.

SUMMARY AND CONCLUSIONS

I. Problem

The prime impetus behind the funding of this research was a growing awareness that excessive runoff was occurring under sprinkler irrigation in the fields of southern Michigan. During the early 1980's, sprinkler irrigation in this region was rapidly expanding due to high probability of drought during some period of the growing season, rapidly permeable soils, and easily exploitable water resources. For some crop producers, irrigation was not just an attractive technology, but a required one. Lucrative seed corn contracts, for example, could only be procured if one had an irrigation system. And seed corn contracts could produce the profits necessary to buy a system.

The USDA Soil Conservation Service (SCS) and the Michigan State University (MSU) Extension Service field personnel welcomed the prosperity that accompanied the expansion of irrigation but were concerned that the addition of water to soil be done so as to maximize the effectiveness of water applied and not lead to long term degradation of soil or water resources.

At that time, the only guidance as to what maximum rate of sprinkled water might be recommended was in a table of the Michigan Irrigation Guide, a publication written by the SCS and MSU Extension Service. The table recommended maximum constant rates for seven soil intake families, three slope ranges, nine application depths (the lowest being 25.4 mm), and five residue levels. An irrigated soil was designated as being in a particular intake family based on its least permeable soil horizon. The recommended rates were associated with the depths infiltrated under ponded conditions for each intake family as reported in the USDA/SCS National Engineering Handbook, Section 15.

In 1983, a field survey of thirty-three irrigated farms in southern Michigan disclosed that excessive runoff was indeed occurring on slopes, soils, and residue levels where the table recommended "no restrictions on maximum rates within practical design criteria". Moreover, a variable rate solution, more typical of moving systems, needed to be developed. A new table also needed to be organized in terms of a selection of application depths less than 40 mm per application and the most common tillages (moldboard and disk plowed).

When this study began, we had no quantitative assessment of the major soils irrigated nor characterization of a typical irrigation application pattern. It was generally believed that the highest irrigation rates were produced by systems with the lowest operating pressures. There was no infiltrometer developed which simulated irrigation droplet sizes or intensities, and there was no infiltration model which incorporated the soil and residue information that we thought was important in the infiltration process. While I was interested in preponding infiltration, most infiltration models assumed that the surface was already ponded. The few models that included preponding infiltration used variables whose measurement seemed elusive (K_{sat}) or difficult to explain (sorptivity and suction behind the wetting front). Field testing, if done at all, was non-systematic and measured in terms of runoff, an indirect indicator of infiltrability at best.

II. Methods

This study focussed on the dominant irrigated soils and the existing range of application patterns by consolidating the classification system of the irrigated soils and surveying the top five irrigated counties as to which soils were the most irrigated. Eighty sprinkler irrigation evaluations from St. Joseph and Kalamazoo counties were used to characterize the range of maximum application rates and investigate the relationship between pivot pressure and maximum rate.

A sprinkling infiltrometer, a hybrid between the Tovey and Zegelin-White infiltrometers, was designed to simulate irrigation droplet sizes and intensities. A infiltrometer test consisted of measuring the times to ponding for six different constant rates applied to the dry soil and between eight to twenty constant rates applied to near-saturated soil, "wet data pairs". One hundred and three infiltration tests were done on three soil series, five tillages and two crops. Usually, a set of ten tests were done on a specific soil/tillage/crop combination, with 5 tests on wheel track furrows and 5 tests on non-wheel track furrows. A time to ponding function represented by two parameters, a and b, were calculated for every set of dry and wet data pairs.

A simple infiltration model was designed which accepted the time to ponding function as determined by the infiltrometer field tests as input. The model was based on the premises that 1), the infiltrability of every soil can be characterized by a single rate vs. cumulative depth function, which can be used to predict the time to ponding for any application pattern, and that 2), this function consists of a modified time to ponding function or a coincident ponded function. This model was first tested on the output of a complex numerical model developed by Smith. After this was successfully accomplished, it was then used to compare predicted infiltration values, such as the time to ponding, cumulative depth at time to ponding, and cumulative depth at the end of application, under four different scenarios for the measured soil/tillage/wheel track treatments. These scenarios were permutations of a high vs. a low maximum application rate, and one application vs. two half application depths. The application patterns were assumed to be well described by a parabolic function. The comparative outcome of the model under the different scenarios helped to distinguish the effects of the soil, tillages, wheel tracks, soil moisture and irrigation strategies.

III. Conclusions

1) Based on the infiltration tests alone, the Michigan Irrigation Guide to maximum sprinkled irrigation rates was proven to be inadequate.
2) The Spinks/Montcalm, Oshtemo, and Fox/Kalamazoo soils were determined by the five-county survey to be the most dominant irrigated soil series (85%) by far in Michigan and the series most likely to be irrigated in the future.
3) At least one-third of all currently irrigated land is classified as erosion-prone.
4) The results of 80 irrigation system evaluations showed no relation between system pressure and maximum irrigation rate, making it possible to recommend lower pressure, energy-saving systems which also have low maximum rates.

5) Seventy nine of the 80 systems had measured maximum application rates between 15 and 65 mm/h.

6) The parabola was proposed as an adequate descriptor of a moving sprinkler application pattern.

7) A new sprinkling infiltrometer was designed that is portable, easy to use, and reliable.

8) The time to ponding function that one determines using the infiltrometer makes it possible to describe most of the variability in the observed rate and time to ponding pairs for many soil treatments, especially the moldboard plowed tillage. The method for converting this into a rate vs. cumulative depth function is explained.

9) The time to ponding for any application function which can be mathematically expressed can be easily predicted, making it possible to compare alternative ways to increase the time to ponding.

10) Knowing the time to ponding and the rate and cumulative infiltration depth at the time of ponding make it possible to estimate parameters for ponded models such as the Philip model for any application pattern and time of ponding.

11) Options such as changing tillage, increasing the frequency of smaller irrigations, and reducing tillage traffic can be systematically compared. In this study, the mean parameters a and b for all measured soil/tillage/wheel track combinations were combined with the model under the four scenarios to yield predictions of the time to ponding, the cumulative depth at time

to ponding, and the cumulative depth at the end of application for each combination.

12) Maximum constant and parabolic application rates were determined for each treatment measured. Given estimates of random roughness and surface storage, it is possible to make specific recommendations about tillage, irrigation system selection, and irrigation strategies.

APPENDICES

APPENDIX A

Review of the Horton, Holtan, and Green and Ampt models

I. The Horton model

Horton's empirical model is an intuitive approach to infiltration as an exhaustive process similar to others observed in nature (Horton 1940, Addink and Miles ASAE Paper 72-725, 1972). All three of its parameters must be determined from experimental data. The original rate equation proposed by Horton is:

$$i = i_c + (i_o - i_c)\ e^{-bt}$$

and its integrated form gives cumulative infiltration explicitly as a function of time (Philip 1957, Collis-George 1977):

$$I = i_c t + [(i_o - i_c)/b\ (1-e^{-bt})]$$

where i = infiltration rate at time t,
I = cumulative infiltration volume to t,
i_c = constant infiltration rate,
i_o = initial infiltration rate, and
i_c, i_o, and b are parameters.

The rate equation is similar to one proposed by Gardner and Widstoe (1921), and assumes an homogeneous profile where $i_c < K_{sat}$ (Skaggs 1980). The parameter b is a function of soil type, surface conditions and application rate (Skaggs et al. 1969, Philip 1957), and can be found by plotting i vs. t on a semi-log scale. However, a non-linear regression may work better because it does not weight some values more than others, as does a semi-log scale. The parameter b is larger for crusted (non-homogeneous) soils than for uncrusted soils, and if the soil is crusted, $i = i_c$ most of the time (Skaggs et al. 1969). Subsequent studies have shown that in fact, all three parameters are related to soil type and initial volumetric soil moisture content, (Blanchard and O'Niell 1983) and Skaggs et al. (1969) attribute the variation within each parameter to variation in crusting and compaction. Because each parameter is a composite of known and unknown variables, they are not considered to have physical meaning.

The main advantage of this equation is that it converges to a non-zero constant as time goes to infinity. Its main disadvantage is that it cannot adequately represent infiltration behavior at small times (Philip 1957). Because of this disadvantage, Philip found that the equation differed from experimental data by 82% at early times. Watson (1959) said that Philip obtained poor results because of entrapped air in his samples, but both Watson and Collis-George (1977) noted that while Horton's equation did not match their own experimental data for short times, it did seem to hold for intermediate and long times. On the other hand, Skaggs et al. (1969), in his extensive comparison of five infiltration models, found that the Horton model had one of the highest correlations, 0.987, of any tested. Rawls et al. (1976 cited by Brakensiek 1983) also showed Horton's model to adequately represent their data obtained on 11 coastal plains soils with a Purdue infiltrometer, with an r^2 of 0.86, the highest correlation of four models investigated.

Horton's model not only can be used as an infiltration model, but also as a model for the crusting process, (Morin and Benyamini 1977, Moore and Larson 1980) a process very important to the understanding of infiltration in cultivated soils.

II. The Holtan model

The Holtan model is an empirical model with some physical aspects which links infiltration rates to soil moisture content in a specific storage zone and is not directly time dependent (Mein and Larson 1971). The model, and modifications of it by Huggins and Monke (1966 as cited by Skaggs 1982) or Holtan and Lopez (1971 also cited by Skaggs 1982) are currently widely used in hydrologic models such as USDAHL, ANSWERS and FESHM (Idike et al. ASAE Paper 77-2558, 1977). It is reported to be easy to use and can be used for non-ponded water applications (Hillel 1980).

The original model (Horton 1940) is:

$$f = aFp^{n} + f_c$$

where f = infiltration rate,
f_c = final, constant infiltration rate,
a,n = parameters, determining by plotting $f - f_c$ vs. F_p,
$a = 0.26 - 0.80$, and $n = 1.387$; and
F_p = remaining potential storage.

Holtan and Creitz (1967 as cited by Skaggs 1982) introduced a more elaborate version of the model, adding a factor characterizing the influence of crop cover, and proposing general values for the parameters involved, based on generally observable conditions such as soil group, surface conditions, and density of plant roots:

$$f_p = GI \times a \times SA^{1.4} + f_c$$

where f_p = infiltration rate,
GI = growth index of crop in percentage maturity,
a = "index of storage porosity" as a function of surface conditions and density of plant roots,
SA = available storage in surface layer, $(\theta_0 - \theta_i)d$,
and f_c = final, constant infiltration rate, estimated from the soil group.

A table of values for "a" was developed by Frere et al. (1975 as cited by Skaggs 1982):

Estimates of Vegetative Parameter "a" in the Holtan Infiltration Equation.

Land use or cover	Basal area rating, adjusted for "weeds" and "grazing".	
	Poor condition	Good condition
Fallow*	0.10	0.30
Row crops	0.10	0.20
Small grains	0.20	0.30
Hay (legumes)	0.20	0.40
Hay (sod)	0.40	0.60
Pasture (Bunch grass)	0.20	0.40
Temporary pasture (sod)	0.20	0.60
Permanent pasture (sod)	0.80	1.00
Woods and forests	0.80	1.00

*For fallow land only, poor condition means "After row crop", and good condition means "After sod".

"d" (used to compute SA) is defined in many ways: Holtan and Creitz (1967 as cited by Skaggs 1982) suggested that d could equal the depth to the B horizon, plow layer, or impeding layer. Huggins and Monke (1966 also cited by Skaggs 1982) pointed out that the depth is dependent on surface condition and cultural practices. The meaning of "d" is unclear for soils with no impeding strata.

The volume of infiltrated water will reduce the value of SA, but this value will recover in part during the same time due to drainage and evapotranspiration (Skaggs 1982).

Musgrave (1955 as cited by Skaggs 1982) developed a table of values for f_c:

Estimates by Hydrology Group for the Final Infiltration Rate f_c in the Holtan Equation

Hydrologic Soil Group	f_c (in/h)
A	0.40 - 0.30
B	0.30 - 0.15
C	0.15 - 0.05
D	0.05 - 0.0

Ewing and Mitchell (ASAE Paper 85-2010, 1985) developed a parameter estimation algorithm for the Holtan model modified by Huggins and Monke (1966 as cited by Skaggs 1982) using the Manning's roughness coefficient. Although the model is generally believed to be well suited as a watershed model and developed for that purpose from a substantial volume of data (Mein and Larson 1971), Chery (1979) expressed his doubts about the accuracy of a watershed model based on the joint distribution of lumped parameters rather than parameters consisting of single physically measured properties. It also needs to be added, though it might be inferred, that the Holtan model is too general to be suited to a point by point analysis (Skaggs 1982).

Even though the larger number of characterizing parameters may lead to a better fit, they can also hinder its usefulness (Hillel 1980). The predicted infiltration rate is highly sensitive to the control depth specified (Mein and Larson 1971) and that specification is not always easy to determine. But perhaps the most objectionable aspect of the Holtan model is that its basic physical assumptions are questionable. Smith (1976) said we should not expect that the Holtan equation adequately describes the infiltration process since we now know that the infiltration process is more influenced by the hydraulic conductivity and hydraulic gradients found within the soil rather than the soil's porosity.

Skaggs et al. (1969) included two versions of the Holtan model in his comparison of models and got a near perfect fit (r^2 =.988 when using porosity, initial water content, volume of water infiltrated, and f_c to first determine the control depth "d". Overton (1964) compared his integrated version of Holtan's equation (where he assumes a time to constant infiltration) and found it equivalent to the Green and Ampt, Horton, and Philip model. Idike et al. (1980) compared the Mein-Larson version of the Green and Ampt equation and Holtan's equation for constant rainfall and found that Holtan's model generally failed to predict a delay in ponding. He compared the two models because of the simulation of the two stages of infiltration pre- and post-ponding.

III. The Green and Ampt model

The Green and Ampt model, with its fundamental concept of a sharp wetting front, is considered by some to be the most "elegant" of the major approximate models (Smith 1976) and a huge volume of literature is devoted to it. As the first of the major models, it has had a long evolution as researchers reinterpreted its assumptions, forms, and applications. It can be either an empirical or a physical model. Time was implicit in its originally form, though now there are forms of the equation where time is explicit or even absent. There are four major interpretations of the Green and Ampt equation: Poiseuille's, Darcy's, Philip's, and Mein and Larson's.

The original Green and Ampt model (1911) was developed using Poiseuille's capillary tube law (Green and Ampt 1911) to describe the velocity of infiltrated flow:

$$P/S \times t = L - (a + k) \log_e (1 + L/(a + k))$$

where P = Permeability to water = volume of water passing in one unit time through a column of one unit area under a head of water equal to the length of the column.
S = Specific pore or interstitial space or free space/initial volume of soil,
k = Capillarity coefficient = tension due to capillary forces/unit area of cross section of the pore spaces which tends to draw water from the saturated to the dry region of the soil,
a = head of water above the soil, and
L = distance to the wetting front.

The assumptions underlying this equation are that the soil is composed of a bundle of capillary tubes, irregular in area, length, direction and shape, but sufficiently minute to reduce the velocity of air or water, to velocities which conform to Poiseuille's law. It also assumed that the water is regarded as at once occupying the whole of the pore space in each layer of the soil as it reaches it or in more modern terms it assumes that a definable wetting front exists where the tension H_f is a constant characteristic of the soil. The soil is also assumed to be homogeneous and ponded with a ponded surface, and a uniform initial water content. Initial soil water mobility is also considered to be zero.

As time went on, it was recognized that the velocity of infiltrated flow could be more easily conceptualized by the use of the more general Darcy's law assuming that the wetting front is a sharp, well-defined discontinuity. Darcy's law states that the flux equals the hydraulic conductivity (K) times the hydraulic gradient. That is: the infiltration rate (i) = K [Sum of the tension and gravity forces at soil (inflow) surface minus the sum of the tension and gravity forces at the wetting front (outflow)] divided by the distance from soil surface to wetting front (inflow - outflow). If L is the distance from the surface to the wetting front, H is the tension at the surface, and S the suction at the wetting front, the infiltration rate (i) can be calculated by:

$$i=K(L-H+S)/L.$$

In the beginning of the sprinkling event, H = S (both >0) and goes to zero as the time to ponding approaches, making the equation:

$$i=K(L+S)/L$$

(Swartzendruber 1974).

Other common forms of the Green and Ampt equation are:

$$i = K + \frac{KMS}{I}$$

where $H = 0$,
$M = \theta_0-\theta_i$, (storage deficit), and
$I = ML$, cumulative application depth,

the Mein and Larson version (1971, 1973, Brakensiek and Rawls, 1983)

$$Kt = I - SM \ln(1 + I/MS)$$

where $i = dI/dt$, and
$I = 0$ at $t=0$.

and

$$i = i + b/I,$$

(Swartzendruber and Hillel 1973).

The form often seen when the Green and Ampt model is used empirically is:

$$i = B + A/I$$

where $B = K_{sat}$,
$I = ML$, and
$A = K_{sat}MS$.

A and B can be determined by either linearly regressing i vs. 1/I or non-linearly regressing i vs. I.

The Green and Ampt model was rederived by Philip (1954) as a special case of his solution to the Richard's flow equation. In this derivation, he relaxed the need for the assumption of saturation behind the wetting front, and made K equal to K at saturation. His Green and Ampt derivation was equivalent to the same mathematical formula as the simplest possible integral method of his approximate solution to the flow equation. This corresponded to the special case where the soil moisture diffusivity function $D(\theta)$ could be represented by a Dirac delta function where all diffusivity is concentrated at the moisture content corresponding to the potential at the water supply surface (Philip 1983). Because of this, the Green and Ampt model is occasionally referred to as the "slug", "delta", "step" or "piston" model in later literature.

Philip explained that "once the physical and mathematical contexts of the Green and Ampt are understood, its strengths and weaknesses are apparent. It is best fitted to approximate homogeneous systems with steep wetting fronts, or at least where moisture profiles preserve similarity of shape. It thus works best for one-dimensional infiltration with constant surface moisture potential (preferably zero or positive) into a homogeneous coarse-textured soil with the initial soil moisture small and uniform. The more the process deviates from this description, the less one could rely on the Green and Ampt model".

Other derivations and versions of the model continue to be written and applied including those by Fok and Hanson (1966), Morel- Seytoux and Kanji (1974), Alekseev (1948) and Budagovskii (1955) (both as cited by Rode 1965), Chu (ASAE Paper 77-2063, 1977, 1978), Smith and Parlange (1978) and others.

The physically-based Green and Ampt parameters most used are K, θ_i, fillable porosity, and suction at the wetting front. Depending on the intent and scope of model application, these can be directly measured in the field and laboratory or estimated from soil survey information. Field and laboratory procedures may be prohibitively complicated for some uses. The empirically deduced parameters A and B have the advantage of lumping soil surface features such as cracking and sealing, and yield generalized values reflecting soil type and conditions (Skaggs 1982, Brakensiek and Onstad 1977, Blanchard and O'Niell 1983), but can also sometimes yield negative or unreasonably large or small values.

K is generally assumed to be 0.5 of the saturated conductivities of the "effective conductivity allowing for air entrapment" (Bouwer 1966, 1969). Likewise, θ_0 is considered to be slightly less than that of the true porosity, hence, the term "fillable porosity" (Skaggs 1982). The most difficult parameter to measure, however, is the suction behind the wetting front and is generally considered to be a constant for a homogeneous soil. There have been many attempts to characterize this parameter (Bouwer 1966, 1969). Morel-Seytoux (1983) discusses major efforts to approximate this parameter, including equations based on capillary tension at initial water content (Whisler and Bouwer 1970), air entry suction (or also called water exit suction), critical pressure head (Bouwer 1966, 1969), approximate critical pressure head (Mein and Farrell 1974), average capillary suction at wetting front (Mein and Larson 1973) or the average of capillary tension at θ_i and at θ_0.

Suction behind the wetting front was measured by Bouwer (1966) in the field, while Rawls and Brakensiek (1983) estimated the Green and Ampt parameters from soil water retention data using the Brook-Corey water retention equation. Their techniques require extensive laboratory work to determine the porous media properties.

Fortunately, sensitivity analysis (Brakensiek and Onstad 1977) has shown infiltration and runoff amount to be most sensitive to errors in fillable porosity, M, and less sensitive to errors in suction at the wetting front.

There is considerable site to site variability in the parameters in the field: K_{sat} is a log-normal variate (Nielson et al. 1973) and the suction behind the wetting front is a power transformed (the exponent being 0.55) variate (Brakensiek and Onstad 1977).

Despite Philip's caution, researchers have extended the Green and Ampt model to situations far beyond its assumptions. This is because not only does it seem to adequately represent the infiltration process almost as well as the Philip model or other numerical solutions to the Richard's equation (Swartzendruber and Youngs 1974, Swartzendruber 1974, Smith 1976), but it is also relatively easy to use.

In a numerical example, Philip compared the Horton, Kostiakov, Green and Ampt, and the Philip two parameter equations: both the Horton and Kostiakov failed, while the Green and Ampt and Philip equations were equally good (Philip 1957).

Bouwer (1969) demonstrated that a tabular procedure using the Green and Ampt solution was appropriate for calculation of ponded infiltration into a layered soil with a nonuniform water content and hydraulic conductivity.

Childs and Bybordi (1969) reported good agreement between the Green and Ampt model and laboratory infiltration measured into layered soil with decreasing conductivities.

Tan et al. (ASAE Paper 87-2002, 1987) evaluated the performance of the layered Mein Larson version of the Green and Ampt model using laboratory runoff obtained for a three layered soil under simulated rainfall. The match between the predicted and observed infiltration patterns ranged from very good to excellent.

Skaggs et al. (1969) used regression analysis on large plot rainfall simulation data to determine equation parameters for the Green and Ampt, Horton, Holtan and Philip two parameter models. Based on the results of 52 field tests, they found that all of the equations would adequately fit the measure infiltration data. They found that the Horton and Holtan models fared better than the Green and Ampt or Philip models. This test also showed that it was possible to obtain negative parameter values.

Whisler and Bouwer (1970) compared several methods of calculating infiltration for vertical columns of porous media with experimental data. The more complex models of Philip and numerical analysis gave closer agreement than the Green and Ampt model in their investigation, but Whisler and Bouwer felt that the Green and Ampt was the easiest to use and gave reasonable results.

Mein and Larson (1971, 1973) used measured parameters from five soils to compare their version of the Green and Ampt and the Richard's equation under constant rainfall and after ponding. The comparison was fair to good depending on soil type.

Chu (ASAE Paper 77-2063, 1977) modified the Green and Ampt equation in the same way as Mein and Larson did to describe the infiltration process during a rainfall event with variable intensities. Measured runoff was compared to calculated runoff (rainfall minus calculated infiltration) for three runoff events from a 113 acre watershed. The calculated runoff was "surprisingly close" for two of the three events.

In a similar way, Slack (1980) employed the Mein and Larson version of the Green and Ampt model to predict the time to surface ponding and corresponding volume of water infiltrated under two types of center pivot irrigation systems. The model did a good job of predicting infiltration for the soil with a well protected surface and a poor job of predicting for the soil with an incomplete surface cover.

Bruce and Thomas (ASAE Paper 83-2501, 1983) used estimated parameters from two Udults and a Boroll soil to compare a Richard's finite difference solution to a Green and Ampt solution. They reported that the use of the Richard's solution highlighted incompatible data parameters and that good agreement between the two methods was often achieved.

Clemmens (1983) reported high regression values for the empirically fitted Green and Ampt equation with two surface infiltration events.

The Green and Ampt infiltration equation was adapted to soils subjected to soil crusting by Brakensiek and Rawls (1983). Their two layer method gave fair results when compared to 60 infiltration rates measured with a rainfall simulator. They concluded that the characteristic transient properties of the soil crust were especially critical.

Ahuja and Ross (1983) also used a Green and Ampt type crusting model to compare with data measured by Morin and Benyamini (1977).

Chu (1985) combined the Mein Larson and Brakensiek and Rawls version of the Green and Ampt equation to simulate infiltration into a tilled three layer (crust, soil and subsoil) soil during a non- uniform rainfall. He obtained reasonable results when using parameter values from a real rainfall event on an ARS watershed.

APPENDIX B

More irrigated soils of Michigan tables

Table B-1 relates the resultant classification system to other existing systems: 1) the Michigan soil management unit system, based primarily on profile texture (Mokma 1978), 2) the Soil Considerations for Irrigation in the Michigan Irrigation Guide (Vitosh and Fisher 1981); and 3), the 1982 and 1987 Michigan guides to soil series (Mokma and Stroesenreuther 1982, Mokma and Frederick 1987). Estimated yield information was obtained from MSU Extension literature on irrigation and fertilizer recommendations (Lucas and Vitosh 1978, Warnke et al. 1985). Considerable information and insight into unlike soils, modern and old names came from the SCS state soils scientists, N.W. Stroesenreuther and L. Berndt, and MSU Crop and Soil Science professor, D. Mokma.

In the table, soils are grouped according to major classes, with mesic soils appearing at the top of each list and frigid at the bottom. The name is the modern soil series name as recognized by the SCS, and the slope is in percent. The soil is cross-referenced with the existing the management group or unit, and the irrigation group. Estimates of some physical properties of relevance, i.e., the number of stories, water-holding capacity, corn yields and areal extent (within the major five irrigated counties) are given. Soils classified by the Michigan land capability scheme to be susceptible to erosion hazard are listed after less-erodible ones. After the last subclass is a list of soils which are classified unsuitable for crops, these usually being soils with higher slopes than soils mentioned earlier.

Table B-1. Detailed Michigan irrigated soils classification.

A. SOILS WITH RAPID PERMEABILITY AND INTAKE FAMILIES = 3-4"/h.

A1. Sands with rapidly permeable horizons and intake families = 4"/h. (3.84" in 60").

Name	Slope	Mgt Group	Irri Group	F/M	No. of Stories	Water Holding Capacity	Yield (bu) Irri	Yield (bu) Non	Area* (A)
Covert	0-4	5a	(2,4)	Mesic	1	3.84	160	55	3944
Croswell	0-6	5a	(2,4)	Frigid	1	3.84	160	50	958
East Lake	0-6	5a	(2,4)	Frigid	2	3.84	160	50	
Kalkaska	0-6	5a	(2,4)	Frigid	1	3.84	160	50	
								Sub	4902
Soils susceptible to erosion hazard									
Plainfield	0-6	5.3a	(2,4)	Mesic	1	3.84	160	55	11766
								Sub	11766
								Total	16668

A2. Sands and loamy sands with rapidly permeable fine sandy horizons and intake family = 3"/h. (4.92" in 60").

Name	Slope	Mgt Group	Irri Group	F/M	No. of Stories	Water Holding Capacity	Yield (bu) Irri	Yield (bu) Non	Area (A)
Chelsea	0-9	5a	(3,3)	Mesic	1	4.92	160	55	
Oakville	0-6	5.3a	(3,3)	Mesic	1	4.92	160	55	842
Blue Lake	0-6	4a	(3,3)	Frigid	1	4.92	170	70	
Graycalm	0-6	5a	(3,3)	Frigid	1	4.92	160	50	
Rouseau	0-6	4a	(3,3)	Frigid	1	4.92	170	70	728
								Sub	1570
Soils susceptible to erosion hazard									
Coloma	0-6	5a	(3,3)	Mesic	1	4.92	160	55	9495
Blue Lake	6-12	4a	(3,3)	Frigid	1	4.92	170	70	
Rouseau	6-12	4a	(3,3)	Frigid	1	4.92	170	70	
Vilas	0-6	5.3a	(3,3)	Frigid	1	4.92	160	50	
								Sub	9495
								Total	11065

* St. Joseph, Branch, Van Buren, Montcalm and Calhoun

Table B-1 (cont'd).

B. SOILS WITH MODERATELY TO MODERATELY-RAPID PERMEABILITY AND INTAKE FAMILIES OF 1.5-2"/h.

B1. Loamy sands and sandy loams, moderately to moderately rapid permeability and low water holding capacities and intake family = 2"/h. (4.5-5.5" in 60").

Name	Slope	Mgt Group	Irri Group	F/M	No. of Stories	Water Holding Capacity	Yield (bu) Irri	Yield (bu) Non	Area (A)
Boyer	0-6	4a	(5,2)	Mesic	2	4.56	170	80	
Bronson	0-2	3a	(5,2)	Mesic	2	4.56	170	105	7263
Ormas	0-6	4a	(5,2)	Mesic	2	4.56	170	80	13830
Ottokee	0-6	4a	(5,2)	Mesic	1	5.28	170	80	3753
Perrin	0-6	4a	(5,2)	Mesic	2	4.56	170	80	
Spinks	0-6	4a	(5,2)	Mesic	1	5.28	170	80	82957
Karlin	0-6	4a	(5,2)	Frigid	2	5.28	170	70	
Keweenaw	0-2	4a	(5,2)	Frigid	1	5.28	170	70	
Leelanau	0-6	4a	(5,2)	Frigid	1	5.28	170	70	
Mancelona	0-6	4a	(5,2)	Frigid	2	4.56	170	70	26914
Montcalm	0-6	4a	(5,2)	Frigid	1	5.28	170	70	35549
								Sub	170266

Soils susceptible to erosion hazard

Name	Slope	Mgt Group	Irri Group	F/M	No. of Stories	Water Holding Capacity	Yield (bu) Irri	Yield (bu) Non	Area (A)
Boyer	6-12	4a	(5,2)	Mesic	2	4.56	170	80	
Bronson	2-6	3a	(5,2)	Mesic	2	4.56	170	105	2421
Ormas	6-12	4a	(5,2)	Mesic	2	4.56	170	80	950
Ottokee	6-8	4a	(5,2)	Mesic	1	5.28	170	80	1251
Spinks	6-12	4a	(5,2)	Mesic	1	5.28	170	80	24183
Karlin	6-12	4a	(5,2)	Frigid	2	5.28	170	70	
Keweenaw	2-12	4a	(5,2)	Frigid	1	5.28	170	70	
Leelanau	0-6	4a	(5,2)	Frigid	1	5.28	170	70	
Mancelona	6-12	4a	(5,2)	Frigid	2	4.56	170	70	11172
Montcalm	6-12	4a	(5,2)	Frigid	1	5.28	170	70	48992
								Sub	88969
								Total	259235

Table B-1 (cont'd).

B2. Loamy sands and sandy loams, moderately to moderately rapid permeability and higher water holding capacities and intake families = 1.5"/h. (6.6-8" in 60")

Name	Slope	Mgt Group	Irri Group	F/M	No. of Stories	Water Holding Capacity	Yield (bu) Irri	Yield (bu) Non	Area (A)
Arkport	0-3	3a	(6,1.5)	Mesic	1	6.6	170	105	
Elston	0-2	4a	(7,1.5)	Mesic	2	7.56	170	80	5775
Hillsdale	2-6	3a	(6,1.5)	Mesic	1	7.68	170	105	32917
LaPeer	0-2	3a	(6,1.5)	Mesic	1	7.68	170	105	
Nottawa	0-3	4a	(12,1)	Mesic	2	6.84	170	80	2855
Oshtemo	0-2	3a	(6,1.5)	Mesic	2	6.6	170	105	67144
Alcona	0-2	3a	(6,1.5)	Frigid	1	6.6	170	80	
Amasa	0-2	3/5a	(6,1.5)	Frigid	2	6.6	170	80	
Chatham	0-2	3a	(6,1.5)	Frigid	2	6.6	170	80	
Emmet	0-2	3a	(6,1.5)	Frigid	1	7.68	170	80	
Omena	0-2	3a	(6,1.5)	Frigid	1	7.68	170	80	
Pence	0-2	4a	(6,1.5)	Frigid	2	6.6	170	70	
								Sub	108691

Soils susceptible to erosion hazard

Arkport	3-15	3a	(6,1.5)**Mesic**	1	6.6	170	105	
Elston	2-12	4a	(7,1.5)**Mesic**	2	7.56	170	80	1925
Hillsdale	6-12	3a	(6,1.5)**Mesic**	1	7.68	170	105	11862
LaPeer	2-12	3a	(6,1.5)**Mesic**	1	7.68	170	105	
Oshtemo	2-12	3a	(6,1.5)**Mesic**	2	6.6	170	105	121026
Alcona	2-12	3a	(6,1.5)**Frigid**	1	6.6	170	80	
Amasa	2-12	3/5a	(6,1.5)**Frigid**	2	6.6	170	80	
Chatham	2-12	3a	(6,1.5)**Frigid**	2	6.6	170	80	
Emmet	2-12	3a	(6,1.5)**Frigid**	1	7.68	170	80	
Omena	2-12	3a	(6,1.5)**Frigid**	1	7.68	170	80	
Pence	2-12	4a	(6,1.5)**Frigid**	2	6.6	170	70	
							Sub	134813
							Total	243504

Table B-1 (cont'd).

C. SOILS WITH MODERATE TO SLOW PERMEABILITY AND INTAKE FAMILY = 1"/h.

C1. Sandy loams and loamy sands with moderate to slow permeability and relatively lower water holding capacity. (6.8-7.5" in 60").

Name	Slope	Mgt Group	Irri Group	F/M	No. of Stories	Water Holding Capacity	Yield (bu) Irri	Yield (bu) Non	Area (A)
Bixby	0-2	3/5a	(9,1)	Mesic	2	6.9	170	105	
Fox	0-2	3/5a	(9,1)	Mesic	2	6.9	170	105	21425
Ionia	0-2	3/5a	(9,1)	Mesic	2	6.9	170	105	
Kalamazoo	0-2	3/5a	(9,1)	Mesic	2	6.9	170	105	30872
Schoolcraft	0-2	3/5a	(12,1)	Mesic	2	6.84	170	105	12295
Gilchrist	0-6	4a	(4,2)	Frigid	2	7.37	170	70	
Antigo	0-2	3/5a	(12,1)	Frigid	2	6.84	170	80	
Newaygo	0-2	3/5a	(12,1)	Frigid	2	6.84	170	80	403
Stambaugh	0-2	3/5a	(12,1)	Frigid	2	6.84	170	80	
								Sub	64995
Soils susceptible to erosion hazard									
Bixby	2-12	3/5a	(9,1)	Mesic	2	6.9	170	105	
Fox	2-12	3/5a	(9,1)	Mesic	2	6.9	170	105	33210
Ionia	2-5	3/5a	(9,1)	Mesic	2	6.9	170	105	
Kalamazoo	2-12	3/5a	(9,1)	Mesic	2	6.9	170	105	99461
Schoolcraft	2-12	3/5a	(12,1)	Mesic	2	6.84	170	105	6450
Antigo	2-12	3/5a	(12,1)	Frigid	2	6.84	170	80	
Gilchrist	6-12	4a	(14,1)	Frigid	2	7.37	170	70	
Newaygo	2-12	3/5a	(12,1)	Frigid	2	6.84	170	80	48
Stambaugh	2-12	3/5a	(12,1)	Frigid	2	6.84	170	80	
								Sub	139169
								Total	204164

Table B-1 (cont'd).

C2. Sandy loams with moderately slow to slow permeability and high water holding capacity. (9.3-11" in 60")

Name	Slope	Mgt Group	Irri Group	F/M	No. of Stories	Water Holding Capacity	Yield (bu) Irri	Yield (bu) Non	Area (A)
Dryden	0-2	3a	(9,1)	Mesic	1	9.36	170	105	
Elmdale	0-2	3a	(9,1)	Mesic	1	9.36	170	105	4478
Fence	0-2	3a	(11,1)	Frigid	1	10.8	170	80	
Trenary	0-2	3a	(9,1)	Frigid	1	9.36	170	80	
							Sub		4478
Soils susceptible to erosion hazard									
Dryden	2-10	3a	(9,1)	Mesic	1	9.36	170	105	
Elmdale	2-12	3a	(9,1)	Mesic	1	9.36	170	105	8957
Trenary	2-6	3a	(9,1)	Frigid	1	9.36	170	80	
Fence	2-12	3a	(11,1)	Frigid	1	10.8	170	80	
							Sub		8957
							Total		13435

Table B-1 (cont'd).

D. SOILS WITH SLOW TO VERY SLOW PERMEABILITY DUE TO FRAGIPANS OR FIRM TILL AND INTAKE FAMILY = 1"/h.

Sandy loams with slow to very slow permeability due to fragipans or orsteins above 24 inches.

Name	Slope	Mgt Group	Irri Group	F/M	No. of Stories	Water Holding Capacity	Yield (bu) Irri	Yield (bu) Non	Area (A)
Sunfield	1-2	3/5a	(14,1)	Mesic	2	3.84	170	105	
McBride	0-2	3a	(14,1)	Frigid	1	3.84	170	80	6662
Munising	0-2	3a	(14,1)	Frigid	1	3.84	170	80	
								Sub	6662
Soils susceptible to erosion hazard									
Sunfield	2-6	3/5a	(14,1)	Mesic	2	3.84	170	105	
McBride	2-12	3a	(14,1)	Frigid	1	3.84	170	80	46288
Munising	2-12	3a	(14,1)	Frigid	1	3.84	170	80	
								Sub	46288
								Total	52950

Table B-1 (cont'd).

U. Classified unsuitable for row crops (6 s)

Name	Slope	Mgt Group	Irri Group	F/M	No. of Stories	Water Holding Capacity	Yield (bu) Irri	Non	Area (A)
Chelsea	9-14	5a	(3,3)	Mesic	1				
Coloma	6-12	5a	(3,3)	Mesic	1				7910
Oakville	6-15	5.3a	(5,2)	Mesic	1				1010
Plainfield	6-12	5.3a	(2,4)	Mesic	1				1623
Croswell	6-12	5a	(2,4)	Frigid	1				55
East Lake	6-18	5a	(2,4)	Frigid	2				
Graycalm	6-18	5a	(3,3)	Frigid	1				
Kalkaska	6-18	5a	(2,4)	Frigid	1				
Vilas	6-12	5.3a	(3,3)	Frigid	1				
							Total		10598

Table B-2. Index to Michigan's irrigated soils

Name	Percent Slope	Mgt Group	Irr Group	F/M	No. Stories	Land Class e/s	Soil Area* (Acres)	NEW CLASS	Topsoil Texture
Alcona	0-2	3a	(6,1.5)	Frigid	1	2 s		B2	sl,fsl,
Alcona	2-6	3a	(6,1.5)	Frigid	1	2 e			vfsl,lfs,
Alcona	6-12	3a	(6,1.5)	Frigid	1	3 e			lvfs
Amasa	0-2	3/5a	(6,1.5)	Frigid	2	2 s		B2	vfsl,fsl
Amasa	2-6	3/5a	(6,1.5)	Frigid	2	2 e			sil
Amasa	6-12	3/5a	(6,1.5)	Frigid	2	3 e			
						(irr)			
Antigo	0-2	3/5a	(12,1)	Frigid	2	1		C1	sil
Antigo	2-6	3/5a	(12,1)	Frigid	2	2 e			
Antigo	6-12	3/5a	(12,1)	Frigid	2	3 e			
Arkport	0-3	3a	(6,1.5)	Mesic	1	2 s		B2	vfsl,
Arkport	3-8	3a	(6,1.5)	Mesic	1	2 e			lvfs,fsl,
Arkport	8-15	3a	(6,1.5)	Mesic	1	3 e			lfs,fs
Bixby	0-2	3/5a	(9,1)	Mesic	2	2 s		C1	l,sil
Bixby	2-6	3/5a	(9,1)	Mesic	2	2 e			
Bixby	6-12	3/5a	(9,1)	Mesic	2	3 e			
Blue Lake	0-6	4a	(3,3)	Frigid	1	3 s		A2	ls,s
Blue Lake	6-12	4a	(3,3)	Frigid	1	3 e			
Boyer	0-6	4a	(5,2)	Mesic	2	3 s		B1	ls,lfs
Boyer	6-12	4a	(5,2)	Mesic	2	3 e			sl,fsl
									l
Bronson	0-2	3a	(5,2)	Mesic	2	2 s	-7263	B1	sl
Bronson	2-6	3a	(5,2)	Mesic	2	2 e	-2421		ls
Chatham	0-2	3a	(6,1.5)	Frigid	2	2 s		B2	fsl,sl
Chatham	2-6	3a	(6,1.5)	Frigid	2	2 e			l
Chatham	6-12	3a	(6,1.5)	Frigid	2	3 e			
Chelsea	0-9	5a	(3,3)	Mesic	1	4 s		A2	lfs,ls
Chelsea	9-14	5a	(3,3)	Mesic	1	6 s		U	fs,s

* St. Joseph, Branch, Van Buren, Montcalm and Calhoun

Table B-2 (cont'd).

Name	Percent Slope	Mgt Group	Irr Group	F/M	No. Stories	Land Class e/s	Soil Area (Acres)	NEW CLASS	Topsoil Texture
					(irr)				
Coloma	0-2	5a	(3,3)	Mesic	1	2 e	-3165	A2	ls
Coloma	2-6	5a	(3,3)	Mesic	1	3 e	-6330	A2	s
Coloma	6-12	5a	(3,3)	Mesic	1	6 s	7910	U	
Covert	0-4	5a	(2,4)	Mesic	1	4 s	13944	A1	ls
									s
Croswell	0-6	5a	(2,4)	Frigid	1	4 s	958	A1	s
Croswell	6-12	5a	(2,4)	Frigid	1	6 s	55	U	ls
Dryden	0-2	3a	(9,1)	Mesic	1	2 s		C2	sl
Dryden	2-6	3a	(9,1)	Mesic	1	2 e			l
Dryden	6-10	3a	(9,1)	Mesic	1	3 e			
East Lake	0-6	5a	(2,4)	Frigid	2	4 s		A1	s,cos
East Lake	6-18	5a	(2,4)	Frigid	2	6 s		U	ls
									gr-ls,gr-s
Elmdale	0-2	3a	(9,1)	Mesic	1	2 s	-4478	C2	sl,fsl
Elmdale	2-6	3a	(9,1)	Mesic	1	2 e	-3582	C2	l
Elmdale	6-12	3a	(9,1)	Mesic	1	3 e	-5374	C2	
Elston	0-2	4a	(7,1.5)	Mesic	2	2 s	-5775	B2	sl,fsl
Elston	2-6	4a	(7,1.5)	Mesic	2	2 e	-1925		l
Elston	6-12	4a	(7,1.5)	Mesic	2	3 e			
Emmet	0-2	3a	(6,1.5)	Frigid	1	2 s		B2	sl,fsl
Emmet	2-6	3a	(6,1.5)	Frigid	1	2 e			l
Emmet	6-12	3a	(6,1.5)	Frigid	1	3 e			ls
									gr-sl
Fence	0-2	3a	(11,1)	Frigid	1	1		C2	sil
Fence	2-6	3a	(11,1)	Frigid	1	2 e			vfsl
Fence	6-12	3a	(11,1)	Frigid	1	3 e			
Fox	0-2	3/5a	(9,1)	Mesic	2	2 s	21425	C1	sil,l
Fox	2-6	3/5a	(9,1)	Mesic	2	2 e	30440		sl,fsl
Fox	6-12	3/5a	(9,1)	Mesic	2	3 e	2770		cl,scl
									gr-l,gr-sil
									gr-sl,gr-fsl
									gr-cl,gr-sicl,gr-scl
Gilchrist	0-6	4a	(4,2)	Frigid	2	3 s		C1	ls,lfs
Gilchrist	6-12	4a	(4,2)	Frigid	2	3 e			s
Graycalm	0-6	5a	(3,3)	Frigid	1	4 s		A2	s
Graycalm	6-18	5a	(3,3)	Frigid	1	6 s		U	ls,lcos

Table B-2 (cont'd).

Name	Percent Slope	Mgt Group	Irr Group	F/M	No. Stories	Land Class e/s	Area (Acres)	NEW CLASS	Topsoil Texture
Hillsdale	0-2	3a	(6,1.5)	Mesic	1	2 s		B2	sl,fsl
Hillsdale	2-6	3a	(6,1.5)	Mesic	1	2 e	32917		ls
Hillsdale	6-12	3a	(6,1.5)	Mesic	1	3 e	11862		l
Ionia	0-2	3/5a	(9,1)	Mesic	2	2 s		C1	sl
Ionia	2-5	3/5a	(9,1)	Mesic	2	2 e			sil,l
Kalamazoo	0-2	3/5a	(9,1)	Mesic	2	2 s	30872	C1	l
Kalamazoo	2-6	3/5a	(9,1)	Mesic	2	2 e	77406		sl
Kalamazoo	6-12	3/5a	(9,1)	Mesic	2	3 e	22055		sil
Kalkaska	0-6	5a	(2,4)	Frigid	1	4 s		A1	s
Kalkaska	6-18	5a	(2,4)	Frigid	1	6 s		U	ls
Karlin	0-6	4a	(5,2)	Frigid	2	3 s		B1	lfs
Karlin	6-12	4a	(5,2)	Frigid	2	3 e			fsl,sl
Keweenaw	0-2	4a	(5,2)	Frigid	1	3 s		B1	ls,lfs
Keweenaw	2-12	4a	(5,2)	Frigid	1	3 e			sl
									gr-ls,gr-lfs
									gr-sl
LaPeer	0-2	3a	(6,1.5)	Mesic	1	2 s		B2	sl,fsl
LaPeer	2-6	3a	(6,1.5)	Mesic	1	2 e			l,sil
LaPeer	6-12	3a	(6,1.5)	Mesic	1	3 e			lfs
									scl
Leelanau	0-6	4a	(5,2)	Frigid	1	3 s		B1	ls
Leelanau	6-12	4a	(5,2)	Frigid	1	3 e			s
Mancelona	0-2	4a	(5,2)	Frigid	2	3 s	10260	B1	ls,lfs,
Mancelona	2-6	4a	(5,2)	Frigid	2	3 s	1665		gr-ls,sl,
Mancelona	6-12	4a	(5,2)	Frigid	2	3 e	11172		gr-sl,s,
									gr-s
McBride	0-2	3a	(14,1)	Frigid	1	2 s	6662	D2	sl,gr-sl
McBride	2-6	3a	(14,1)	Frigid	1	2 e	37456		ls
McBride	6-12	3a	(14,1)	Frigid	1	3 e	14719		
Montcalm	0-2	4a	(5,2)	Frigid	1	3 s	3894	B1	ls
Montcalm	2-6	4a	(5,2)	Frigid	1	3 s	31655		gr-ls
Montcalm	6-12	4a	(5,2)	Frigid	1	3 e	48992		sl
Munising	0-2	3a	(14,1)	Frigid	1	2 s		D2	sl,fsl
Munising	2-6	3a	(14,1)	Frigid	1	2 e		D2	ls,lfs
Munising	6-12	3a	(14,1)	Frigid	1	3 e		D2	
Newaygo	0-2	3/5a	(12,1)	Frigid	2	2 s	403	C1	sl
Newaygo	2-6	3/5a	(12,1)	Frigid	2	2 e	48		l
Newaygo	6-12	3/5a	(12,1)	Frigid	2	3 e			

Table B-2 (cont'd).

Name	Percent Slope	Mgt Group	Irr Group	F/M	No. Stories	Land Class e/s	Area (Acres)	NEW CLASS	Topsoil Texture
Nottawa	0-3	4a	(12,1)	Mesic	2	2 s	2855	B2	sl
									l
Oakville	0-6	5.3a	(3,3)	Mesic	1	4 s	-842	A2	ls,lfs
Oakville	6-15	5.3a	(3,3)	Mesic	1	6 s	-1010	U	fs,s
Omena	0-2	3a	(6,1.5)	Frigid	1	2 s		B2	sl,fsl
Omena	2-6	3a	(6,1.5)	Frigid	1	2 e			
Omena	6-12	3a	(6,1.5)	Frigid	1	3 e			
Ormas	0-6	4a	(5,2)	Mesic	2	3 s	13830	B1	ls,lfs
Ormas	6-12	4a	(5,2)	Mesic	2	3 e	950		s
						(irr)			
Oshtemo	0-2	3a	(6,1.5)	Mesic	2	3 s	-67144	B2	sl,fsl
Oshtemo	2-6	3a	(6,1.5)	Mesic	2	3 e	-89526		ls,lfs
Oshtemo	6-12	3a	(6,1.5)	Mesic	2	3 e	31500		
Ottokee	0-2	4a	(5,2)	Mesic	1	3 s	-1251	B1	lfs,ls
Ottokee	2-6	4a	(5,2)	Mesic	1	3 s	-2502	B1	fs,s
Ottokee	6-8	4a	(5,2)	Mesic	1	3 e	-1251	B1	
Pence	0-2	4a	(6,1.5)	Frigid	2	3 s		B2	sl,fsl
Pence	2-6	4a	(6,1.5)	Frigid	2	3 e			l
Pence	6-12	4a	(6,1.5)	Frigid	2	4 e			ls
Perrin	0-6	4a	(5,2)	Mesic	2	3 s		B1	ls
									gr-ls
									sl
						(irr)			
Plainfield	0-6	5.3a	(2,4)	Mesic	1	3 e	11766	A1	ls,lfs
Plainfield	6-12	5.3a	(2,4)	Mesic	1	6 s	1623	U	s,fs
Rouseau	0-6	4a	(3,3)	Frigid	1	3 s	728	A2	fs
Rouseau	6-12	4a	(3,3)	Frigid	1	3 e			lfs
Schoolcraft	0-2	3/5a	(12,1)	Mesic	2	2 s	12295	C1	l
Schoolcraft	2-6	3/5a	(12,1)	Mesic	2	2 e	6450		sil
Schoolcraft	6-12	3/5a	(12,1)	Mesic	2	3 e			sl
Spinks	0-6	4a	(5,2)	Mesic	1	3 s	82957	B1	ls,lfs
Spinks	6-12	4a	(5,2)	Mesic	1	3 e	24183		s,fs
Stambaugh	0-2	3/5a	(12,1)	Frigid	2	2 s		C1	sil
Stambaugh	2-6	3/5a	(12,1)	Frigid	2	2 e			vfsl
Stambough	6-12	3/5a	(12,1)	Frigid	2	3 e			
Sunfield	1-2	3/5a	(14,1)	Mesic	2	2 s		D2	l,sl
Sunfield	2-6	3/5a	(14,1)	Mesic	2	2 e			

Table B-2 (cont'd).

Name	Percent Slope	Mgt Group	Irri Group	F/M	No. Stories	Land Class e/s	Soil Area (Acres)	NEW CLASS	
Trenary	0-2	3a	(9,1)	Frigid	1	2 s		C2	fsl,vfsl
Trenary	2-6	3a	(9,1)	Frigid	1	2 e			
						(irr)			
Vilas	0-6	5.3a	(3,3)	Frigid	1	3 e		A2	ls
Vilas	6-12	5.3a	(3,3)	Frigid	1	6 s		U	s

Table B-3. Presently irrigated crop acreage partitioned into non-erodible and erodible parts, assuming: 1) irrigated land is generally equal to or less than six percent slope, and 2) that the irrigated lands have about the same proportion of slopes as the soil group as a whole. The percent of grand total is to the lower right of the acreage. (Top five irrigated counties in Michigan*)

Soil Class	Soil Name	Non-Erodible (Acres)	%	Erosion Susceptible (Acres)	%	Totals	%
A1	Plainfield	530	0			530	0
A2	Coloma	1147	1			1147	1
B1	Ormas	4809	4			4809	4
	Spinks	26130	21			26130	21
	Mancelona	1508	1			1508	1
	Montcalm	11200	9			11200	9
B2	Hillsdale	7623	6			7623	6
	Oshtemo	18352	14	25454	20	43806	35
C1	Fox	10694	8	6554	5	17248	14
	Kalamazoo	3451	3	4447	4	7898	6
D2	McBride	1270	1	3530	3	4800	4
	Totals	85037	67	41662	33	126699	100

* St. Joseph, Branch, Van Buren, Montcalm and Calhoun

Table B-4. Erosion-prone acreage and percentage of ALL potentially irrigable soils (less than or equal to six percent, with profile characteristics similar to those presently irrigated). (For the five top irrigated counties in MI*)

Soil Class	Soil Name	% Slope	Non-erodible	%	% Slope	Erosion Susceptible	%	Totals	%
A1	Covert	0-4	3944	1				3944	1
	Plainfield				0-6	11766	2	11766	2
	Croswell	0-6	958	0				958	0
A2	Coloma				0-6	9495	2	9495	2
	Oakville	0-6	842	0				842	0
	Rousseau	0-6	728	0				728	0
B1	Bronson	0-2	7263	1	2-6	2421	0	9684	2
	Ormas	0-6	13830	3				13830	3
	Ottokee	0-6	3753	1				3753	1
	Spinks	0-6	82957	16				82957	16
	Mancelona	0-6	26914	5				26914	5
	Montcalm	0-6	35549	7				35549	7
B2	Elston	0-2	5775	1	2-6	770	0	5645	1
	Hillsdale	2-6	32917	6				32917	6
	Nottawa	0-3	2855	0				2855	1
	Oshtemo	0-2	67144	13	2-6	48410	9	115554	23
C1	Fox	0-2	21425	4	2-6	13284	5	34709	7
	Kalamazoo	0-2	30872	6	2-6	39784	8	70656	14
	Schoolcraft	0-2	12295	2	2-6	2580	1	14875	3
	Newaygo	0-2	403	0	2-6	19	0	422	0
C2	Elmdale	0-2	4478	1	2-6	3582	1	8060	2
D2	McBride	0-2	6662	1	2-6	18515	4	25177	5
	Totals		361564	71		150626	29	512190	100

* St. Joseph, Branch, Van Buren, Montcalm and Calhoun

APPENDIX C

The MSU infiltrometer: construction notes and diagrams

by Andrew H. Granskog, Research Assistant, Department of Agricultural Engineering, Michigan State University. Jan 20, 1989

I. Introduction

The MSU infiltrometer is a portable device used to measure time to ponding in the field. The infiltrometer consists of a 325 gallon water tank, a gasoline generator, and a spray boom with six independently controlled nozzles. Desired application rates are achieved by a timing circuit that controls the nozzles so that six different application rates can be achieved. See the overall infiltrometer schematic in Figure C-1.

The purpose of this paper is to document the construction of the MSU infiltrometer in enough detail so that through the use of these notes, drawings, and circuit diagrams, a working facsimile of the MSU infiltrometer can be made and used to measure times-to-ponding in the field. For information and discussion on how the infiltrometer was used and the results gained, see the paper entitled: "The MSU Infiltrometer: A Device to Measure Times-To-Ponding" by Patricia A. Crowley, Andrew H. Granskog, research assistants, and Dr. George E. Merva, Professor, Department of Agricultural Engineering, Michigan State University, East Lansing, MI 48824.

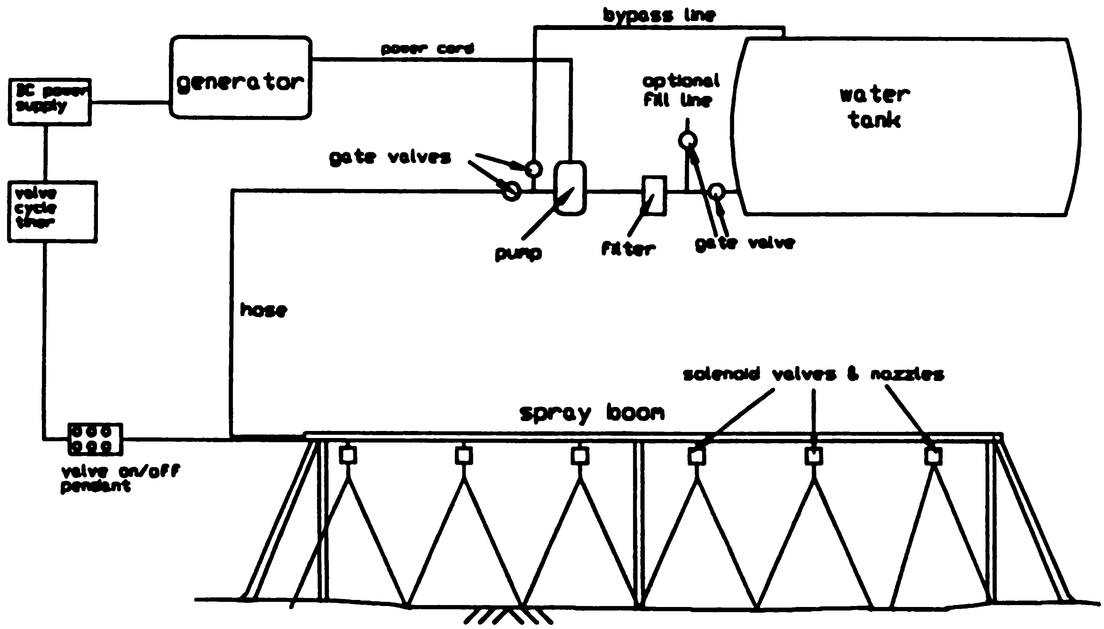

Figure C-1. The MSU infiltrometer schematic.

II. Construction notes:

A. Spray boom

The spray boom was designed to be in two separable sections, each having three nozzles. Two 12′ lengths of 1" square 1/8" wall steel tubing were used for the two sections of the boom. A 1/2" pipe nipple was butt welded on to both sections at each end. By putting a pipe cap on one end and applying water pressure to the other, any leaks in the welds could be discovered and sealed. Three holes were drilled and tapped (1/4" NPT) for the nozzles (see Figures C-2 and C-3, boom diagrams 1 & 2) on both sections.

For boom 1, a 1/2" x 3/4" pipe bushing was screwed on to the 1/2" nipple. Then a NPT to hose adapter was added. This allowed that end of the pipe to be attached to the supply hose. The other end of the first boom section was hooked to the second boom using a short section of 3/4" hose (secured by hose clamps) and the male end of a 1/2" Camlock E05 Quick Coupling. The hose offered a flexible connection making it easier to put the two booms together (see Figure C-2, boom detail 1).

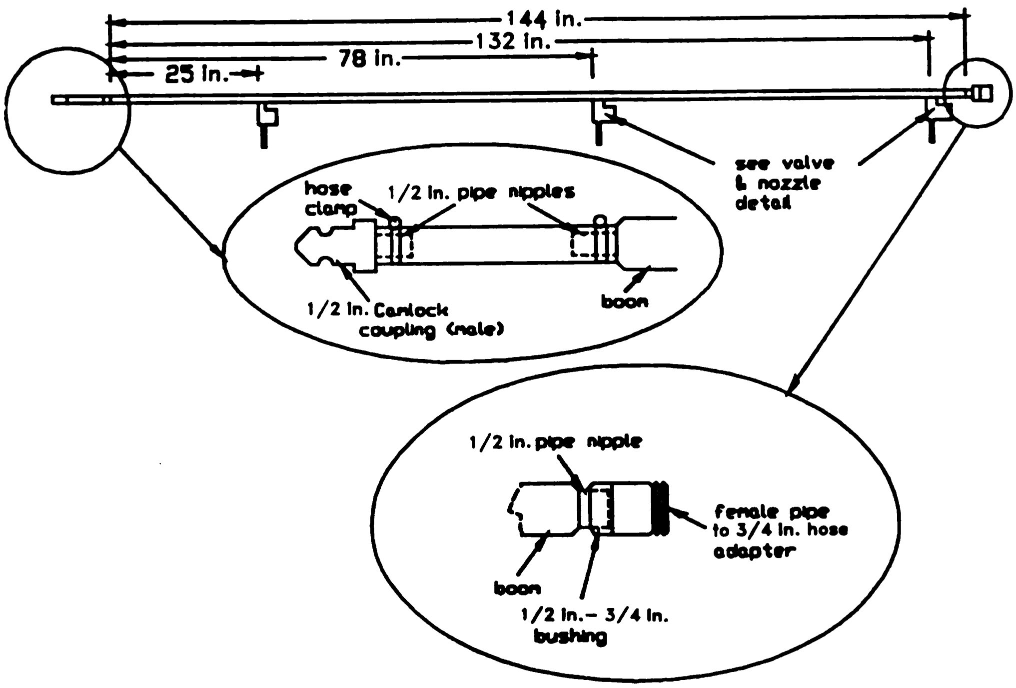

Figure C-2. Boom detail 1.

For boom 2, the female end of the 1/2" Camlock E05 Quick Coupling was screwed onto the 1/2" nipple. Holes were drilled and tapped (as per Figure C-3, boom diagram 2) for the nozzles. Finally, a globe valve was attached via a 1/2" x 3/4" bushing to the other end. The purpose of the globe valve was to enable air to be purged from the system before startup.

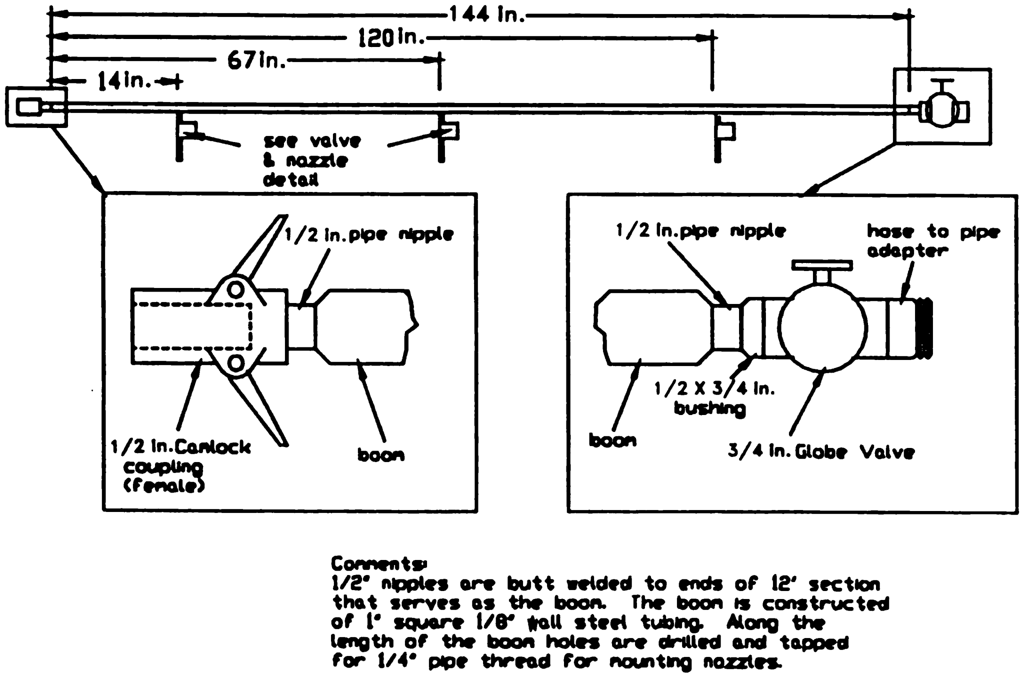

Figure C-3. Boom detail 2.

B. Boom supports, tripod and bipod legs

The spray boom was to be supported at a height of about 1 m with a tripod on each end and a bipod in the middle. To facilitate leveling on uneven ground, telescoping legs were used.

The telescoping legs (for both tripods and bipod) were constructed of two sections of steel tubing. The inner leg was 16 gauge 3/4" tube while the outer was 12 gauge 1" square tube. The inner leg section was 18" long and the outer was 43". One end of the inner leg section was cut at a 65 degree angle and a 2" x 4" x 1/8" plate was welded to serve as a footpad. Each outer leg section had a 1/4" hole drilled in one end to affix it to the head (bipod or tripod). Also a 1/4" hole was drilled through one wall of the outer leg about 6" from the end with the footpad. A 1/4" nut was aligned and spot welded over the hole. A 3/4" x 1/4" diameter bolt with a handle spot welded to it was screwed into the 1/4" nut welded to the leg. This nut/bolt arrangement served as a locking mechanism to hold the inner leg at the desired position so the telescoping legs could be adjusted in length and locked. Finally, chains were attached between the legs of the tripods and bipod (away from the spray pattern) to keep them from opening too wide during use (see Figure C-4, bipod & tripod detail).

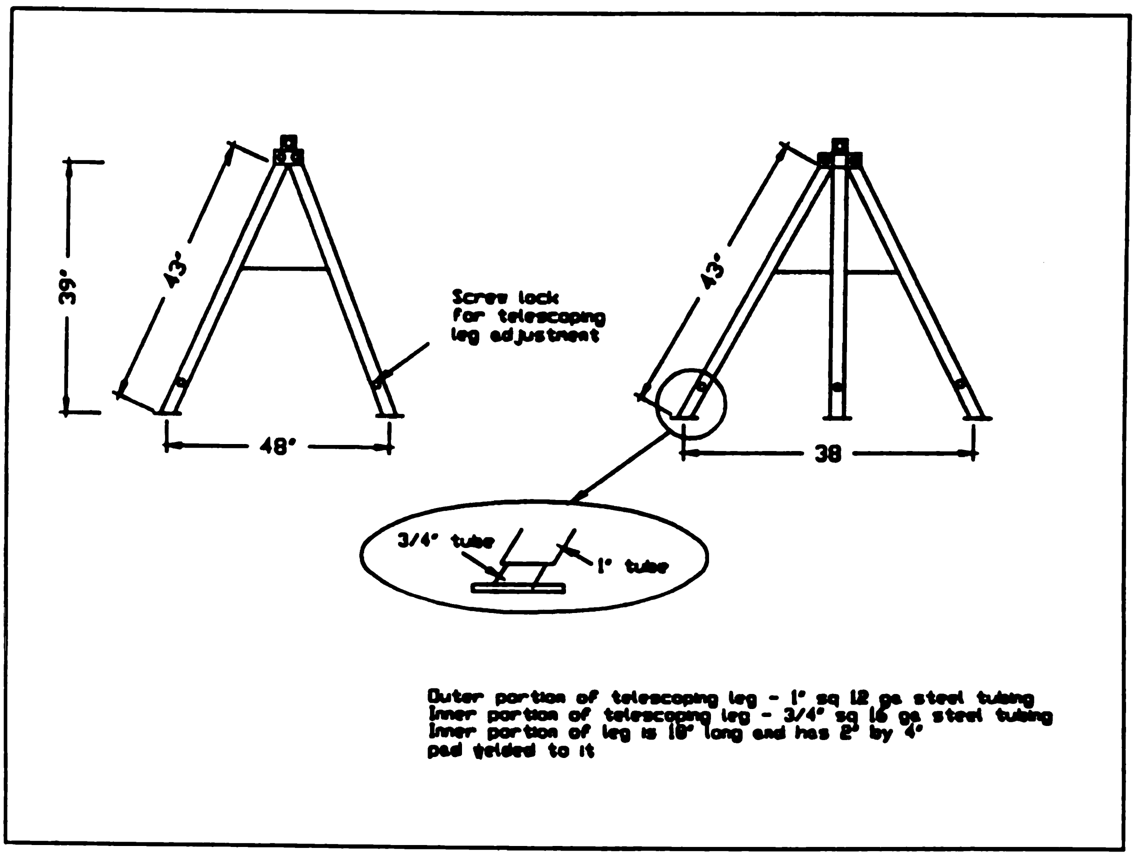

Figure C-4. Bipod and tripod detail.

C. Tripod and bipod heads

The tripod heads (see Figure C-5, tripod head detail) were constructed of lightweight 1/8" flat steel and welded. The bipod head was also constructed in similar fashion and welded, although the main length of the bipod head was made of 1/4" flat steel (see Figure C-6, bipod head detail). Note that the heads are designed to receive the square booms and hold them securely without twisting.

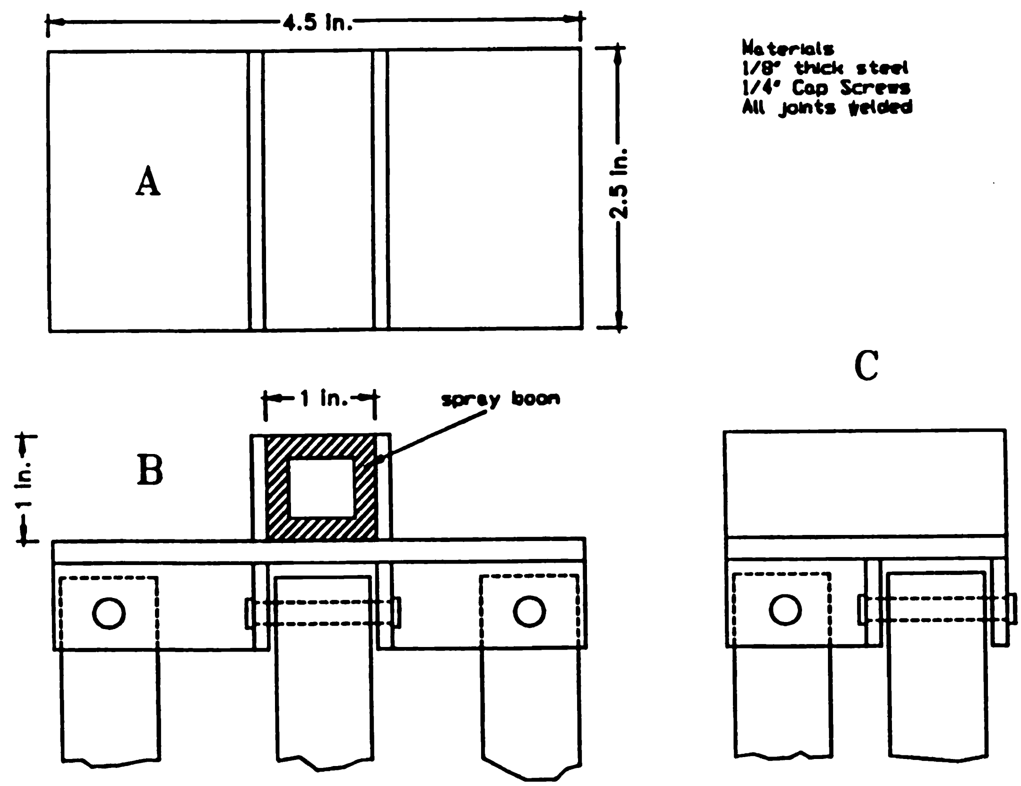

Figure C-5. Tripod head detail: A) Top view, B),C) Side view.

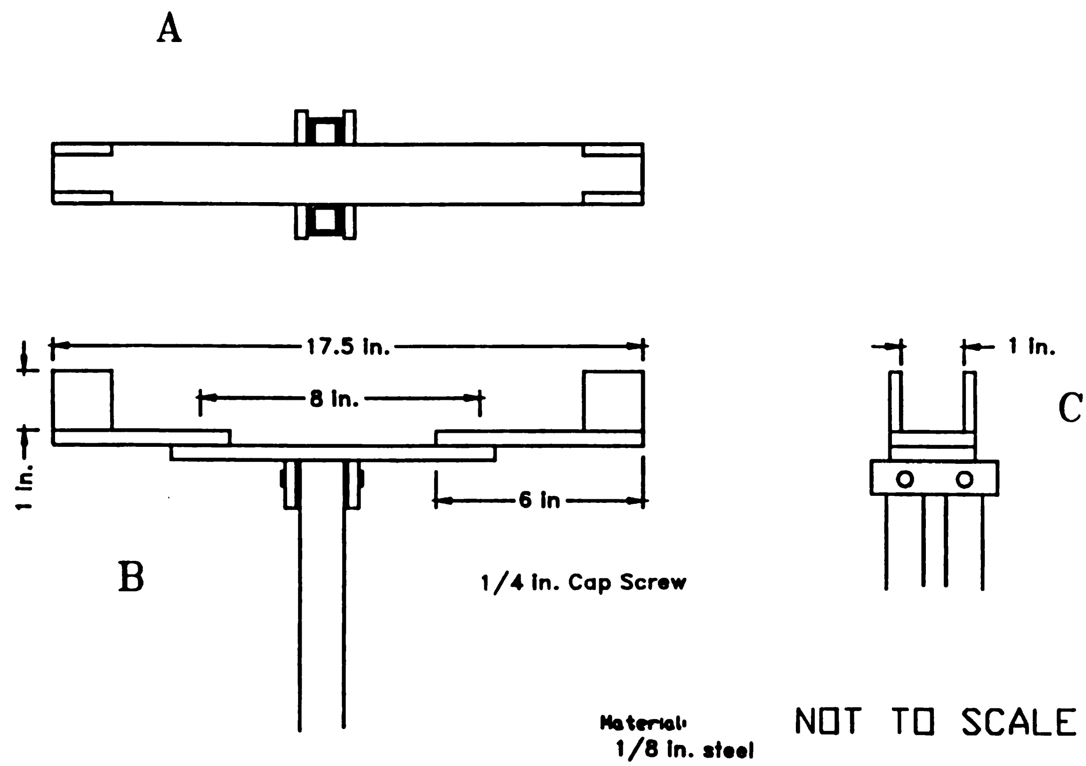

Figure C-6. Bipod head detail: A) Top view, B,C) Side views.

D. Valves and nozzles

A diagram of how the valve and nozzles were put together is shown in Figure C-7, valve and nozzle detail. In all pipe connections, 1-1/2 turns of teflon tape was used to prevent leaking. Nozzle orientation to the ground was accomplished using 6" flexible gooseneck tubing. These gooseneck tubes were flexible metal coolant lines with 1/4" brass male NPT fittings on each end. They were custom made by Cathey Co. of Lansing, MI.

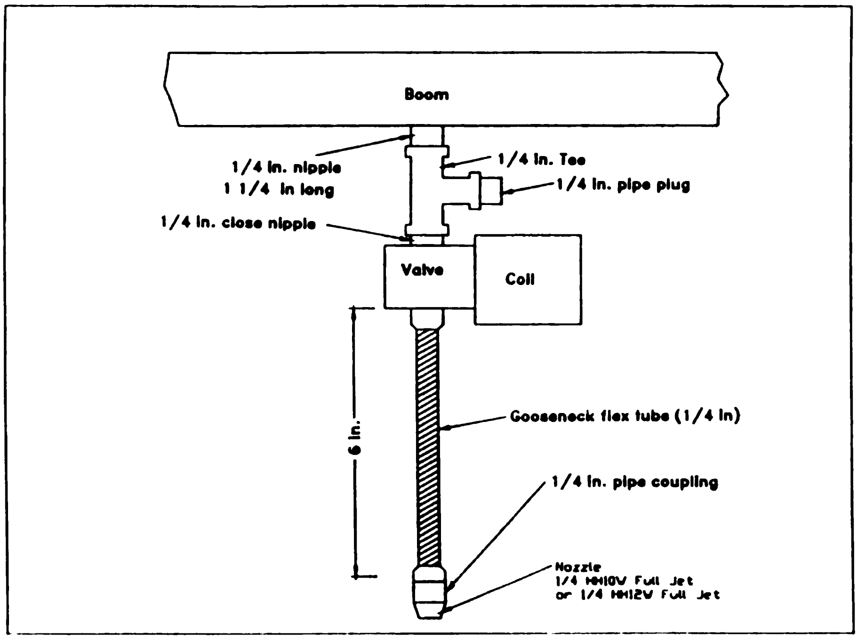

Figure C-7. Valve and nozzle detail.

E. Trailer

A 14′ tandem axle trailer (7000 lb. payload) was purchased and outfitted with tail lights and plates for highway use. The installation of major components was as follows:

The 325 gallon polypropylene tank was placed in the center just forward of the axle of the trailer (see Figure C-8, infiltrometer trailer detail). Four 1/2" holes were drilled through the trailer deck and underlying 2" square steel frame. Two straps were made of 1" wide by 1/8" thick flat steel 84" long. To each end of the straps, 18" long 1/2" diameter threaded rods were welded with 12" of the rod protruding. The straps were then bent over the tank and the bolts were pushed down through the holes. One half inch nuts and washers on the bolts finished the arrangement, firmly and tightly securing the water tank to the trailer. Note that it is important to secure the tank to the trailer securely because of its extreme weight when full (note: the spray tank used had no inner baffles so it is recommended that during transportation it be either completely full or empty). As per the diagram, the generator was bolted to the deck in a forward corner of the trailer. It was suspended by spring loaded rubber feet to reduce vibration. An equipment box 4′ x 2′ x 2′ in size was secured to the deck (with # 10 wood screws 1-1/2" long) in the opposite corner. It was used to hold the boom supports, electronic circuitry, miscellaneous tools, etc. and was fitted with a hasp and lock to discourage theft. A hose spool constructed of 3/4" square tubing is also shown. It was mounted on a spindle bolted to the deck of the trailer and stored 260 feet of 3/4" hose that went from the trailer to the boom. The plumbing circuit shown was assembled out of 3/4" pipe, fittings and a section of 3/4 garden hose (the bypass line). All plumbing connections were made with 1-1/2 turns of teflon tape on the male end. After the circuit was put together, the pump was bolted to the trailer deck with two bands made of 1/4" diameter 18" long threaded rod. A small sheet metal cover was made for the pump to protect it from the rain.

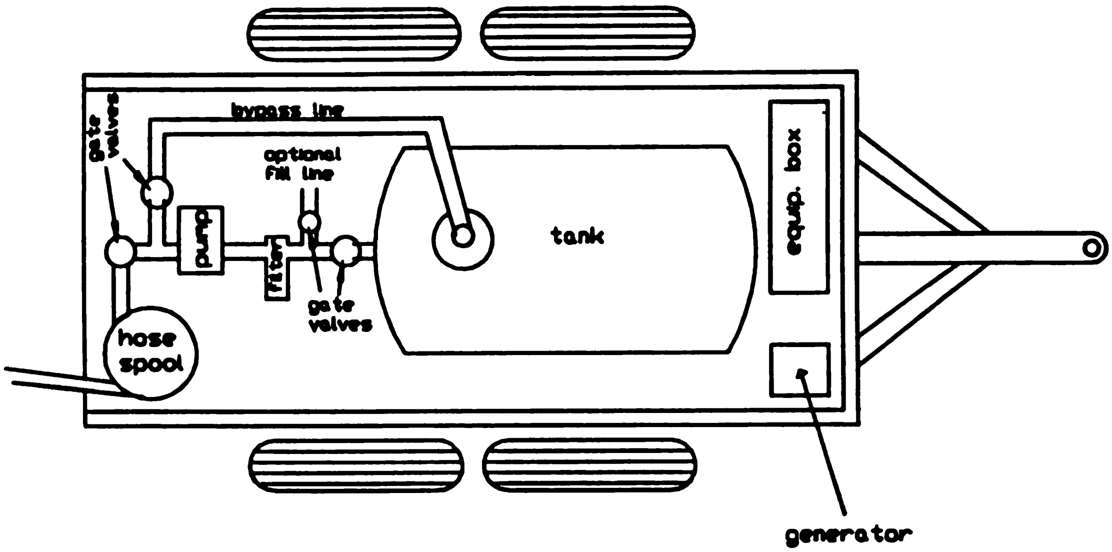

Figure C-8. Infiltrometer trailer, top view.

F. Timing circuit

The entire timing control circuit (power supply, timer control box, and valve pendant switch) was located near the spray boom during the test. Application rates were adjusted with the potentiometer knobs on the timer control box. Individual valves could be turned on or off with toggle switches located on the valve control pendant. For nozzle number six, the timing circuit could be bypassed leaving the valve continuously on if desired.

Four circuit diagrams are included in this paper. The first, Figure C-9, is a general block diagram of the entire circuit showing the power supply, timer box and the valve control pendant. The system was run using 120 VAC power from the gasoline generator. The AC current was converted to DC with the dual power supply. The power supply (see Figure C-10, power supply schematic) supplied a constant 28 VDC @ 3A on one side and 13.5 VDC @ 1A on the other. The 28 VDC was used to power the solenoid valves while the 13.5 VDC was used for the timing circuitry. The power supply was encased in its own separate NEMA enclosure (9 1/2" x 6 3/4" x 3").

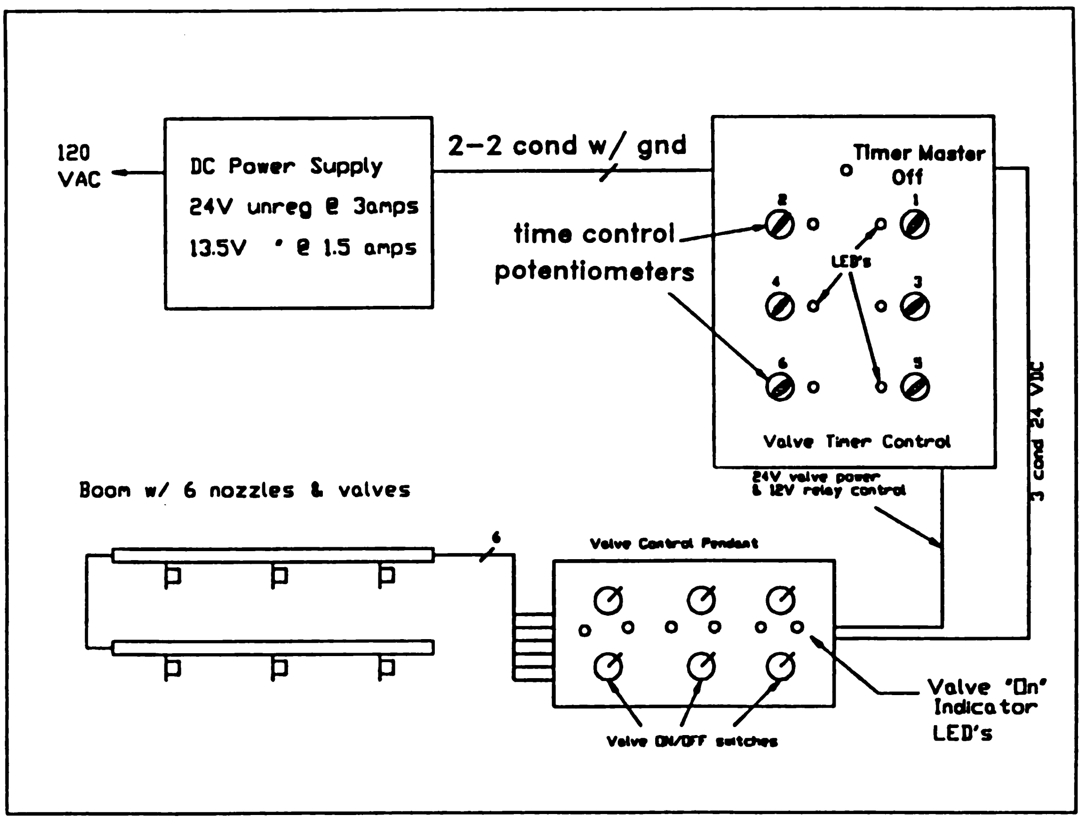

Figure C-9. Timing control circuit block diagram.

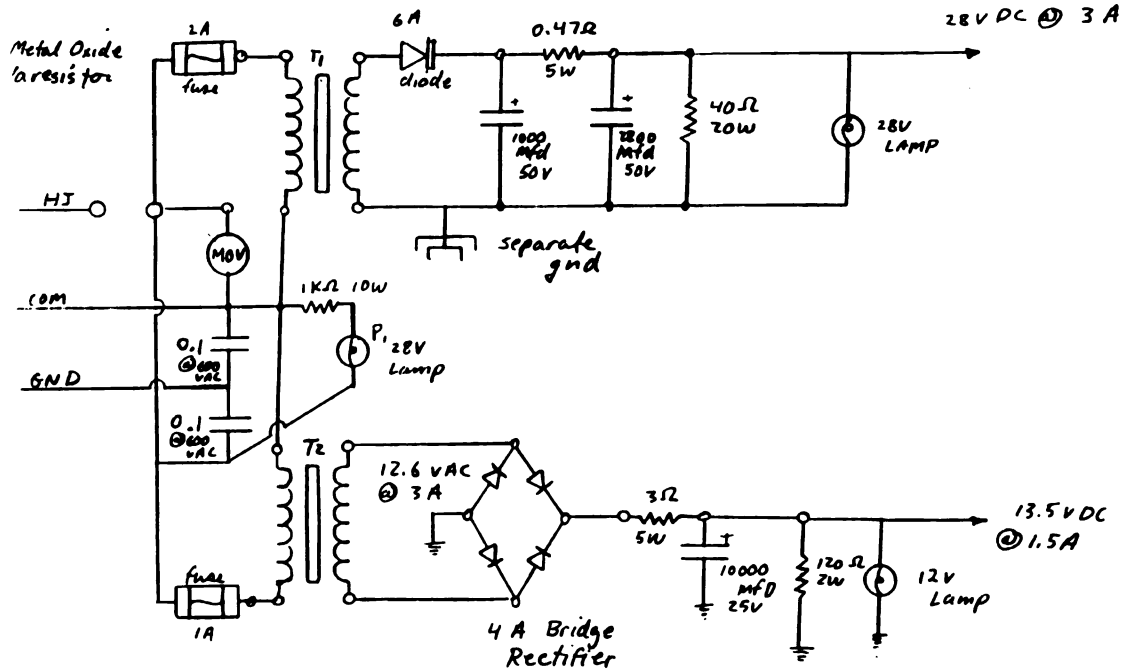

Figure C-10. Power supply schematic.

The timer control box (see Figure C-11, timer control box) contains the timing circuitry required to turn the solenoid valves on and off to achieve the required application rates. The timer box consisted of six valve cycle timer circuits on perforated hobby boards connected with 6 dual 1 megaohm potentiometers all connected to a 10V regulator circuit and encased in a 14" x 11" x 2" aluminum box. Also shown is a cutoff switch for the 13.5 VDC supply and fuses for both 28 VDC circuit and the 13.5 VDC (note: the 28 VDC and 24 VDC circuits are the same as well as the 13.5 VDC and 12 VDC) circuit.

The timer circuit (see Figure C-12, valve timer schematic) is based on two 555 timers cross coupled to trigger each other resulting in a timed flip flop. Dual 1 megaohm potentiometers controlled the two timers. In this way, the potentiometers could be used to control the valve "on" times and "off" times inversely proportional to each other. Later the "on" time potentiometer was fixed and the "off" time was varied to change the application rate. The dual potentiometer and dual timer circuit was implemented for each solenoid valve. See Figure C-12 (valve timer schematic) for details and parts used.

The regulator circuit is shown in detail in Figure C-13. Two regulator circuits are shown, one was the circuit actually used and the other is an improved, more inexpensive version.

Lastly, the valve control pendant detail is given (see Figure C-13). The valve control pendant (encased in a small plastic box) was on the control cable near the spray boom. It was originally intended that the valve control pendant could be near the spray boom while the rest of the electronics was located at the trailer. During field use it was beneficial to have the timer control also near the spray boom so in the future it is recommended that the two be combined into one unit.

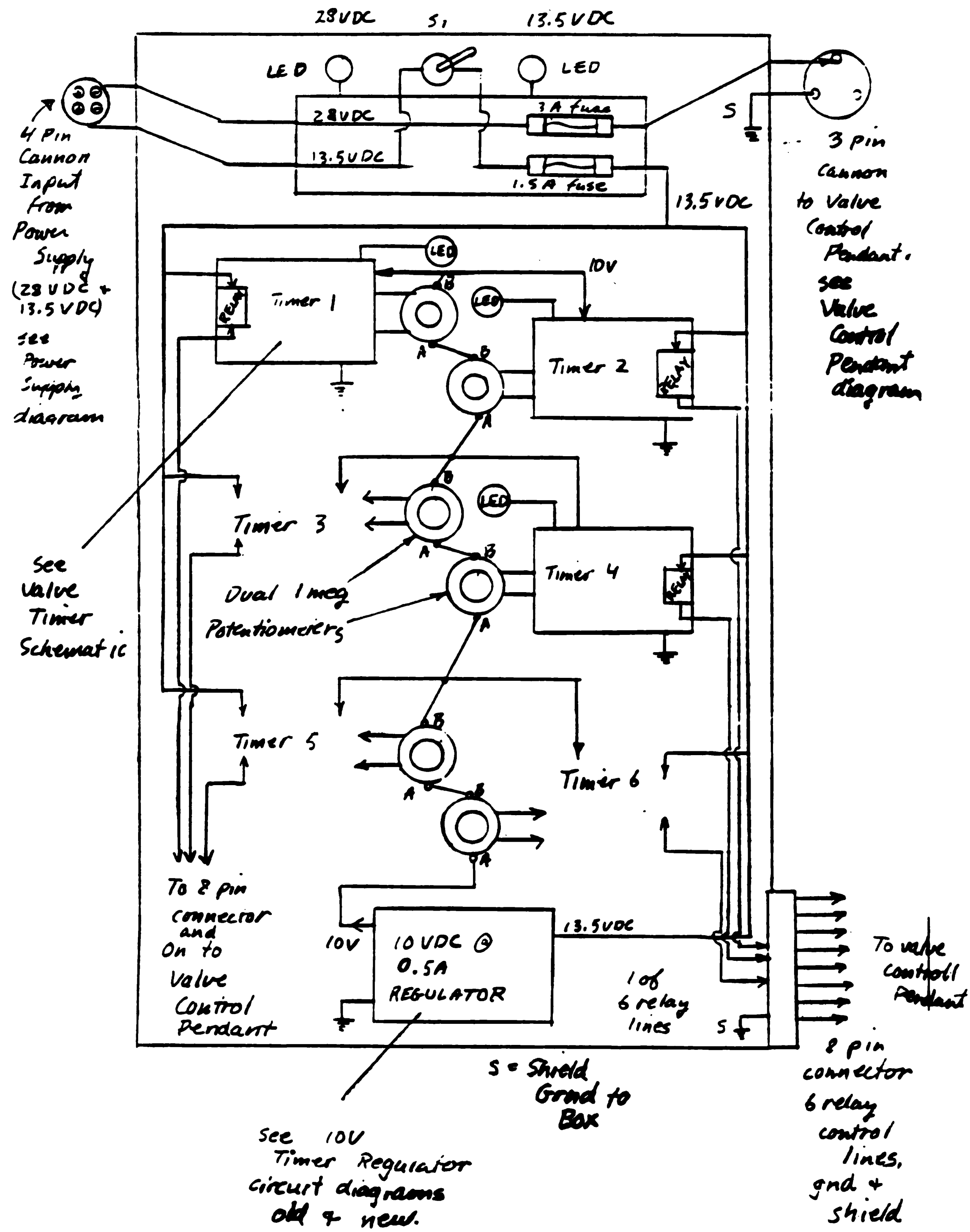

Figure C-11. Timer control box.

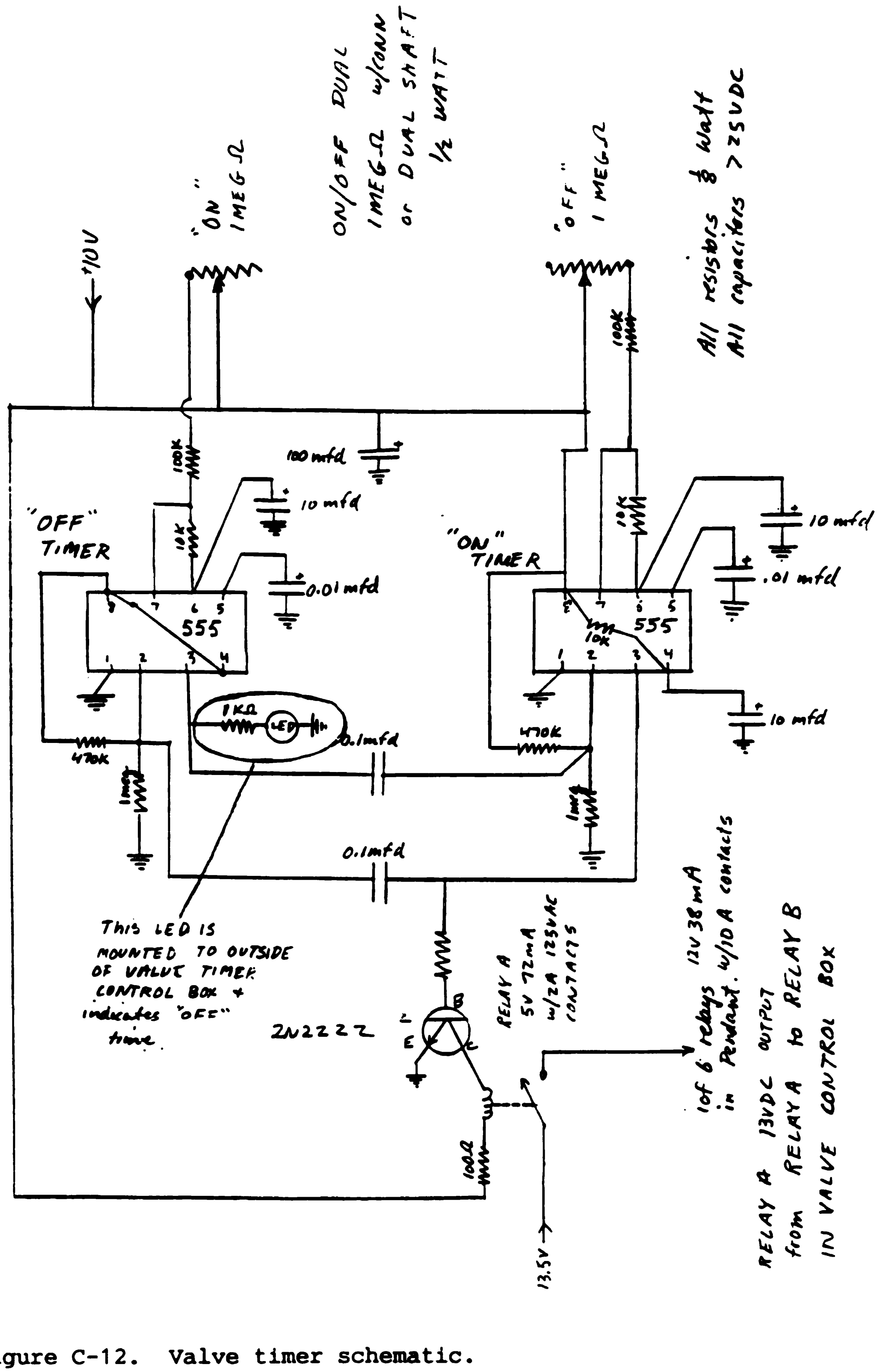

Figure C-12. Valve timer schematic.

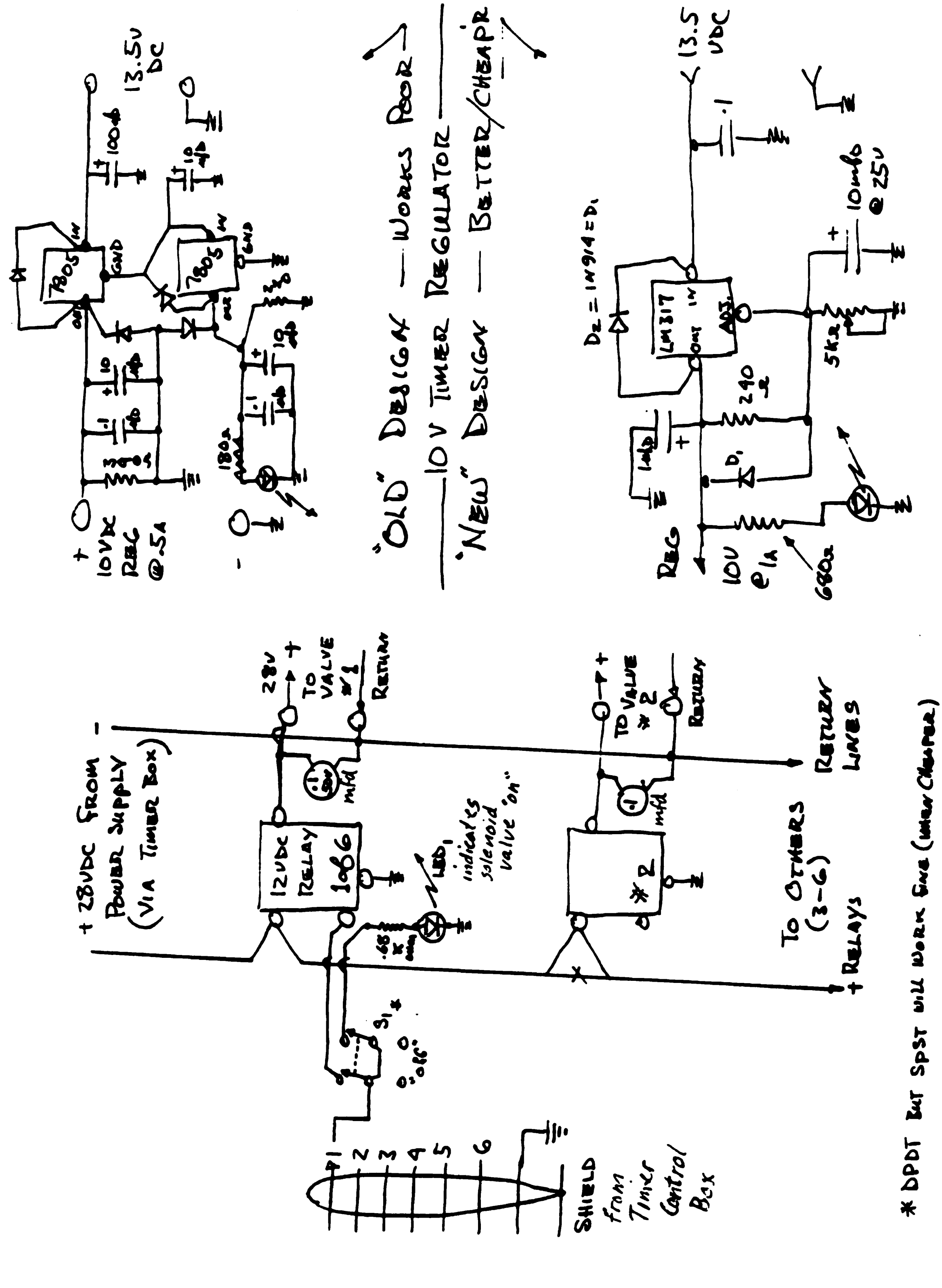

Figure C-13. Valve control pendant detail.

III. Parts List

Large Components	Suggested Price
1 Norwesco 325 gal polypropylene spray tank	250.00$
1 Tandem Axle Trailer 14′ 7000# payload	1350.00$
1 Teel 1/2 Hp self priming centrifugal pump	85.00$
1 Gasoline Generator 4000 W continuous output	400.00$
Plumbing Supplies	
6 solenoid valves (3A432-8 Graingers Catalog)	85.00$
6 solenoid coils (6X5432-1 " "	60.00$
6 1/4" tees	3.12$
4 1/2" close pipe nipples	0.60$
6 1/4" " " "	1.20$
6 1/4 x 1-1/2" pipe nipples	1.28$
6 1/4" pipe plugs	1.20$
4 3/4" gate valves	12.88$
1 3/4" globe valve	3.22$
1 100 mesh screen T line filter	9.50$
1 2" to 1" plastic pipe bushing	1.00$
1 1" to 3/4" plastic pipe bushing	0.75$
3 3/4" garden hose to NPT pipe adapters	2.50$
1 7′ length 3/4" garden hose	4.48$
1 250′ length 3/4" garden hose	160.00$
1 EO5 male Camlock Coupler 1/2"	3.12$
1 EO5 female Camlock Coupler 1/2"	7.64$
3 3/4" x 3" nipples	1.50$
3 3/4" elbows	1.50$
2 3/4" hose clamps	1.50$
3 1/4HH12W	
3 1/4HH10W Full-Jet Nozzles Spraying Systems Co. Wheaton IL	
Construction Materials	
48′ 12 gauge 1" square steel tube	60.00$
14′ 16 gauge 3/4" square steel tube	6.00$
24′ 1" 1/8" wall square steel tube	36.00$
3′ 3" x 1/8" flat steel	3.00$
4 2" x 4" x 8′ boards	6.08$
1 1/2" x 4′ x 8′ plywood	17.80$
1 1/4" x 4′ x 8′ "	12.31$
misc. fasteners and wood glue	6.00$
Electronic Parts	
See Circuit Diagrams	275.00$

Total not including labor	2721.99$

APPENDIX D

Three methods for measuring bulk density, θ_g, and θ_v

Three methods for the measurement of bulk density (BD), percent gravimetric soil moisture (θ_g), and percent volumetric moisture (θ_v) were selected: the Grossman compliant cavity method, the Madera sampler method, and the modified Grossman method. We included these three because we wanted to make sure that the variables were estimated as well as possible and we wanted to understand the advantages and disadvantages of each method so we could streamline the collection of field data associated with the sprinkling infiltrometer tests.

I. The Grossman compliant cavity method.

The Grossman compliant cavity method is a relatively compaction-free technique by which the volume of a soil sample can be determined in situ by calculating the equal volume of water needed to replace the excavated soil.

A 5 cm-thick x 5 cm-wide foam rubber ring with a 13 cm inner diameter is placed over a soil surface which has been cleared of loose residue. Next, a 1 cm-thick x 9 cm-wide Plexiglas plate with the same inner diameter is then positioned over the foam ring and stabilized by driving three pins through holes in the Plexiglas to about 25 cm into the soil. The Plexiglas plate is leveled using a carpenter's level and the foam ring becomes somewhat compressed against the soil surface.

A 46 cm-wide sheet of plastic film is laid closely over the soil, along the sides of the foam, and over the Plexiglas. A hook gage apparatus is then set into the Plexiglas ring so that the hook protrudes into the center of the rings. Water is poured into the plastic-lined hole until an exact water level is obtained when the hook barely dimples the water. The plastic film, full of water, is then carefully removed, and the volume of water (V1) measured with a graduated cylinder.

About 5 cm deep of soil is removed from the area encircled by the foam interior diameter, taking care not to excavate rocks that extend far beyond that diameter. The soil is then placed into an air-tight plastic bag.

The plastic film is again placed carefully over the soil and along the interior edges of the rings, the hook apparatus reinstalled, and a second, larger volume of water poured into the excavation, to the same level on the hook gage. This second volume of water (V2) is measured.

The soil in the plastic bag is weighed (M_s+M_w+C), dried in a 105°C oven overnight, and re-weighed (M_s+C).

Two excavations are done at each study site, one on each end of the sprinkling infiltrometer apparatus on the same day as the sprinkling infiltration tests are done. Each excavation removes about 600 cm^3 of soil from the center of the furrow. The entire procedure requires about 30 minutes, from on-site arrival to departure.

When the Grossman compliant cavity method is used, four measurements are needed to calculate BD and θ_v, and three measurements are needed to calculate θ_g. BD, θ_g and θ_v are defined below in terms of the measurements mentioned earlier in parentheses, assuming the density of water is 1 g/cm^3.:

$$BD(g/cm^3) = [(M_s+C)-(C)]/[(V2)-(V1)],$$

$$\theta_g(\%) = [(M_s+M_w+C)-(M_s+C)]/[(M_s+C)-(C)]x100, \text{ and}$$

$$\theta_i(\%) = [(M_s+M_w+C)-(M_s+C)]/[(V2)-(V1)]x100.$$

Exact dimensions cannot be excavated using the Grossman method in stony soils, but the sample can include desired rocks up to 12 cm in diameter. It should be further noted that there is a significant tendency for the plastic film to tear and leak water onto soil.

II. The Madera sampler method.

The Madera sampler method is a procedure which uses the Madera (tm) sampler to collect soil samples of identical volume without compaction.

A stainless steel tube with a slightly flared end is driven into the soil with a force generated by stepping vertically onto a solid steel rod placed horizontally through holes drilled into a cylindrical carrier holding the steel tube. The soil sample is detached from the adjacent soil with a slight twist of the tube, removed, and cut to a 60 cm^3 volume with steel spatulas slipped into slots in the tube above and below the desired sample. The moist soil from the tube is then transferred to an air-tight container and weighed (M_s+M_w+C); dried in a 105°C oven overnight, and re-weighed (M_s+C).

The least compacting version of the Madera sampler method is accomplished when the leading soil edge is allowed to proceed unhindered beyond the top slot as the tube is pushed into the soil, leaving the desired sample volume between the two slots, ready to be cut to the exact volume with the spatulas. But since the desired sample in this case included the soil surface itself, it was impossible to allow the leading soil edge, (the actual soil surface), to proceed beyond the top slot. For this reason, a spatula was inserted through the top slot in order to prohibit the movement of the soil edge beyond. It was recognized that the soil sample might become compacted as the result of the force placed on the soil area in contact with the spatula. Therefore, where soils of low bulk density were encountered (e.g. MBN and CPN), the soil tube was inserted by hand down to the spatula surface protruding from the slot, and the tube carefully removed by twisting. Where soil densities were higher, the driving force was provided by foot pressure to where the outside spatula surface just contacted the surface of the soil.

Ten madera samples are taken from each study site immediately before the sprinkling infiltrometer tests are conducted. Two samples from the center of each furrow are taken from each of the five areas between the six ponding observation areas under the sprinkling infiltrometer. It takes about 10 minutes to take ten samples, even under stony conditions.

When the Madera sampler method is used, two measurements and one assumption are needed to estimate BD and θ_v, and three measurements are needed to estimate θ_g. BD, θ_g and θ_v are defined as:

$$BD(g/cm^3) = [(M_s+C)-(C)]/60\ cm^3,$$

$$\theta_g(\%) = [(M_s+M_w+C)-(M_s+C)]/[(M_s+C)-(C)]x100,\ and$$

$$\theta_v(\%) = \{[(M_s+M_w+C)-(M_s+C)]/60\ cm^3\}x100.$$

The variance among the ten Madera samples per site helps to quickly characterize site homogeneity. There are problems in collecting samples with the Madera sampler in very dry or very rocky soil. When the soil was very dry, as it was at a MBN site on 6 July 88 (θ_g=2.14 as measured by the Grossman method), the sample fell out of the tube when the tube was lifted out of the ground. When the soil was very stony, the edge of the tube often rested on stone and the tube could not be pushed to the proper depth. Stones larger than the inner diameter of the tube cannot be included in the sample.

III. The modified Grossman method.

The modified Grossman method determines the BD, θ_v, and θ_g of the soil fraction that is less that 2 mm, using the mass of the dry soil sample remaining on a 2 mm (USA Standard Test Sieve No 10) sieve in combination with the measurements of the total soil sample obtained by the Grossman method mentioned above.

The dry soil sample from the Grossman compliant cavity method is wet-sieved through a 2 mm mesh and the portion remaining is dried and weighed ($M_{s>2mm}$+C). The mass of the fraction of soil less than 2 mm is then estimated to be $[(M_s+C)-(M_{s>2mm}+C)]$. The volume of the same fraction is determined by dividing the mass $[(M_s+C)-(M_{s>2mm}+C)]$ by the density of quartz (2.65 g/cm^3) and subtracting that quotient from the whole sample volume (V2 - V1). The mass and volume of the fraction of soil less than 2 mm is combined with the mass and volume of the water removed from the whole soil sample (using the first method) to calculate BD, θ_g, and θ_i.

When the modified Grossman compliant cavity method is used, five measurements and one assumption are needed to estimate BD, six measurements and one assumption are needed to estimate θ_v, and three measurements are needed to estimate θ_g. BD, θ_g and θ_v are defined in terms of the following measurements:

$$BD(g/cm^3)=[(M_s+C)-(M_{s>2mm}+C)]/([(V2)-(V1)]-\{[(M_{s>2mm}+C)-(C)]/2.65\}),$$

$$\theta_g(\%)=\{[(M_s+M_w+C)-(M_s+C)]/[(M_s+C)-(M_{s>2mm}+C)]\}x100, \text{ and}$$

$$\theta_v(\%)=[(M_s+M_w+C)-(M_s+C)]/([(V2)-(V1)]-\{[(M_{s>2mm}+C)-(C)]/2.65\})x100.$$

APPENDIX E

Time to ponding parameters, measurements, and model outputs

Four irrigation application scenarios which apply *the same total application depth* were selected to demonstrate the differences and similarities of the infiltration characteristics of the various soil, tillage, wheel track, and initial soil moisture (dry and wet) conditions. The four application scenarios originate from the permutation of the two basic variables of the parabolic pattern: the maximum application rate and the application period. The four scenarios are: 1) high maximum rate and one application period (H1); 2) high maximum rate and two application periods, each applying one-half the total application depth (H2); 3) low maximum rate and one application period (L1); and 4) low maximum rate and two application periods (L2).

Tables 1 through 4 show the effects of scenarios H1 ,H2, L1, and L2 on dry soils on a SITE basis; Tables 5 through 8 show the H1 through L2 effects dry soils COLLECTIVELY. Tables 9 through 12 show the effects of scenarios H1 through L2 on wet soils close to saturation COLLECTIVELY. Tables either show the data, parameters, and model results for all the fields on one page (as for COLLECTIVE tables), or on one field per page (as for SITE tables).

Table E-1. (H1) SITE. Appl. depth = 25.4mm, DRY data, high (57.4mm/h) maximum rate.

FIELD #1, KALAMAZOO SL, 1988

		%								(min)			(min)		(min)				(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	%D_s	CUMWT
3.27	MBW1	4	16.0	1.46		78.6	-0.620	0.98	3.1	7.2	2.20	34.0	2.0	5.68	34.7	8.25	10.45	41.1	37
6.03	MBW2	1	13.5	1.30		96.0	-0.720	0.87	2.3	7.5	2.37	35.1	2.1	6.13	34.4	8.23	10.60	41.7	44
AVG	MBW	3	14.7	1.38		87.3	-0.670	0.93	2.7	7.4	2.28	34.6	2.1	5.91	34.5	8.24	10.52	41.4	41
STD		1.4	1.2	0.1		8.7	0.0	0.1	0.4	0.1	0.1	0.5	0.0	0.2	0.1	0.0	0.1	0.3	4
CV		51	8	6		10	-7	6	16	2	4	2	2	4	0	0	1	1	9
6.08	MBN1	6	6.0	1.09		245.9	-0.840	0.99	3.1	12.1	5.58	48.5	3.6	11.06	31.3	12.04	17.63	69.4	44
5.31	MBN2	6	6.7	1.04		354.2	-0.817	.79*	5.1	16.0	8.96	55.1	5.1	14.60	29.0	13.81	22.76	89.6	37
5.24	SAMP	6	14.5	0.95		137.7	-0.730	0.83	3.1	9.4	3.58	41.4	2.7	8.12	33.1	10.20	13.79	54.3	37
AVG	MBN	6	9.1	1.03		245.9	-0.796	0.910	3.8	12.7	6.04	48.3	3.8	11.26	31.2	12.02	18.06	71.1	39
STD		0.0	3.9	0.1		88.4	0.0	0.1	0.9	3.3	2.2	5.6	1.0	2.6	1.7	1.5	3.7	14.5	3
CV		0	43	6		36	-6	9	25	26	37	12	26	24	5	12	20	20	8
5.25	CPW1	18	16.9	1.37		60.0	-0.390	0.75	7.9	7.5	2.34	34.9	2.3	5.25	34.6	10.21	12.55	49.4	37
6.06	CPW2	16	12.2	1.42		97.0	-0.540	0.91	5.9	9.1	3.40	40.6	2.7	7.37	33.4	10.88	14.28	56.2	44
AVG	CPW	17	14.5	1.40		78.5	-0.465	0.83	6.9	8.3	2.87	37.8	2.5	6.31	34.0	10.55	13.41	52.8	41
STD		0.9	2.4	0.0		18.5	0.1	0.1	1.0	0.8	0.5	2.8	0.2	1.1	0.6	0.3	0.9	3.4	4
CV		6	16	2		24	-16	10	15	10	18	7	9	17	2	3	6	6	9
6.01	CPN1	21	7.0	1.04		143.3	-0.490	0.65	11.2	13.7	6.90	51.7	4.5	11.07	30.7	14.69	21.59	85.0	37
6.09	CPN2	16	5.9	1.00		94.4	-0.407	.73*	11.4	10.8	4.58	45.3	3.5	8.16	32.5	13.61	18.19	71.6	44
AVG	CPN	19	6.4	1.02		118.8	-0.449	0.65	11.3	12.2	5.74	48.5	4.0	9.62	31.6	14.15	19.89	78.3	41
STD		2.8	0.6	0.0		24.4	0.0	0.0	0.1	1.4	1.2	3.2	0.5	1.5	0.9	0.5	1.7	6.7	4
CV		15	9	2		21	-9	0	1	12	20	7	13	15	3	4	9	9	9
6.07	NTW1	100	23.2	1.41		91.1	-0.350	.12*	14.8	11.53	5.15	47.2	3.9	8.25	32.2	14.87	20.02	78.8	44
5.26	NTW2	100	24.0	1.42		3445	-1.420	0.53											37
AVG	NTW	100	23.6	1.42		1768	-0.885	0.53	14.8	11.5	5.15	47.2	3.9	8.25	32.2	14.87	20.02	78.8	41
STD		0.0	0.4	0.0		1677	0.5												4
CV		0	2	0		95	-60												9
6.03	NTN1	100	25.5	1.41		193.4	-0.710	0.97	4.8	12.2	5.66	48.7	3.7	10.85	31.3	12.55	18.22	71.7	44
6.1	NTN2	100	16.2	1.23		388.7	-0.58	1.00*	19.1	39.8	25.4						25.40	100.0	44
AVG	NTN	100	20.8	1.32		291	-0.645	0.97	12.0	26.0	15.53	48.7	3.7	10.85	31.3	12.55	21.81	85.9	44
STD		0.0	4.6	0.1		98	0.1		7.1	13.8	9.9						3.6	14.1	0
CV		0	22	7		34	-10		60	53	64						16	16	0

Table E-1 (H1) (cont'd).

FIELD #2, OSHTEMO SL, 1988

		%								(min)				(min)		(min)			(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	$\%D_a$	CUMWT
7.11	MBW1	0	7.5	1.46		105.9	-0.666	0.92	3.3	8.5	2.95	38.4	2.4	7.03	33.8	9.47	12.43	48.9	162
7.19	MBW2	0	14.6	1.29		120.3	-0.724	0.98	2.8	8.7	3.11	39.2	2.5	7.38	33.6	9.50	12.61	49.6	185
7.26	MBW3	10	17.1	1.43		76.5	-0.555	0.96	4.3	7.6	2.40	35.3	2.2	5.90	34.4	9.00	11.40	44.9	216
8.01	MBW4	3	7.2	1.37		96.3	-0.545	0.80	5.7	9.1	3.38	40.5	2.7	7.38	33.4	10.80	14.19	55.9	229
8.08	MBW5	5	13.4	1.44		85.2	-0.712	0.95	2.1	7.0	2.09	33.3	1.9	5.62	34.8	7.68	9.77	38.5	282
AVG	MBW	4	11.9	1.40		96.8	-0.640	0.92	3.6	8.2	2.79	37.3	2.3	6.66	34.0	9.29	12.08	47.55	215
STD		3.7	4.0	0.1		15.4	0.1	0.1	1.2	0.8	0.5	2.6	0.3	0.8	0.5	1.0	1.5	5.7	41
CV		103	33	4		16	-12	7	34	9	17	7	11	11	2	11	12	12	19
7.12	MBN1	0	13.4	1.23		106.0	-0.587	0.89	5.0	9.2	3.47	40.9	2.7	7.62	33.3	10.68	14.15	55.7	162
7.19	MBN2	5	18.2	1.40		128.0	-0.774	0.99	2.3	8.6	3.03	38.8	2.4	7.32	33.7	9.23	12.26	48.3	185
7.26	MBN3	3	12.0	1.00		90.1	-0.604	0.91	3.9	8.1	2.72	37.2	2.3	6.54	34.1	9.36	12.08	47.6	216
8.01	MBN4	10	10.0	1.30		126.9	-0.620	0.94	5.1	10.1	4.06	43.4	3.0	8.54	32.7	11.33	15.38	60.6	229
8.08	MBN5	10	9.2	1.21		115.2	-0.595	0.70	5.2	9.8	3.84	42.5	2.9	8.18	32.9	11.16	15.00	59.1	282
AVG	MBN	6	12.6	1.23		113.2	-0.636	0.89	4.3	9.2	3.42	40.6	2.7	7.64	33.3	10.35	13.77	54.23	215
STD		3.9	3.2	0.1		14.1	0.1	0.1	1.1	0.7	0.5	2.3	0.3	0.7	0.5	0.9	1.4	5.4	41
CV		70	25	11		12	-11	11	26	8	14	6	10	9	1	9	10	10	19
6.24	CPW1-1	61	20.1	1.19		97.0	-0.500	0.90	7.2	9.7	3.76	42.2	2.9	7.71	33.1	11.69	15.45	60.8	122
6.28	CPW1-2	80	10.7	1.13		(380.9	-1.160	0.837)											124
6.24	CPW1-3	84	19.1	1.07		84.8	-0.417	0.48	9.7	9.7	3.80	42.4	3.0	7.34	33.2	12.50	16.30	64.2	124
6.29	CPW1-4	39	11.6	1.35		141.4	-0.779	0.89	2.5	9.2	3.43	40.7	2.6	7.96	33.3	9.81	13.23	52.1	122
6.30	CPW1-5	61	7.0	1.00		(956.9	-1.502	0.791)											122
AVG	CPW1	65	13.7	1.15		107.8	-0.565	0.76	6.5	9.5	3.66	41.7	2.9	7.67	33.2	11.33	14.99	59.02	123
STD		16.1	5.1	0.1		24.3	0.2	0.2	3.0	0.2	0.2	0.7	0.2	0.3	0.1	1.1	1.3	5.1	1
CV		25	37	10		23	-27	26	46	3	5	2	6	3	0	10	9	9	1
7.15	CPW2-1	59	6.1	1.29		168.5	-0.763	0.87	3.2	10.4	4.28	44.2	3.0	9.19	32.5	10.98	15.25	60.0	162
7.21	CPW2-2	54	14.8	1.16		92.0	-0.465	0.48	8.2	9.7	3.80	42.4	3.0	7.61	33.1	12.04	15.84	62.3	189
7.28	CPW2-3	86	16.3	1.11		ONLY 1	PONDED												229
8.03	CPW2-4	63	19.3	1.30		104.9	-0.765	0.96	2.0	7.7	2.47	35.7	2.1	6.36	34.3	8.28	10.75	42.3	241
8.11	CPW2-5	40	18.0	1.24		71.4	-0.493	0.55	5.5	7.5	2.36	35.1	2.2	5.65	34.5	9.39	11.75	46.3	294
AVG	CPW2	60	14.9	1.22		109.2	-0.622	0.72	4.7	8.8	3.23	39.3	2.6	7.20	33.6	10.17	13.40	52.75	223
STD		15.0	4.7	0.1		36.2	0.1	0.2	2.4	1.3	0.8	4.0	0.4	1.3	0.8	1.4	2.2	8.6	45
CV		25	31	6		33	-23	29	50	14	26	10	16	19	3	14	16	16	20

Table E-1 (H1) (cont'd).

FIELD #2, OSHTEMO SL, 1988 (CONT)

DATE	SITE	% RES	θ_i	BD	TXT	a	b	r^2	k	t_p (min)	D_{tp}	r_{tp}	t_1 (min)	f	t_2 (min)	D_p	D_{tot}	%D_a	CUMWT (mm)
6.27	CPN1-1	89	6.6	1.18		171.2	-0.546	.92*	10.0	14.4	7.57	53.0	4.7	12.06	30.2	14.59	22.16	87.2	122
6.29	CPN1-2	46	10.1	1.16		122.6	-0.595	0.92	5.6	10.3	4.19	43.9	3.1	8.65	32.6	11.60	15.79	62.2	124
6.3	CPN1-3	56	7.3	1.27		134.5	-0.568	0.85	7.0	11.5	5.10	47.0	3.5	9.68	31.9	12.76	17.86	70.3	124
6.27	CPN1-4	51	9.7	1.22		61.6	-0.303	.54*	12.8	8.48	2.96	38.5	2.8	5.52	34.1	12.63	15.60	61.4	122
6.28	CPN1-5	66	5.0	1.10		116.0	-0.390	.85*	15.3	13.1	6.46	50.7	4.5	9.70	31.2	15.49	21.95	86.4	122
AVG	CPN1	62	7.7	1.19		121.2	-0.480	0.88	10.2	11.5	5.26	46.6	3.7	9.12	32.0	13.42	18.67	73.51	123
STD		15.2	1.9	0.1		35.4	0.1	0.0	3.6	2.1	1.6	5.1	0.8	2.1	1.3	1.4	2.9	11.3	1
CV		25	25	5		29	-24	4	35	18	31	11	21	23	4	11	15	15	1
7.14	CPN2-1	84	7.2	1.04		116.9	-0.432	.76*	12.4	12.6	6.02	49.6	4.2	9.80	31.4	14.65	20.67	81.4	162
7.22	CPN2-2	89	10.3	1.09		110.8	-0.360	0.90	17.1	13.8	7.03	52.0	4.9	9.93	30.9	16.02	23.05	90.7	189
7.29	CPN2-3	60	16.9	1.09		64.7	-0.306	.75*	13.2	8.9	3.24	39.9	2.9	5.89	33.9	13.05	16.30	64.2	229
8.04	CPN2-4	54	11.9	1.02		64.0	-0.314	.57*	12.5	8.7	3.11	39.2	2.8	5.80	34.0	12.71	15.82	62.3	229
8.11	CPN2-5	53	16.0	1.13		101.1	-0.440	0.46	10.3	10.9	4.68	45.7	3.5	8.50	32.4	13.37	18.05	71.1	294
AVG	CPN2	68	12.4	1.07		91.5	-0.370	0.68	13.1	11.0	4.82	45.3	3.6	7.98	32.5	13.96	18.78	73.92	221
STD		15.4	3.6	0.0		22.7	0.1	0.2	2.2	2.0	1.5	5.1	0.8	1.8	1.2	1.2	2.7	10.7	45
CV		23	29	4		25	-15	33	17	18.2	31.8	11.3	21.0	22.8	3.8	8.7	14.5	14.5	20
7.14	NTW1	90	10.6	1.43		59.5	-0.204	.11*	20.6	9.69	3.78	42.3	3.5	5.26	33.7	15.69	19.47	76.7	162
7.21	NTW2	98	14.2	1.46		160.8	-0.619	.81*	6.5	12.1	5.61	48.6	3.7	10.47	31.5	12.94	18.55	73.0	189
7.27	NTW3	100	22.8	1.50		242.7	-0.698	.93*	6.5	14.7	7.79	53.4	4.7	13.08	29.8	13.87	21.66	85.3	229
8.02	NTW4	93	11.0	1.37		66.9	-0.370	0.33	9.8	8.3	2.87	38.0	2.6	5.88	34.1	11.56	14.43	56.8	241
8.1	NTW5	80	18.3	1.28		96.1	-0.469	0.84	8.4	10.1	4.10	43.6	3.1	8.02	32.8	12.37	16.47	64.8	294
AVG	NTW	92	15.4	1.41		125.2	-0.472	0.59	10.4	11.0	4.83	45.2	3.5	8.54	32.4	13.29	18.12	71.32	223
STD		7.1	4.6	0.1		68.7	0.2	0.3	5.3	2.2	1.7	5.3	0.7	2.9	1.6	1.4	2.5	9.8	45
CV		8	30	5		55	-37	44	51	20	36	12	19	34	5	11	14	14	20
7.12	NTN1	86	13.3	1.24		232.0	-0.747	0.71	4.8	13.3	6.57	51.0	4.1	12.01	30.6	13.04	19.61	77.2	162
7.21	NTN2	100	16.2	1.38		100.9	-0.487	0.47	8.0	10.1	4.10	43.6	3.1	8.09	32.8	12.26	16.36	64.4	189
7.27	NTN3	100	23.3	1.37		353.3	-0.753	.82*	7.1	17.9	10.73	56.8	6.0	15.78	28.0	14.15	24.88	97.9	216
8.02	NTN4	97	10.8	1.34		89.6	-0.33	.99*	16.1	11.8	5.35	47.8	4.0	8.22	32.1	15.31	20.66	81.3	229
8.1	NTN5	100	21.8	1.40		1385.	-0.93	.99*	11.1	39.8	25.4						25.40	100.0	294
AVG	NTN	97	17.1	1.35		432.3	-0.649	0.59	9.4	18.6	10.43	49.8	4.3	11.02	30.9	13.69	21.38	84.18	218
STD		5.4	4.8	0.1		486.4	0.2	0.1	3.9	10.9	7.8	4.8	1.1	3.2	1.8	1.1	3.4	13.3	45
CV		6	28	4		113	-33	20	42	59	75	10	25	29	6	8	16	16	20

Table E-1 (H1) (cont'd).

FIELD #3, MONTCALM SL, 1989

DATE	SITE	RES (%)	θ_i	BD	TXT	a	b	r^2	k	t_p (min)	D_{tp}	r_{tp}	t_1	f	t_2 (min)	D_p (min)	D_{tot}	$\%D_a$	CUMWT (mm)
7.31	MBW1	0	2.7	1.50	SL	120.7	-0.738	0.85	2.6	8.6	3.03	38.8	2.4	7.27	33.7	9.33	12.36	48.7	301
8.03	MBW2	3	11.5	1.47	SL	94.7	-0.755	0.99	1.9	7.2	2.20	34.1	2.0	5.86	34.6	7.79	9.99	39.3	332
7.25	MBW3	0	7.5	1.47	SL	119.8	-0.792	0.80	2.0	8.1	2.72	37.1	2.3	6.82	34.0	8.66	11.38	44.8	288
7.06	MBW5	1	7.7	1.49	SL	122.0	-0.755	0.79	2.4	8.5	2.96	38.4	2.4	7.18	33.8	9.17	12.13	47.8	216
6.26	MBW6	0	9.3	1.46	SL	SITE WETTED BY ACCIDENT													203
AVG	MBW	1	7.7	1.48	SL	114.3	-0.760	0.86	2.2	8.1	2.73	37.1	2.3	6.784	34.0	8.74	11.47	45.1	268
STD		1.3	2.9	0.0		11.3	0.0	0.1	0.3	0.5	0.3	1.9	0.2	0.6	0.4	0.6	0.9	3.6	50
CV		155	37	1		10	-3	9	14	7	12	5	7	8	1	7	8	8	19
7.06	MBN2	0	6.0	1.35	SL	135.7	-0.812	0.94	2.0	8.6	3.02	38.8	2.4	7.36	33.7	9.12	12.15	47.8	216
7.25	MBN3	3	5.9	1.28	SL	135.9	-0.863	0.96	1.5	8.2	2.78	37.5	2.3	7.00	33.9	8.61	11.39	44.8	288
7.31	MBN4	2	2.6	1.38	SL	133.2	-0.723	0.95	3.1	9.3	3.49	41.0	2.7	7.96	33.2	10.09	13.58	53.5	301
8.03	MBN5	3	10.9	1.28	SL	86.5	-0.524	0.97	5.7	8.5	3.00	38.6	2.5	6.74	33.8	10.33	13.33	52.5	332
6.26	MBN6	0	6.9	1.45	SL	143.7	-0.783	0.95	2.5	9.2	3.43	40.7	2.6	7.97	33.3	9.80	13.23	52.1	203
AVG	MBN	2	6.4	1.35	SL	127.0	-0.741	0.95	3.0	8.7	3.14	39.3	2.5	7.405	33.6	9.59	12.73	50.1	268
STD		1.5	2.7	0.1		20.6	0.1	0.0	1.5	0.4	0.3	1.3	0.1	0.5	0.3	0.6	0.8	3.3	50
CV		89	41	5		16	-16	1	49	5	9	3	6	7	1	7	7	7	19
8.03	DPW1	0	16.1	1.60	SL	106.1	-0.848	0.94	1.3	7.2	2.17	33.9	2.0	5.88	34.6	7.52	9.69	38.2	332
6.28	DPW2	3	12.4	1.53	SL	(162.4-1.165)													210
7.25	DPW3	3	10.1	1.43	SL	93.4	-0.632	0.77	3.5	8.0	2.68	36.9	2.3	6.52	34.1	9.14	11.82	46.5	288
7.10	DPW5	1	7.9	1.58	SL	100.6	-0.692	0.98	2.8	8.0	2.64	36.7	2.2	6.55	34.1	8.82	11.46	45.1	216
7.28	DPW6	0	11.1	1.54	SL	106.9	-0.765	0.93	2.0	7.7	2.49	35.9	2.1	6.40	34.3	8.33	10.83	42.6	301
AVG	DPW	1	11.5	1.54	SL	101.7	-0.734	0.90	2.4	7.7	2.49	35.8	2.2	6.34	34.3	8.46	10.95	43.1	269
STD		1.4	2.7	0.1		5.4	0.1	0.1	0.8	0.3	0.2	1.2	0.1	0.3	0.2	0.6	0.8	3.2	48
CV		102	24	4		5	-11	9	34	4	8	3	6	4	1	7	7	7	18
8.02	DPN1	5	14.9	1.40	SL	83.3	-0.727	0.92	1.9	6.8	1.98	32.6	1.9	5.42	34.9	7.40	9.38	36.9	332
7.10	DPN2	3	6.0	1.39	SL	93.9	-0.693	0.90	2.6	7.6	2.44	35.6	2.1	6.23	34.3	8.45	10.90	42.9	216
6.28	DPN4	7	12.9	1.43	SL	85.6	-0.706	0.92	2.2	7.1	2.11	33.5	2.0	5.64	34.7	7.75	9.86	38.8	210
7.24	DPN5	10	12.9	1.35	SL	71.5	-0.655	0.98	2.4	6.6	1.84	31.5	1.8	5.07	35.1	7.32	9.15	36.0	288
7.28	DPN6	12	8.9	1.33	SL	75.8	-0.752	0.97	1.5	6.3	1.71	30.6	1.7	4.91	35.3	6.72	8.43	33.2	301
AVG	DPN	7	11.11	1.38	SL	82.0	-0.707	0.94	2.1	6.9	2.01	32.7	1.9	5.46	34.9	7.53	9.54	37.6	269
STD		3.3	3.2	0.0		7.8	0.0	0.0	0.4	0.5	0.3	1.7	0.1	0.5	0.3	0.6	0.8	3.2	48
CV		46	29	3		10	-5	4	17	7	13	5	7	9	1	8	9	9	18

Table E-1 (H1) (cont'd).

FIELD #4, MONTCALM LS, 1989

		%								(min)				(min)		(min)			(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	$\%D_a$	CUMWT
7.11	NTW1	83	2.0	1.38	S	107.7	-0.313	.68*	21.2	15.1	8.17	54.0	5.6	10.07	30.4	16.90	25.08	98.7	216
6.29	NTW2	67	7.1	1.39	S	131.2	-0.544	.81*	7.8	11.3	5.00	46.8	3.5	9.42	32.0	12.90	17.90	70.5	210
8.02	NTW3	82	15.3	1.44	S	112.3	-0.175	.11*	45.3	39.8	25.4						25.40	100.0	332
7.24	NTW4	88	11.7	1.47	S	110.3	-0.157	.07*	48.8	39.8	25.4						25.40	100.0	288
7.27	NTW5	72	7.6	1.44	LS	89.3	-0.352	.76*	14.4	11.3	4.94	46.6	3.8	8.07	32.3	14.64	19.58	77.1	301
AVG	NTW	78	8.7	1.42	S-	110.2	-0.308		27.5	23.5	13.78	49.1	4.3	9.18	31.6	14.81	22.67	89.3	269
STD		8.0	4.5	0.0	LS	13.3	0.1		16.6	13.4	9.6	3.5	1.0	0.8	0.8	1.6	3.3	12.8	48
CV		10	51	2		12	-45		60	57	69	7	22	9	3	11	14	14	18
7.27	NTN1	75	15.1	1.49	LS	1460.	-0.828	.74*	19.8	39.8	25.4						25.40	100.0	301
6.29	NTN3	72	6.2	1.40	LS	119.3	-0.371	.89*	17.4	14.7	7.78	53.4	5.2	10.62	30.4	16.15	23.93	94.2	210
7.24	NTN4	67	11.9	1.49	LS	62.2	-0.061	.09*	45.3	15.3	8.36	54.3	7.9	3.27	32.5	17.04	25.40	100.0	288
8.02	NTN5	73	17.5	1.43	LS	132.2	-0.389	.77*	17.5	15.8	8.77	54.9	5.7	11.52	29.8	16.17	24.94	98.2	332
7.11	NTN6	82	2.1	1.37	LS	ONLY I	PONDED												216
AVG	NTN	74	10.5	1.44	LS	443.5	-0.412		25.0	21.4	12.58	54.2	6.3	8.5	30.9	16.45	24.92	98.1	269
STD		4.9	5.6	0.0		587.6	0.3		11.8	10.7	7.4	0.6	1.2	3.7	1.1	0.4	0.6	2.4	48
CV		7	54	3		132	-66		47	50	59	1	19	44	4	3	2	2	18

Table E-1 (H1) (cont'd).

FIELD #5, MONTCALM LS, 1989

DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	%D_a	CUMWT
		%								(min)			(min)		(min)				(mm)
7.13	PMBW1	0	11.7	1.49	LS	104.1	-0.654	0.94	3.5	8.4	2.94	38.4	2.4	6.99	33.8	9.52	12.46	49.1	101
8.07	PMBW2	4	16.0	1.50	LS	65.3	-0.497	0.98	4.9	7.1	2.14	33.6	2.1	5.31	34.8	8.82	10.96	43.1	216
8.01	PMBW4	3	12.0	1.58	S	92.3	-0.490	.96*	7.2	9.4	3.56	41.3	2.8	7.40	33.3	11.49	15.04	59.2	110
6.30	PMBW5	0	12.8	1.58	LS	73.2	-0.449	0.84	7.1	8.2	2.78	37.5	2.5	6.15	34.1	10.54	13.32	52.4	95
7.26	PMBW6	34	10.8	1.60	LS	83.3	-0.472	.88*	7.2	8.8	3.19	39.6	2.7	6.83	33.7	11.06	14.25	56.1	103
AVG	PMBW	8	12.7	1.55	LS-	83.7	-0.512	0.92	6.0	8.4	2.92	38.1	2.5	6.53	33.9	10.29	13.21	52.0	125
STD		13.0	1.8	0.0	S	13.7	0.1	0.1	1.5	0.8	0.5	2.6	0.3	0.7	0.5	1.0	1.4	5.6	46
CV		159	14	3		16	-14	7	25	9	16	7	11	11	1	10	11	11	37
7.13	PMBN1	0	9.3	1.34	LS	81.5	-0.612	0.82	3.4	7.4	2.33	34.9	2.1	5.90	34.5	8.57	10.90	42.9	101
8.01	PMBN2	6	14.2	1.30	LS	96.0	-0.581	1.00	4.7	8.7	3.10	39.2	2.5	7.07	33.7	10.14	13.24	52.1	110
8.07	PMBN3	6	14.3	1.31	LS	132.7	-0.732	0.99	3.0	9.2	3.41	40.6	2.6	7.86	33.3	9.95	13.36	52.6	216
6.30	PMBN4	0	10.8	1.33	LS	123.8	-0.622	0.87	4.9	9.9	3.93	42.9	2.9	8.38	32.9	11.15	15.08	59.4	95
7.26	PMBN5	20	5.9	1.32	LS	159.8	-0.596	0.99	7.2	12.5	5.91	49.4	3.9	10.71	31.2	13.31	19.22	75.7	103
AVG	PMBN	6	10.9	1.32	LS	118.8	-0.629	0.93	4.6	9.5	3.74	41.4	2.8	7.98	33.1	10.62	14.36	56.5	125
STD		7.3	3.2	0.0		27.6	0.1	0.1	1.5	1.7	1.2	4.8	0.6	1.6	1.1	1.6	2.8	10.9	46
CV		115	29	1		23	-9	8	32	18	32	12	21	20	3	15	19	19	37
7.26	PPTW1	25	7.0	1.56	LS	121.8	-0.548	.89*	7.1	10.8	4.59	45.4	3.3	8.97	32.3	12.39	16.98	66.9	103
8.07	PPTW2	17	12.2	1.61	S	99.1	-0.621	0.97	3.9	8.5	2.95	38.4	2.4	6.93	33.8	9.68	12.62	49.7	216
7.05	PPTW4	0	14.7	1.58	LS	69.6	-0.453	0.71	6.6	7.8	2.55	36.2	2.3	5.83	34.3	10.06	12.62	49.7	100
8.01	PPTW5	9	17.0	1.64	LS	106.2	-0.799	0.79	1.7	7.5	2.34	35.0	2.1	6.17	34.4	7.97	10.31	40.6	110
7.14	PPTW6	0	14.2	1.58	LS	69.9	-0.465	0.91	6.2	7.7	2.50	35.9	2.3	5.80	34.4	9.86	12.36	48.7	101
AVG	PPTW	10	13.0	1.59	LS-	93.3	-0.577	0.85	5.1	8.5	2.99	38.2	2.5	6.74	33.9	9.99	12.98	51.1	126
STD		9.7	3.4	0.0	S	20.6	0.1	0.1	2.0	1.2	0.8	3.8	0.4	1.2	0.8	1.4	2.2	8.6	45
CV		95	26	2		22	-22	12	40	14	28	10	17	18	2	14	17	17	36
7.26	PPTN1	33	6.5	1.34	LS	137.8	-0.572	0.99	7.1	11.5	5.13	47.1	3.5	9.71	31.9	12.79	17.91	70.5	103
7.14	PPTN2	0	10.9	1.30	LS	70.2	-0.382	0.75	9.7	8.6	3.04	38.9	2.7	6.18	33.9	11.70	14.75	58.1	101
8.07	PPTN3	5	14.5	1.31	LS	91.2	-0.542	0.97	5.5	8.7	3.11	39.2	2.6	6.96	33.7	10.40	13.50	53.2	216
7.05	PPTN4	0	6.0	1.33	S	103.2	-0.515	0.94	7.1	9.9	3.94	42.9	3.0	8.00	32.9	11.83	15.77	62.1	100
8.01	PPTN5	15	16.1	1.32	S	116.1	-0.767	0.96	2.2	8.1	2.74	37.3	2.3	6.82	34.0	8.76	11.50	45.3	110
AVG	PPTN	11	10.8	1.32	LS-	103.7	-0.556	0.92	6.3	9.4	3.59	41.1	2.8	7.54	33.3	11.10	14.68	57.8	126
STD		12.6	4.1	0.0	S	22.8	0.1	0.1	2.5	1.2	0.9	3.6	0.4	1.2	0.8	1.4	2.2	8.5	45
CV		118	38	1		22	-22	10	39	13	24	9	15	16	2	13	15	15	36

Table E-2. (H2) SITE. Appl. depth = 12.7mm, DRY data, high (57.4mm/h) maximum rate.

FIELD #1, KALAMAZOO SL, 1988

		%								(min)			(min)		(min)				(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_b	D_{tot}	$\%D_a$	CUMWT
3.27	MBW1	4	16.0	1.46		78.6	-0.620	0.98	3.1	4.9	1.90	42.3	1.4	5.99	16.4	5.23	7.13	56.1	37
6.03	MBW2	1	13.5	1.30		96.0	-0.720	0.87	2.3	5.2	2.14	44.2	1.5	6.61	16.2	5.34	7.49	58.9	44
AVG	MBW	3	14.7	1.38		87.3	-0.670	0.93	2.7	5.0	2.02	43.2	1.4	6.30	16.3	5.28	7.31	57.5	41
STD		1.4	1.2	0.1		8.7	0.0	0.1	0.4	0.2	0.1	0.9	0.0	0.3	0.1	0.1	0.2	1.4	4
CV		51	8	6		10	-7	6	16	3	6	2	3	5	1	1	2	2	9
6.08	MBN1	6	6.0	1.09		245.9	-0.840	0.99	3.1	9.0	5.40	56.8	2.9	11.86	13.9	6.73	12.13	95.5	44
5.31	MBN2	6	6.7	1.04		354.2	-0.817	.79*	5.1	12.9	9.04	52.8	5.4	14.31	12.5	3.66	12.70	100.0	37
5.24	SAMP	6	14.5	0.95		137.7	-0.730	0.83	3.1	6.7	3.31	51.0	2.0	8.75	15.3	6.31	9.62	75.7	37
AVG	MBN	6	9.1	1.03		245.9	-0.796	0.910	3.8	9.5	5.92	53.5	3.4	11.64	13.9	5.57	11.48	90.4	39
STD		0.0	3.9	0.1		88.4	0.0	0.1	0.9	2.6	2.4	2.4	1.4	2.3	1.1	1.4	1.3	10.5	3
CV		0	43	6		36	-6	9	25	27	40	5	42	20	8	24	12	12	8
5.25	CPW1	18	16.9	1.37		60.0	-0.390	0.75	7.9	4.7	1.78	41.2	1.4	5.15	16.7	5.84	7.62	60.0	37
6.06	CPW2	16	12.2	1.42		97.0	-0.540	0.91	5.9	6.2	2.88	48.9	1.9	7.62	15.6	6.43	9.31	73.3	44
AVG	CPW	17	14.5	1.40		78.5	-0.465	0.83	6.9	5.4	2.33	45.1	1.7	6.38	16.1	6.13	8.46	66.6	41
STD		0.9	2.4	0.0		18.5	0.1	0.1	1.0	0.7	0.6	3.8	0.2	1.2	0.5	0.3	0.8	6.6	4
CV		6	16	2		24	-16	10	15	13	24	9	14	19	3	5	10	10	9
6.01	CPN1	21	7.0	1.04		143.3	-0.490	0.65	11.2	9.8	6.18	57.4	3.6	11.27	13.7	6.52	12.70	100.0	37
6.09	CPN2	16	5.9	1.00		94.4	-0.407	.73*	11.4	7.1	3.68	52.5	2.4	8.15	15.2	7.40	11.08	87.2	44
AVG	CPN	19	6.4	1.02		118.8	-0.449	0.65	11.3	8.5	4.93	55.0	3.0	9.71	14.4	6.96	11.89	93.6	41
STD		2.8	0.6	0.0		24.4	0.0	0.0	0.1	1.3	1.3	2.4	0.6	1.6	0.7	0.4	0.8	6.4	4
CV		15	9	2		21	-9	0	1	16	25	4	21	16	5	6	7	7	9
6.07	NTW1	100	23.2	1.41		91.1	-0.350	.12*	14.8	7.49	4.02	53.7	2.6	8.11	15.0	7.81	11.83	93.1	44
5.26	NTW2	100	24.0	1.42		3445	-1.420												37
AVG	NTW	100	23.6	1.42		1768	-0.885		14.8	7.5	4.02	53.7	2.6	8.11	15.0	7.81	11.83	93.1	41
STD		0.0	0.4	0.0		1677	0.5												4
CV		0	2	0		95	-60												9
6.03	NTN1	100	25.5	1.41		193.4	-0.710	0.97	4.8	8.9	5.31	56.7	2.9	11.46	14.0	6.88	12.19	96.0	44
6.1	NTN2	100	16.2	1.23		388.7	-0.58	1.00*	19.1	19.9	12.7						12.7	100.0	44
AVG	NTN	100	20.8	1.32		291	-0.645	0.97	12.0	14.4	9.00	56.7	2.9	11.46	14.0	6.88	12.44	98.0	44
STD		0.0	4.6	0.1		98	0.1		7.1	5.5	3.7						0.3	2.0	
CV		0	22	7		34	-10		60	38	41						2	2	

Table E-2 (H2) (cont'd).

FIELD #2, OSHTEMO SL, 1988

DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	$\%D_e$	CUMWT
		%								(min)			(min)		(min)				(mm)
7.11	MBW1	0	7.5	1.46		105.9	-0.666	0.92	3.3	5.9	2.63	47.5	1.7	7.48	15.8	5.92	8.55	67.3	162
7.19	MBW2	0	14.6	1.29		120.3	-0.724	0.98	2.8	6.1	2.82	48.6	1.8	7.92	15.6	5.99	8.81	69.4	185
7.26	MBW3	10	17.1	1.43		76.5	-0.555	0.96	4.3	5.0	2.00	43.1	1.5	6.07	16.4	5.51	7.51	59.2	216
8.01	MBW4	3	7.2	1.37		96.3	-0.545	0.80	5.7	6.1	2.82	48.6	1.9	7.54	15.7	6.37	9.19	72.4	229
8.08	MBW5	5	13.4	1.44		85.2	-0.712	0.95	2.1	4.9	1.88	42.1	1.4	6.06	16.4	5.04	6.92	54.5	282
AVG	MBW	4	11.9	1.40		96.8	-0.640	0.92	3.6	5.6	2.43	46.0	1.6	7.01	16.0	5.76	8.20	64.55	215
STD		3.7	4.0	0.1		15.4	0.1	0.1	1.2	0.5	0.4	2.8	0.2	0.8	0.4	0.5	0.8	6.7	41
CV		103	33	4		16	-12	7	34	10	17	6	11	11	2	8	10	10	19
7.12	MBN1	0	13.4	1.23		106.0	-0.587	0.89	5.0	6.3	3.00	49.5	1.9	7.95	15.5	6.39	9.39	74.0	162
7.19	MBN2	5	18.2	1.40		128.0	-0.774	0.99	2.3	6.1	2.82	48.6	1.8	7.98	15.6	5.92	8.75	68.9	185
7.26	MBN3	3	12.0	1.00		90.1	-0.604	0.91	3.9	5.5	2.34	45.6	1.6	6.82	16.1	5.76	8.10	63.8	216
8.01	MBN4	10	10.0	1.30		126.9	-0.620	0.94	5.1	7.0	3.62	52.3	2.2	9.01	15.1	6.68	10.31	81.2	229
8.08	MBN5	10	9.2	1.21		115.2	-0.595	0.70	5.2	6.7	3.32	51.1	2.1	8.49	15.3	6.58	9.90	78.0	282
AVG	MBN	6	12.6	1.23		113.2	-0.636	0.89	4.3	6.3	3.02	49.4	1.9	8.05	15.5	6.27	9.29	73.15	215
STD		3.9	3.2	0.1		14.1	0.1	0.1	1.1	0.5	0.4	2.3	0.2	0.7	0.3	0.4	0.8	6.2	41
CV		70	25	11		12	-11	11	26	8	15	5	11	9	2	6	9	9	19
6.24	CPW1-1	61	20.1	1.19		97.0	-0.500	0.90	7.2	6.4	3.11	50.1	2.0	7.84	15.5	6.72	9.83	77.4	122
6.28	CPW1-2	80	10.7	1.13		154.1	-0.652	.78*	5.2	7.95	4.44	55.0	2.5	10.24	14.5	6.90	11.34	89.3	124
6.24	CPW1-3	84	19.1	1.07		84.8	-0.417	0.48	9.7	6.3	2.99	49.4	2.0	7.27	15.6	6.97	9.96	78.4	124
6.29	CPW1-4	39	11.6	1.35		141.4	-0.779	0.89	2.5	6.5	3.15	50.2	1.9	8.56	15.4	6.15	9.29	73.2	122
6.3	CPW1-5	61	7.0	1.00		139.2	-0.583	.65*	6.7	8	4.48	55.1	2.6	10.06	14.5	7.05	11.54	90.8	122
AVG	CPW1	65	13.7	1.15		123.3	-0.586	0.76	6.3	7.0	3.63	52.0	2.2	8.79	15.1	6.76	10.39	81.82	123
STD		16.1	5.1	0.1		27.2	0.1	0.2	2.4	0.8	0.7	2.5	0.3	1.2	0.5	0.3	0.9	7.0	1
CV		25	37	10		22	-21	26	38	11	19	5	13	13	3	5	9	9	1
7.15	CPW2-1	59	6.1	1.29		118.4	-0.581	.93*	5.8	7.0	3.55	52.1	2.2	8.80	15.1	6.74	10.29	81.1	162
7.21	CPW2-2	54	14.8	1.16		92.0	-0.465	0.48	8.2	6.4	3.08	49.9	2.0	7.64	15.5	6.83	9.91	78.0	189
7.28	CPW2-3	86	16.3	1.11		124.1	-0.468	.99*	10.9	8.6	5.06	56.3	3.0	10.12	14.3	7.42	12.48	98.3	229
8.03	CPW2-4	63	19.3	1.30		104.9	-0.765	0.96	2.0	5.4	2.26	45.0	1.5	6.90	16.1	5.41	7.68	60.4	241
8.11	CPW2-5	40	18.0	1.24		71.4	-0.493	0.55	5.5	5.0	1.99	43.0	1.5	5.89	16.4	5.68	7.67	60.4	294
AVG	CPW2	60	14.9	1.22		102.2	-0.554	0.66	6.5	6.5	3.19	49.3	2.0	7.87	15.5	6.42	9.61	75.63	223
STD		15.0	4.7	0.1		19.0	0.1	0.2	3.0	1.3	1.1	4.8	0.5	1.5	0.7	0.8	1.8	14.2	45
CV		25	31	6		19	-20	32	46	20	34	10	27	19	5	12	19	19	20

Table E-2 (H2) (cont'd).

FIELD #2, OSHTEMO SL, 1988 (CONT).

DATE	SITE	% RES	θ_i	BD	TXT	a	b	r^2	k	t_p (min)	D_{tp}	r_{tp}	t_1	f	t_2 (min)	D_p	D_{tot} (min)	%D_a	CUMWT (mm)
6.27	CPN1-1	89	6.6	1.18		171.2	-0.546	.92*	10.0	10.77	7.11	57.1	3.7	14.24	12.9	5.59	12.70	100.0	122
6.29	CPN1-2	46	10.1	1.16		122.6	-0.595	0.92	5.6	7.1	3.63	52.4	2.1	9.75	15.0	6.10	9.74	76.7	124
6.3	CPN1-3	56	7.3	1.27		134.5	-0.568	0.85	7.0	7.9	4.41	54.9	2.4	11.00	14.4	6.37	10.78	84.9	124
6.27	CPN1-4	51	9.7	1.22		61.6	-0.303	.54*	12.8	5.2	2.14	44.1	1.5	6.86	16.2	4.99	7.13	56.1	122
6.28	CPN1-5	66	5.0	1.10		116.0	-0.390	.85*	15.3	9.4	5.83	57.2	3.1	12.91	13.5	6.44	12.27	96.6	122
AVG	CPN1	62	7.7	1.19		121.2	-0.480	0.88	10.2	8.1	4.62	53.1	2.5	10.95	14.4	5.90	10.52	82.86	123
STD		15.2	1.9	0.1		35.4	0.1	0.0	3.6	1.9	1.7	4.8	0.8	2.6	1.1	0.5	2.0	15.8	1
CV		25	25	5		29	-24	4	35	24	37	9	31	23	8	9	19	19	1
7.14	CPN2-1	84	7.2	1.04		116.9	-0.432	.76*	12.4	8.63	5.07	56.3	3.0	9.81	14.3	7.63	12.70	100.0	162
7.22	CPN2-2	89	10.3	1.09		110.8	-0.360	0.90	17.1	9.6	5.95	57.3	3.6	10.28	14.0	6.75	12.70	100.0	189
7.29	CPN2-3	60	16.9	1.09		64.7	-0.306	.75*	13.2	5.5	2.35	45.7	1.5	7.33	16.0	5.21	7.56	59.6	229
8.04	CPN2-4	54	11.9	1.02		64.0	-0.314	.57*	12.5	5.4	2.27	45.1	1.7	5.88	16.2	6.60	8.87	69.8	229
8.11	CPN2-5	53	16.0	1.13		101.1	-0.440	0.46	10.3	7.3	3.81	53.0	2.2	9.53	14.9	6.58	10.39	81.8	294
AVG	CPN2	68	12.4	1.07		91.5	-0.370	0.68	13.1	7.3	3.89	51.5	2.4	8.57	15.1	6.55	10.44	82.24	221
STD		15.4	3.6	0.0		22.7	0.1	0.2	2.2	1.7	1.5	5.2	0.8	1.7	0.9	0.8	2.0	16.1	45
CV		23	29	4		25	-15	33	17	22.9	37.5	10.0	32.5	19.6	5.9	11.8	19.6	19.6	20
7.14	NTW1	90	10.6	1.43		59.5	-0.204	.11*	20.6	5.7	2.51	46.7	1.9	6.03	16.1	10.19	12.70	100.0	162
7.21	NTW2	98	14.2	1.46		160.8	-0.619	.81*	6.5	8.66	5.10	56.3	3.0	10.28	14.2	7.60	12.70	100.0	189
7.27	NTW3	100	22.8	1.50		242.7	-0.698	.93*	6.5	11.3	7.59	56.5	4.0	14.64	12.7	5.11	12.70	100.0	229
8.02	NTW4	93	11.0	1.37		66.9	-0.370	0.33	9.8	5.3	2.20	44.6	1.7	5.36	16.4	6.97	9.17	72.2	241
8.1	NTW5	80	18.3	1.28		96.1	-0.469	0.84	8.4	6.6	3.27	50.8	2.0	8.82	15.3	6.19	9.46	74.5	294
AVG	NTW	92	15.4	1.41		125.2	-0.472	0.59	10.4	7.5	4.14	51.0	2.5	9.02	14.9	7.21	11.35	89.34	223
STD		7.1	4.6	0.1		68.7	0.2	0.3	5.3	2.2	2.0	4.9	0.9	3.3	1.3	1.7	1.7	13.1	45
CV		8	30	5		55	-37	44	51	29	48	10	35	37	9	24	15	15	20
7.12	NTN1	86	13.3	1.24		232.0	-0.747	0.71	4.8	9.8	6.19	57.4	3.3	12.95	13.4	6.51	12.70	100.0	162
7.21	NTN2	100	16.2	1.38		100.9	-0.487	0.47	8.0	6.8	3.40	51.4	2.0	9.35	15.1	5.99	9.39	73.9	189
7.27	NTN3	100	23.3	1.37		353.3	-0.753	.82*	7.1	19.9	12.70						12.70	100.0	216
8.02	NTN4	97	10.8	1.34		89.6	-0.33	.99*	16.1	7.6	4.13	54.1	2.3	10.20	14.7	6.56	10.69	84.1	229
8.1	NTN5	100	21.8	1.40		1385.	-0.93	.99*	11.1	19.9	12.70						12.70	100.0	294
AVG	NTN	97	17.1	1.35		432.3	-0.649	0.59	9.4	12.8	7.82	54.3	2.5	10.83	14.4	6.35	11.63	91.61	218
STD		5.4	4.8	0.1		486.4	0.2	0.1	3.9	5.9	4.1	2.4	0.6	1.5	0.7	0.3	1.4	10.8	45
CV		6	28	4		113	-33	20	42	46	52	5	22	14	5	4	12	12	20

Table E-2 (H2) (cont'd).

FIELD #3, MONTCALM SL, 1989

		%								(min)			(min)		(min)				(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	%D_s	CUMWT
7.31	MBW1	0	2.7	1.50	SL	120.7	-0.738	0.85	2.6	6.0	2.75	48.2	1.7	8.14	15.6	5.56	8.31	65.4	301
8.03	MBW2	3	11.5	1.47	SL	94.7	-0.755	0.99	1.9	5.0	2.01	43.2	1.4	6.60	16.3	4.86	6.87	54.1	332
7.25	MBW3	0	7.5	1.47	SL	119.8	-0.792	0.80	2.0	5.7	2.53	46.8	1.6	7.69	15.8	5.37	7.90	62.2	288
7.06	MBW5	1	7.7	1.49	SL	122.0	-0.755	0.79	2.4	6.0	2.72	48.0	1.7	8.08	15.7	5.54	8.26	65.0	216
6.26	MBW6	0	9.3	1.46	SL	SITE WETTED BY ACCIDENT													203
AVG	MBW	1	7.7	1.48	SL	114.3	-0.760	0.86	2.2	5.7	2.50	46.5	1.6	7.63	15.8	5.33	7.84	61.7	268
STD		1.3	2.9	0.0		11.3	0.0	0.1	0.3	0.4	0.3	2.0	0.1	0.6	0.3	0.3	0.6	4.6	50
CV		155	37	1		10	-3	9	14	7	12	4	8	8	2	5	7	7	19
7.06	MBN2	0	6.0	1.35	SL	135.7	-0.812	0.94	2.0	6.1	2.84	48.7	1.8	8.01	15.6	5.95	8.79	69.2	216
7.25	MBN3	3	5.9	1.28	SL	135.9	-0.863	0.96	1.5	5.9	2.65	47.6	1.7	7.94	15.7	5.48	8.13	64.0	288
7.31	MBN4	2	2.6	1.38	SL	133.2	-0.723	0.95	3.1	6.5	3.19	50.4	1.9	8.96	15.3	5.86	9.05	71.2	301
8.03	MBN5	3	10.9	1.28	SL	86.5	-0.524	0.97	5.7	5.7	2.49	46.6	1.6	7.34	15.9	5.65	8.14	64.1	332
6.26	MBN6	0	6.9	1.45	SL	143.7	-0.783	0.95	2.5	6.5	3.17	50.4	1.9	8.89	15.3	5.89	9.06	71.4	203
AVG	MBN	2	6.4	1.35	SL	127.0	-0.741	0.95	3.0	6.1	2.87	48.7	1.8	8.23	15.6	5.77	8.64	68.0	268
STD		1.5	2.7	0.1		20.6	0.1	0.0	1.5	0.3	0.3	1.5	0.1	0.6	0.2	0.2	0.4	3.3	50
CV		89	41	5		16	-16	1	49	6	10	3	6	7	2	3	5	5	19
8.03	DPW1	0	16.1	1.60	SL	106.1	-0.848	0.94	1.3	5.1	2.05	43.5	1.5	6.01	16.3	5.77	7.82	61.6	332
6.28	DPW2	3	12.4	1.53	SL	(162.4-1.165)													210
7.25	DPW3	3	10.1	1.43	SL	93.4	-0.632	0.77	3.5	5.5	2.33	45.5	1.5	7.29	16.0	5.19	7.53	59.3	288
7.10	DPW5	1	7.9	1.58	SL	100.6	-0.692	0.98	2.8	5.5	2.36	45.7	1.6	6.98	16.0	5.65	8.00	63.0	216
7.28	DPW6	0	11.1	1.54	SL	106.9	-0.765	0.93	2.0	5.4	2.30	45.3	1.5	7.04	16.0	5.37	7.67	60.4	301
AVG	DPW	1	11.5	1.54	SL	101.7	-0.734	0.90	2.4	5.4	2.26	45.0	1.5	6.83	16.1	5.50	7.76	61.1	269
STD		1.4	2.7	0.1		5.4	0.1	0.1	0.8	0.2	0.1	0.9	0.0	0.5	0.1	0.2	0.2	1.4	48
CV		102	24	4		5	-11	9	34	3	5	2	2	7	1	4	2	2	18
8.02	DPN1	5	14.9	1.40	SL	83.3	-0.727	0.92	1.9	4.7	1.79	41.3	1.3	5.76	16.6	5.03	6.82	53.7	332
7.10	DPN2	3	6.0	1.39	SL	93.9	-0.693	0.90	2.6	5.3	2.19	44.5	1.5	6.73	16.2	5.35	7.53	59.3	216
6.28	DPN4	7	12.9	1.43	SL	85.6	-0.706	0.92	2.2	4.9	1.89	42.2	1.3	6.31	16.4	4.71	6.60	52.0	210
7.24	DPN5	10	12.9	1.35	SL	71.5	-0.655	0.98	2.4	4.4	1.60	39.6	1.3	5.38	16.7	4.74	6.35	50.0	288
7.28	DPN6	12	8.9	1.33	SL	75.8	-0.752	0.97	1.5	4.4	1.55	39.1	1.2	5.42	16.8	4.41	5.96	47.0	301
AVG	DPN	7	11.11	1.38	SL	82.0	-0.707	0.94	2.1	4.7	1.80	41.3	1.3	5.92	16.5	4.85	6.65	52.4	269
STD		3.3	3.2	0.0		7.8	0.0	0.0	0.4	0.3	0.2	1.9	0.1	0.5	0.2	0.3	0.5	4.1	48
CV		46	29	3		10	-5	4	17	7	13	5	8	9	1	7	8	8	18

Table E-2 (H2) (cont'd).

FIELD #4, MONTCALM LS, 1989

		%								(min)					(min)		(min)		(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	%D_a	CUMWT
7.11	NTW1	83	2.0	1.38	S	107.7	-0.313	.68*	21.2	10.96	7.29	56.9	3.8	14.40	12.8	5.41	12.70	100.0	216
6.29	NTW2	67	7.1	1.39	S	131.2	-0.544	.81*	7.8	8.02	4.50	55.1	2.5	11.14	14.4	6.39	10.90	85.8	210
8.02	NTW3	82	15.3	1.44	S	112.3	-0.175	.11*	45.3	19.9	12.7						12.70	100.0	332
7.24	NTW4	88	11.7	1.47	S	110.3	-0.157	.07*	48.8	19.9	12.7						12.70	100.0	288
7.27	NTW5	72	7.6	1.44	LS	89.3	-0.352	.76*	14.4	7.3	3.84	53.1	2.2	10.11	14.8	6.19	10.04	79.0	301
AVG	NTW	78	8.7	1.42	S-	110.2	-0.308		27.5	13.2	8.21	55.1	2.8	11.88	14.0	6.00	11.81	93.0	269
STD		8.0	4.5	0.0	LS	13.3	0.1		16.0	5.6	3.8	1.5	0.7	1.8	0.9	0.4	1.1	8.9	48
CV		10	51	2		12	-45		60	42	47	3	26	15	6	7	10	10	18
7.27	NTN1	75	15.1	1.49	LS	1460.	-0.828	.74*	19.8	19.9	12.7						12.70	100.0	301
6.29	NTN3	72	6.2	1.40	LS	119.3	-0.371	.89*	17.4	10.6	6.90	57.2	4.1	11.26	13.5	5.80	12.70	100.0	210
7.24	NTN4	67	11.9	1.49	LS	62.2	-0.061	.09*	45.3	8.3	4.76	55.7	2.6	11.52	14.2	6.44	11.20	88.2	288
8.02	NTN5	73	17.5	1.43	LS	132.2	-0.389	.77*	17.5	19.9	12.70						12.70	100.0	332
7.11	NTN6	82	2.1	1.37	LS	ONLY I PONDED													216
AVG	NTN	74	10.5	1.44	LS	443.5	-0.412		25.0	14.7	9.26	56.5	3.3	11.39	13.8	6.12	12.32	97.0	269
STD		4.9	5.6	0.0		587.6	0.3		11.8	5.3	3.5	0.8	0.8	0.1	0.3	0.3	0.6	5.1	48
CV		7	54	3		132	-66		47	36	38	1	23	1	2	5	5	5	18

Table E-2 (H2) (cont'd).

FIELD #5, MONTCALM LS, 1989

DATE	SITE	% RES	θ_i	BD	TXT	a	b	r^2	k	t_p (min)	D_{tp}	r_{tp}	t_1 (min)	f	t_2 (min)	D_p	D_{tot}	%D_a	CUMWT (mm)
7.13	PMBW1	0	11.7	1.49	LS	104.1	-0.654	0.94	3.5	5.8	2.60	47.3	1.7	7.85	15.8	5.44	8.04	63.3	101
8.07	PMBW2	4	16.0	1.50	LS	65.3	-0.497	0.98	4.9	4.6	1.73	40.8	1.3	5.94	16.6	4.51	6.24	49.1	216
8.01	PMBW4	3	12.0	1.58	S	92.3	-0.490	.96*	7.2	6.2	2.95	49.2	1.8	8.52	15.5	5.70	8.65	68.1	110
6.30	PMBW5	0	12.8	1.58	LS	73.2	-0.449	0.84	7.1	5.3	2.20	44.6	1.5	7.01	16.1	5.06	7.27	57.2	95
7.26	PMBW6	34	10.8	1.60	LS	83.3	-0.472	.88*	7.2	5.8	2.60	47.3	1.7	7.84	15.8	5.44	8.04	63.3	103
AVG	PMBW	8	12.7	1.55	LS-	83.7	-0.512	0.92	6.0	5.6	2.42	45.8	1.6	7.43	15.9	5.23	7.65	60.2	125
STD		13.0	1.8	0.0	S	13.7	0.1	0.1	1.5	0.6	0.4	2.9	0.2	0.9	0.4	0.4	0.8	6.5	46
CV		159	14	3		16	-14	7	25	10	17	6	11	12	2	8	11	11	37
7.13	PMBN1	0	9.3	1.34	LS	81.5	-0.612	0.82	3.4	5.0	2.01	43.1	1.5	5.73	16.4	5.94	7.94	62.6	101
8.01	PMBN2	6	14.2	1.30	LS	96.0	-0.581	1.00	4.7	5.9	2.66	47.6	1.8	7.03	15.8	6.46	9.12	71.8	110
8.07	PMBN3	6	14.3	1.31	LS	132.7	-0.732	0.99	3.0	6.5	3.12	50.1	1.9	8.85	15.3	5.82	8.95	70.5	216
6.30	PMBN4	0	10.8	1.33	LS	123.8	-0.622	0.87	4.9	6.9	3.47	51.7	2.1	8.63	15.2	6.73	10.20	80.3	95
7.26	PMBN5	20	5.9	1.32	LS	159.8	-0.596	0.99	7.2	8.9	5.33	56.7	2.9	12.05	13.9	6.60	11.94	94.0	103
AVG	PMBN	6	10.9	1.32	LS	118.8	-0.629	0.93	4.6	6.6	3.32	49.9	2.0	8.46	15.3	6.31	9.63	75.8	125
STD		7.3	3.2	0.0		27.6	0.1	0.1	1.5	1.3	1.1	4.5	0.5	2.1	0.8	0.4	1.4	10.7	46
CV		115	29	1		23	-9	8	32	20	34	9	22	25	6	6	14	14	37
7.26	PPTW1	25	7.0	1.56	LS	121.8	-0.548	.89*	7.1	7.4	3.98	53.6	2.3	9.60	14.8	6.77	10.75	84.7	103
8.07	PPTW2	17	12.2	1.61	S	99.1	-0.621	0.97	3.9	5.8	2.57	47.1	1.8	6.84	15.9	6.41	8.97	70.6	216
7.05	PPTW4	0	14.7	1.58	LS	69.6	-0.453	0.71	6.6	5.0	2.02	43.3	1.4	6.61	16.3	4.87	6.89	54.3	100
8.01	PPTW5	9	17.0	1.64	LS	106.2	-0.799	0.79	1.7	5.3	2.18	44.5	1.6	6.41	16.2	5.73	7.91	62.3	110
7.14	PPTW6	0	14.2	1.58	LS	69.9	-0.465	0.91	6.2	5.0	2.00	43.1	1.4	6.39	16.3	5.07	7.07	55.7	101
AVG	PPTW	10	13.0	1.59	LS-	93.3	-0.577	0.85	5.1	5.7	2.55	46.3	1.7	7.17	15.9	5.77	8.32	65.5	126
STD		9.7	3.4	0.0	S	20.6	0.1	0.1	2.0	0.9	0.7	3.9	0.3	1.2	0.6	0.7	1.4	11.2	45
CV		95	26	2		22	-22	12	40	16	29	8	20	17	4	13	17	17	36
7.26	PPTN1	33	6.5	1.34	LS	137.8	-0.572	0.99	7.1	8.0	4.52	55.1	2.5	10.90	14.4	6.56	11.08	87.2	103
7.14	PPTN2	0	10.9	1.30	LS	70.2	-0.382	0.75	9.7	5.4	2.32	45.4	1.6	6.48	16.1	6.08	8.40	66.1	101
8.07	PPTN3	5	14.5	1.31	LS	91.2	-0.542	0.97	5.5	5.8	2.61	47.3	1.7	7.86	15.8	5.44	8.05	63.4	216
7.05	PPTN4	0	6.0	1.33	S	103.2	-0.515	0.94	7.1	6.7	3.30	51.0	2.0	8.47	15.3	6.55	9.86	77.6	100
8.01	PPTN5	15	16.1	1.32	S	116.1	-0.767	0.96	2.2	5.7	2.52	46.8	1.7	7.43	15.9	5.66	8.18	64.4	110
AVG	PPTN	11	10.8	1.32	LS-	103.7	-0.556	0.92	6.3	6.3	3.05	49.1	1.9	8.23	15.5	6.06	9.11	71.7	126
STD		12.6	4.1	0.0	S	22.8	0.1	0.1	2.5	0.9	0.8	3.5	0.3	1.5	0.6	0.5	1.2	9.3	45
CV		118	38	1		22	-22	10	39	15	26	7	18	18	4	8	13	13	36

Table E-3. (L1) SITE. Appl. depth = 25.4mm, DRY data, low (16mm/h) maximum rate.

FIELD #1, KALAMAZOO SL, 1988

		%								(min)			(min)		(min)				(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	%D_a	CUMWT
3.27	MBW1	4	16.0	1.46		78.6	-0.620	0.98	3.1	36.4	4.12	12.2	11.7	3.98	118.0	13.22	17.34	68.3	37
6.03	MBW2	1	13.5	1.30		96.0	-0.720	0.87	2.3	34.0	3.64	11.6	10.4	3.89	119.2	11.86	15.51	61.0	44
AVG	MBW	3	14.7	1.38		87.3	-0.670	0.93	2.7	35.2	3.88	11.9	11.0	3.93	118.6	12.54	16.42	64.6	41
STD		1.4	1.2	0.1		8.7	0.0	0.1	0.4	1.2	0.2	0.3	0.6	0.0	0.6	0.7	0.9	3.6	4
CV		51	8	6		10	-7	6	16	3	6	2	6	1	0	5	6	6	9
6.08	MBN1	6	6.0	1.09		245.9	-0.840	0.99	3.1	49.5	7.03	14.5	16.3	5.92	109.7	14.71	21.74	85.6	44
5.31	MBN2	6	6.7	1.04		354.2	-0.817	.79*	5.1	68.1	11.82	16.0	26.4	7.22	101.1	13.58	25.40	100.0	37
5.24	SAMP	6	14.5	0.95		137.7	-0.730	0.83	3.1	42.6	5.43	13.4	13.8	4.93	114.0	14.05	19.48	76.7	37
AVG	MBN	6	9.1	1.03		245.9	-0.796	0.910	3.8	53.4	8.09	14.6	18.8	6.02	108.2	14.11	22.21	87.4	39
STD		0.0	3.9	0.1		88.4	0.0	0.1	0.9	10.8	2.7	1.1	5.5	0.9	5.3	0.5	2.4	9.6	3
CV		0	43	6		36	-6	9	25	20	34	7	29	16	5	3	11	11	8
5.25	CPW1	18	16.9	1.37		60.0	-0.390	0.75	7.9	56.6	8.81	15.3	23.3	4.61	109.5	16.59	25.40	100.0	37
6.06	CPW2	16	12.2	1.42		97.0	-0.540	0.91	5.9	53.2	7.95	15.0	19.8	5.22	109.4	16.88	24.82	97.7	44
AVG	CPW	17	14.5	1.40		78.5	-0.465	0.83	6.9	54.9	8.38	15.1	21.5	4.91	109.4	16.73	25.11	98.9	41
STD		0.9	2.4	0.0		18.5	0.1	0.1	1.0	1.7	0.4	0.2	1.7	0.3	0.0	0.1	0.3	1.1	4
CV		6	16	2		24	-16	10	15	3	5	1	8	6	0	1	1	1	9
6.01	CPN1	21	7.0	1.04		143.3	-0.490	0.65	11.2	143.0	25.40						25.40	100.0	37
6.09	CPN2	16	5.9	1.00		94.4	-0.407	.73*	11.4	142.8	25.40						25.40	100.0	44
AVG	CPN	19	6.4	1.02		118.8	-0.449	0.65	11.3	142.9	25.40						25.40	100.0	41
STD		2.8	0.6	0.0		24.4	0.0	0.0	0.1	0.1									4
CV		15	9	2		21	-9	0	1	0									9
6.07	NTW1	100	23.2	1.41		91.1	-0.350	.12*	14.8	142.8	25.4						25.40	100.0	44
5.26	NTW2	100	24.0	1.42		3445	-1.420	0.53											37
AVG	NTW	100	23.6	1.42		1768	-0.885	0.53	14.8	142.8	25.40						25.40	100.0	41
STD		0.0	0.4	0.0		1677	0.5	0.0											4
CV		0	2	0		95	-60	0											9
6.03	NTN1	100	25.5	1.41		193.4	-0.710	0.97	4.8	57.6	9.06	15.4	20.9	6.24	106.1	16.10	25.16	99.1	44
6.1	NTN2	100	16.2	1.23		388.7	-0.58	1.00*	19.1	142.5	25.40						25.40	100.0	44
AVG	NTN	100	20.8	1.32		291	-0.645	0.97	12.0	100.1	17.23	15.4	20.9	6.24	106.1	16.10	25.28	99.5	44
STD		0.0	4.6	0.1		98	0.1		7.1	42.5	8.2						0.1	0.5	0.0
CV		0	22	7		34	-10		60	42	47						0	0	0

Table E-3 (L1) (cont'd).

FIELD #2, OSHTEMO SL, 1988

		%									(min)			(min)		(min)			(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	%D_a	CUMWT
7.11	MBW1	0	7.5	1.46		105.9	-0.666	0.92	3.3	41.2	5.13	13.1	13.4	4.64	115.0	14.10	19.22	75.7	162
7.19	MBW2	0	14.6	1.29		120.3	-0.724	0.98	2.8	39.5	4.76	12.8	12.5	4.57	115.8	13.35	18.11	71.3	185
7.26	MBW3	10	17.1	1.43		76.5	-0.555	0.96	4.3	42.1	5.32	13.3	14.3	4.41	115.0	15.09	20.41	80.4	216
8.01	MBW4	3	7.2	1.37		96.3	-0.545	0.80	5.7	52.7	7.83	14.9	19.5	5.26	109.5	16.74	24.58	96.8	229
8.08	MBW5	5	13.4	1.44		85.2	-0.712	0.95	2.1	32.0	3.26	11.1	9.7	3.63	120.5	11.27	14.53	57.2	282
AVG	MBW	4	11.9	1.40		96.8	-0.640	0.92	3.6	41.5	5.26	13.1	13.9	4.50	115.1	14.11	19.37	76.3	215
STD		3.7	4.0	0.1		15.4	0.1	0.1	1.2	6.6	1.5	1.2	3.2	0.5	3.5	1.8	3.3	12.8	41
CV		103	33	4		16	-12	7	34	16	28	9	23	12	3	13	17	17	19
7.12	MBN1	0	13.4	1.23		106.0	-0.587	0.89	5.0	49.9	7.14	14.6	17.8	5.19	110.7	16.23	23.36	92.0	162
7.19	MBN2	5	18.2	1.40		128.0	-0.774	0.99	2.3	37.1	4.26	12.3	11.4	4.37	117.1	12.45	16.71	65.8	185
7.26	MBN3	3	12.0	1.00		90.1	-0.604	0.91	3.9	42.1	5.32	13.3	14.1	4.55	114.7	14.74	20.07	79.0	216
8.01	MBN4	10	10.0	1.30		126.9	-0.620	0.94	5.1	52.5	7.77	14.9	18.9	5.50	109.2	16.31	24.08	94.8	229
8.08	MBN5	10	9.2	1.21		115.2	-0.595	0.70	5.2	53.1	7.92	15.0	19.3	5.50	109.0	16.43	24.35	95.9	282
AVG	MBN	6	12.6	1.23		113.2	-0.636	0.89	4.3	47.0	6.48	14.0	16.3	5.02	112.1	15.23	21.71	85.5	215
STD		3.9	3.2	0.1		14.1	0.1	0.1	1.1	6.3	1.4	1.0	3.0	0.5	3.2	1.5	2.9	11.5	41
CV		70	25	11		12	-11	11	26	13	22	7	19	9	3	10	14	14	19
6.24	CPW1-1	61	20.1	1.19		97.0	-0.500	0.90	7.2	61.3	10.02	15.7	24.9	5.45	106.4	15.38	25.40	100.0	122
6.28	CPW1-2	80	10.7	1.13		154.1	-0.652	.78*	5.2	56.6	8.81	15.3	20.8	5.95	107.0	16.59	25.40	100.0	124
6.24	CPW1-3	84	19.1	1.07		84.8	-0.417	0.48	9.7	79.6	14.87	15.8	40.8	5.00	104.0	10.53	25.40	100.0	124
6.29	CPW1-4	39	11.6	1.35		141.4	-0.779	0.89	2.5	39.6	4.77	12.8	12.4	4.70	115.6	20.63	25.40	100.0	122
6.3	CPW1-5	61	7.0	1.00		139.2	-0.583	.65*	6.7	64.9	10.97	15.9	26.3	6.05	104.2	14.43	25.40	100.0	122
AVG	CPW1	65	13.7	1.15		123.3	-0.586	0.76	6.3	60.4	9.89	15.1	25.0	5.43	107.4	15.51	25.40	100.0	123
STD		16.1	5.1	0.1		27.2	0.1	0.2	2.4	12.9	3.3	1.2	9.3	0.5	4.2	3.3			1
CV		25	37	10		22	-21	26	38	21	33	8	37	10	4	21			1
7.15	CPW2-1	59	6.1	1.29		118.4	-0.581	.93*	5.8	56.0	8.65	15.3	21.0	5.60	107.8	16.75	25.40	100.0	162
7.21	CPW2-2	54	14.8	1.16		92.0	-0.465	0.48	8.2	68.7	11.97	16.0	30.3	5.51	104.4	13.43	25.40	100.0	189
7.28	CPW2-3	86	16.3	1.11		124.1	-0.468	.99*	10.9	142.8	25.40						25.40	100.0	229
8.03	CPW2-4	63	19.3	1.30		104.9	-0.765	0.96	2.0	33.2	3.49	11.4	10.0	3.86	119.6	11.36	14.84	58.4	241
8.11	CPW2-5	40	18.0	1.24		71.4	-0.493	0.55	5.5	46.8	6.39	14.1	16.9	4.56	112.9	16.50	22.89	90.1	294
AVG	CPW2	60	14.9	1.22		102.2	-0.554	0.66	6.5	69.5	11.18	14.2	19.5	4.88	111.2	14.51	22.79	89.7	223
STD		15.0	4.7	0.1		19.0	0.1	0.2	3.0	38.4	7.6	1.7	7.3	0.7	5.7	2.2	4.1	16.1	45
CV		25	31	6		19	-20	32	46	55	68	12	37	15	5	15	18	18	20

Table E-3 (L1) (cont'd).

FIELD #2, OSHTEMO SL, 1988 (cont).

		%								(min)			(min)		(min)				(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	I_{tp}	t_1	f	t_2	D_p	D_{tot}	$\%D_a$	CUMWT
6.27	CPN1-1	89	6.6	1.18		171.2	-0.546	.92*	10.0	142.8	25.4						25.40	100.0	122
6.29	CPN1-2	46	10.1	1.16		122.6	-0.595	0.92	5.6	56.0	8.65	15.3	20.8	5.70	107.6	16.63	25.27	99.5	124
6.3	CPN1-3	56	7.3	1.27		134.5	-0.568	0.85	7.0	68.1	11.81	16.0	28.5	6.15	103.2	13.59	25.40	100.0	124
6.27	CPN1-4	51	9.7	1.22		61.6	-0.303	.54*	12.8	142.8	25.4						25.40	100.0	122
6.28	CPN1-5	66	5.0	1.10		116.0	-0.390	.85*	15.3	142.8	25.4						25.40	100.0	122
AVG	CPN1	62	7.7	1.19		121.2	-0.480	0.88	10.2	110.5	19.33	15.6	24.6	5.92	105.4	15.11	25.37	99.9	123
STD		15.2	1.9	0.1		35.4	0.1	0.0	3.6	39.7	7.5	0.4	3.8	0.2	2.2	1.5	0.1	0.2	1
CV		25	25	5		29	-24	4	35	36	39	2	16	4	2	10	0	0	1
7.14	CPN2-1	84	7.2	1.04		116.9	-0.432	.76*	12.4	142.5	25.40						25.40	100.0	162
7.22	CPN2-2	89	10.3	1.09		110.8	-0.360	0.90	17.1	143.0	25.40						25.40	100.0	189
7.29	CPN2-3	60	16.9	1.09		64.7	-0.306	.75*	13.2	142.8	25.40						25.40	100.0	229
8.04	CPN2-4	54	11.9	1.02		64.0	-0.314	.57*	12.5	142.8	25.40						25.40	100.0	229
8.11	CPN2-5	53	16.0	1.13		101.1	-0.440	0.46	10.3	143.0	25.40						25.40	100.0	294
AVG	CPN2	68	12.4	1.07		91.5	-0.370	0.68	13.1	142.8	25.40						25.40	100.0	221
STD		15.4	3.6	0.0		22.7	0.1	0.2	2.2	0.2									45
CV		23	29	4		25	-15	33	17	0									20
7.14	NTW1	90	10.6	1.43		59.5	-0.204	.11*	20.6	142.8	25.40						25.40	100.0	162
7.21	NTW2	98	14.2	1.46		160.8	-0.619	.81*	6.5	65.7	11.16	15.9	26.4	6.26	103.6	14.24	25.40	100.0	189
7.27	NTW3	100	22.8	1.50		242.7	-0.698	.93*	6.5	73.0	13.12	16.0	30.9	6.83	100.6	12.28	25.40	100.0	229
8.02	NTW4	93	11.0	1.37		66.9	-0.370	0.33	9.8	70.5	12.45	16.0	33.7	4.64	106.0	12.95	25.40	100.0	241
8.1	NTW5	80	18.3	1.28		96.1	-0.469	0.84	8.4	73.0	13.13	16.0	33.4	5.65	103.2	12.27	25.40	100.0	294
AVG	NTW	92	15.4	1.41		125.2	-0.472	0.59	10.4	85.0	15.05	16.0	31.1	5.85	103.3	12.93	25.40	100.0	223
STD		7.1	4.6	0.1		68.7	0.2	0.3	5.3	29.0	5.2	0.0	2.9	0.8	1.9	0.8			45
CV		8	30	5		55	-37	44	51	34	35	0	9	14	2	6			20
7.12	NTN1	86	13.3	1.24		232.0	-0.747	0.71	4.8	61.0	9.95	15.7	22.5	6.65	104.3	15.45	25.40	100.0	162
7.21	NTN2	100	16.2	1.38		100.9	-0.487	0.47	8.0	69.3	12.13	16.0	30.4	5.66	103.9	13.27	25.40	100.0	189
7.27	NTN3	100	23.3	1.37		353.3	-0.753	.82*	7.1	85.8	16.47	15.4	41.8	6.91	98.9	8.93	25.40	100.0	216
8.02	NTN4	97	10.8	1.34		89.6	-0.33	.99*	16.1	142.8	25.40						25.40	100.0	229
8.1	NTN5	100	21.8	1.40		1385.	-0.93	.99*	11.1	142.8	25.40						25.40	100.0	294
AVG	NTN	97	17.1	1.35		432.3	-0.649	0.59	9.4	100.3	17.87	15.7	31.6	6.41	102.4	12.55	25.40	100.0	218
STD		5.4	4.8	0.1		486.4	0.2	0.1	3.9	35.6	6.5	0.3	7.9	0.5	2.5	2.7			45
CV		6	28	4		113	-33	20	42	35	36	2	25	8	2	22			20

Table E-3 (L1) (cont'd).

FIELD #3, MONTCALM SL, 1989

		%								(min)				(min)		(min)			(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	%D_s	CUMWT
7.31	MBW1	0	2.7	1.50	SL	120.7	-0.738	0.85	2.6	38.3	4.50	12.6	12.0	4.45	116.5	12.96	17.46	68.7	301
8.03	MBW2	3	11.5	1.47	SL	94.7	-0.755	0.99	1.9	31.6	3.17	11.0	9.4	3.63	120.7	10.89	14.06	55.4	332
7.25	MBW3	0	7.5	1.47	SL	119.8	-0.792	0.80	2.0	34.2	3.68	11.7	10.3	4.03	118.9	11.54	15.23	59.9	288
7.06	MBW5	1	7.7	1.49	SL	122.0	-0.755	0.79	2.4	37.2	4.28	12.3	11.5	4.35	117.1	12.59	16.87	66.4	216
6.26	MBW6	0	9.3	1.46	SL	SITE WETTED BY ACCIDENT													203
AVG	MBW	1	7.7	1.48	SL	114.3	-0.760	0.86	2.2	35.3	3.91	11.9	10.8	4.11	118.3	12.00	15.90	62.6	268
STD		1.3	2.9	0.0		11.3	0.0	0.1	0.3	2.6	0.5	0.6	1.0	0.3	1.6	0.8	1.3	5.3	50
CV		155	37	1		10	-3	9	14	7	13	5	9	8	1	7	8	8	19
7.06	MBN2	0	6.0	1.35	SL	135.7	-0.812	0.94	2.0	35.7	3.97	12.0	10.8	4.25	117.9	11.87	15.84	62.4	216
7.25	MBN3	3	5.9	1.28	SL	135.9	-0.863	0.96	1.5	32.6	3.36	11.3	9.6	3.89	119.8	10.71	14.08	55.4	288
7.31	MBN4	2	2.6	1.38	SL	133.2	-0.723	0.95	3.1	42.3	5.36	13.3	13.6	4.87	114.2	14.02	19.38	76.3	301
8.03	MBN5	3	10.9	1.28	SL	86.5	-0.524	0.97	5.7	50.3	7.24	14.6	18.5	4.95	110.9	16.73	23.98	94.4	332
6.26	MBN6	0	6.9	1.45	SL	143.7	-0.783	0.95	2.5	39.2	4.69	12.7	12.2	4.64	115.8	12.96	17.64	69.5	203
AVG	MBN	2	6.4	1.35	SL	127.0	-0.741	0.95	3.0	40.0	4.92	12.8	12.9	4.52	115.7	13.26	18.18	71.6	268
STD		1.5	2.7	0.1		20.6	0.1	0.0	1.5	6.1	1.3	1.1	3.1	0.4	3.1	2.1	3.4	13.4	50
CV		89	41	5		16	-16	1	49	15	27	9	24	9	3	16	19	19	19
8.03	DPW1	0	16.1	1.60	SL	106.1	-0.848	0.94	1.3	28.8	2.68	10.3	8.3	3.35	122.3	9.55	12.22	48.1	332
6.28	DPW2	3	12.4	1.53	SL	(162.4-1.165)													210
7.25	DPW3	3	10.1	1.43	SL	93.4	-0.632	0.77	3.5	40.3	4.92	13.0	13.2	4.43	115.7	14.14	19.06	75.0	288
7.10	DPW5	1	7.9	1.58	SL	100.6	-0.692	0.98	2.8	37.2	4.28	12.3	11.7	4.23	117.3	12.95	17.23	67.8	216
7.28	DPW6	0	11.1	1.54	SL	106.9	-0.765	0.93	2.0	33.5	3.54	11.5	10.1	3.89	119.4	11.45	14.99	59.0	301
AVG	DPW	1	11.5	1.54	SL	101.7	-0.734	0.90	2.4	34.9	3.85	11.8	10.8	3.98	118.7	12.02	15.88	62.5	269
STD		1.4	2.7	0.1		5.4	0.1	0.1	0.8	4.3	0.8	1.0	1.8	0.4	2.5	1.7	2.6	10.1	48
CV		102	24	4		5	-11	9	34	12	22	8	17	10	2	14	16	16	18
8.02	DPN1	5	14.9	1.40	SL	83.3	-0.727	0.92	1.9	30.6	3.00	10.8	9.2	3.46	121.4	10.72	13.71	54.0	332
7.10	DPN2	3	6.0	1.39	SL	93.9	-0.693	0.90	2.6	35.6	3.95	12.0	11.1	4.05	118.3	12.48	16.43	64.7	216
6.28	DPN4	7	12.9	1.43	SL	85.6	-0.706	0.92	2.2	32.4	3.32	11.2	9.8	3.66	120.3	11.43	14.75	58.1	210
7.24	DPN5	10	12.9	1.35	SL	71.5	-0.655	0.98	2.4	31.7	3.19	11.0	9.7	3.48	120.9	11.50	14.69	57.8	288
7.28	DPN6	12	8.9	1.33	SL	75.8	-0.752	0.97	1.5	27.5	2.47	10.0	8.0	3.09	123.3	9.53	11.99	47.2	301
AVG	DPN	7	11.11	1.38	SL	82.0	-0.707	0.94	2.1	31.6	3.19	11.0	9.6	3.55	120.8	11.13	14.31	56.4	269
STD		3.3	3.2	0.0		7.8	0.0	0.0	0.4	2.6	0.5	0.7	1.0	0.3	1.6	1.0	1.5	5.7	48
CV		46	29	3		10	-5	4	17	8	15	6	10	9	1	9	10	10	18

Table E-3 (L1) (cont'd).

FIELD #4, MONTCALM LS, 1989

DATE	SITE	% RES	θ_i	BD	TXT	a	b	r^2	k	t_p (min)	D_{tp}	r_{tp}	t_1	f (min)	t_2	D_p (min)	D_{tot}	$\%D_a$	CUMWT	(mm)
7.11	NTW1	83	2.0	1.38	S	107.7	-0.313	.68*	21.2	142.8	25.40							25.40	100.0	216
6.29	NTW2	67	7.1	1.39	S	131.2	-0.544	.81*	7.8	71.65	12.76	16.0	31.6	5.97	102.8	12.64		25.40	100.0	210
8.02	NTW3	82	15.3	1.44	S	112.3	-0.175	.11*	45.3	142.8	25.40							25.40	100.0	332
7.24	NTW4	88	11.7	1.47	S	110.3	-0.157	.07*	48.8	142.8	25.40							25.40	100.0	288
7.27	NTW5	72	7.6	1.44	LS	89.3	-0.352	.76*	14.4	142.8	25.40							25.40	100.0	301
AVG	NTW	78	8.7	1.42	S-	110.2	-0.308		27.5	128.6	22.87	16.0	31.6	5.97	102.8	12.64		25.40	100.0	269
STD		8.0	4.5	0.0	LS	13.3	0.1		16.6	28.5	5.1									48
CV		10	51	2		12	-45		60	22	22									18
7.27	NTN1	75	15.1	1.49	LS	1460.	-0.828	.74*	19.8	142.8	25.40							25.40	100.0	301
6.29	NTN3	72	6.2	1.40	LS	119.3	-0.371	.89*	17.4	142.8	25.40							25.40	100.0	210
7.24	NTN4	67	11.9	1.49	LS	62.2	-0.061	.09*	45.3	142.8	25.40							25.40	100.0	288
8.02	NTN5	73	17.5	1.43	LS	132.2	-0.389	.77*	17.5	142.8	25.40							25.40	100.0	332
7.11	NTN6	82	2.1	1.37	LS	ONLY I PONDED														216
AVG	NTN	74	10.5	1.44	LS	443.5	-0.412		25.0	142.8	25.40							25.40	100.0	269
STD		4.9	5.6	0.0		587.6	0.3		11.8											48
CV		7	54	3		132	-66		47											18

Table E-3 (L1) (cont'd).

FIELD #5, MONTCALM LS, 1989

		%								(min)					(min)	(min)			(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_3	D_p	D_{tot}	%D_a	CUMWT
7.13	PMBW1	0	11.7	1.49	LS	104.1	-0.654	0.94	3.5	41.5	5.18	13.2	13.6	4.61	114.9	14.27	19.45	76.6	101
8.07	PMBW2	4	16.0	1.50	LS	65.3	-0.497	0.98	4.9	42.6	5.42	13.4	14.9	4.21	115.1	15.73	21.15	83.3	216
8.01	PMBW4	3	12.0	1.58	S	92.3	-0.490	.96*	7.2	60.4	9.78	15.6	24.5	5.35	106.9	15.62	25.40	100.0	110
6.30	PMBW5	0	12.8	1.58	LS	73.2	-0.449	0.84	7.1	55.1	8.43	15.2	21.8	4.85	109.5	16.97	25.40	100.0	95
7.26	PMBW6	34	10.8	1.60	LS	83.3	-0.472	.88*	7.2	58.0	9.16	15.4	23.2	5.13	108.0	16.24	25.40	100.0	103
AVG	PMBW	8	12.7	1.55	LS-	83.7	-0.512	0.92	6.0	51.5	7.59	14.6	19.6	4.83	110.9	15.77	23.36	92.0	125
STD		13.0	1.8	0.0	S	13.7	0.1	0.1	1.5	7.9	1.9	1.1	4.5	0.4	3.5	0.9	2.6	10.1	46
CV		159	14	3		16	-14	7	25	15	25	7	23	8	3	6	11	11	37
7.13	PMBN1	0	9.3	1.34	LS	81.5	-0.612	0.82	3.4	38.1	4.46	12.5	12.4	4.14	117.1	13.74	18.19	71.6	101
8.01	PMBN2	6	14.2	1.30	LS	96.0	-0.581	1.00	4.7	47.1	6.47	14.1	16.4	4.95	112.1	15.84	22.31	87.8	110
8.07	PMBN3	6	14.3	1.31	LS	132.7	-0.732	0.99	3.0	41.3	5.15	13.2	13.2	4.79	114.7	13.76	18.91	74.4	216
6.30	PMBN4	0	10.8	1.33	LS	123.8	-0.622	0.87	4.9	51.5	7.52	14.8	18.3	5.45	109.7	16.16	23.68	93.2	95
7.26	PMBN5	20	5.9	1.32	LS	159.8	-0.596	0.99	7.2	71.3	12.68	16.0	30.7	6.27	102.2	12.72	25.40	100.0	103
AVG	PMBN	6	10.9	1.32	LS	118.8	-0.629	0.93	4.6	49.9	7.25	14.1	18.2	5.12	111.1	14.44	21.70	85.4	125
STD		7.3	3.2	0.0		27.6	0.1	0.1	1.5	11.7	2.9	1.2	6.6	0.7	5.1	1.3	2.8	10.9	46
CV		115	29	1		23	-9	8	32	23	40	9	36	14	5	9	13	13	37
7.26	PPTW1	25	7.0	1.56	LS	121.8	-0.548	.89*	7.1	64.7	10.91	15.9	26.6	5.85	104.7	14.49	25.40	100.0	103
8.07	PPTW2	17	12.2	1.61	S	99.1	-0.621	0.97	3.9	43.2	5.57	13.5	14.5	4.70	114.1	14.88	20.45	80.5	216
7.05	PPTW4	0	14.7	1.58	LS	69.6	-0.453	0.71	6.6	51.6	7.54	14.8	19.7	4.67	111.0	17.42	24.96	98.3	100
8.01	PPTW5	9	17.0	1.64	LS	106.2	-0.799	0.79	1.7	31.4	3.14	11.0	9.3	3.66	120.7	10.61	13.75	54.1	110
7.14	PPTW6	0	14.2	1.58	LS	69.9	-0.465	0.91	6.2	49.7	7.10	14.5	18.7	4.62	111.7	17.14	24.24	95.4	101
AVG	PPTW	10	13.0	1.59	LS-	93.3	-0.577	0.85	5.1	48.1	6.85	13.9	17.7	4.70	112.4	14.91	21.76	85.7	126
STD		9.7	3.4	0.0	S	20.6	0.1	0.1	2.0	10.9	2.5	1.7	5.7	0.7	5.2	2.4	4.4	17.2	45
CV		95	26	2		22	-22	12	40	23	37	12	32	15	5	16	20	20	36
7.26	PPTN1	33	6.5	1.34	LS	137.8	-0.572	0.99	7.1	67.1	11.54	15.9	27.9	6.05	103.6	13.86	25.40	100.0	103
7.14	PPTN2	0	10.9	1.30	LS	70.2	-0.382	0.75	9.7	71.7	12.78	16.0	34.3	4.80	105.4	12.62	25.40	100.0	101
8.07	PPTN3	5	14.5	1.31	LS	91.2	-0.542	0.97	5.5	50.0	7.16	14.6	18.2	5.01	110.9	16.56	23.72	93.4	216
7.05	PPTN4	0	6.0	1.33	S	103.2	-0.515	0.94	7.1	61.7	10.13	15.7	25.0	5.55	106.1	15.27	25.40	100.0	100
8.01	PPTN5	15	16.1	1.32	S	116.1	-0.767	0.96	2.2	35.2	3.87	11.9	10.7	4.12	118.3	11.96	15.82	62.3	110
AVG	PPTN	11	10.8	1.32	LS-	103.7	-0.556	0.92	6.3	57.1	9.10	14.8	23.2	5.10	108.9	14.05	23.15	91.1	126
STD		12.6	4.1	0.0	S	22.8	0.1	0.1	2.5	13.1	3.2	1.6	8.1	0.7	5.3	1.7	3.7	14.6	45
CV		118	38	1		22	-22	10	39	23	35	10	35	13	5	12	16	16	36

Table E-4. (L2) SITE. Appl. depth = 12.7mm, DRY data, low (16mm/h) maximum rate.

FIELD #1, KALAMAZOO SL, 1988

		%								(min)			(min)		(min)				(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	%D_s	CUMWT
3.27	MBW1	4	16.0	1.46		78.6	-0.620	0.98	3.1	25.4	3.67	14.7	8.4	4.31	54.4	7.40	11.07	87.1	37
6.03	MBW2	1	13.5	1.30		96.0	-0.720	0.87	2.3	24.1	3.36	14.3	7.6	4.29	55.0	6.95	10.31	81.2	44
AVG	MBW	3	14.7	1.38		87.3	-0.670	0.93	2.7	24.7	3.51	14.5	8.0	4.30	54.7	7.18	10.69	84.2	41
STD		1.4	1.2	0.1		8.7	0.0	0.1	0.4	0.6	0.2	0.2	0.4	0.0	0.3	0.2	0.4	3.0	4
CV		51	8	6		10	-7	6	16	3	4	1	5	0	0	3	4	4	9
6.08	MBN1	6	6.0	1.09		245.9	-0.840	0.99	3.1	37.8	6.90	15.9	14.4	6.28	48.0	5.80	12.70	100.0	44
5.31	MBN2	6	6.7	1.04		354.2	-0.817	.79*	5.1	71.4	12.70						12.70	100.0	37
5.24	SAMP	6	14.5	0.95		137.7	-0.730	0.83	3.1	31.1	5.12	15.7	10.8	5.37	51.2	7.58	12.70	100.0	37
AVG	MBN	6	9.1	1.03		245.9	-0.796	0.910	3.8	46.8	8.24	15.8	12.6	5.82	49.6	6.69	12.70	100.0	39
STD		0.0	3.9	0.1		88.4	0.0	0.1	0.9	17.6	3.2	0.1	1.8	0.5	1.6	0.9	0.0	0.0	3
CV		0	43	6		36	-6	9	25	38	39	1	14	8	3	13	0	0	8
5.25	CPW1	18	16.9	1.37		60.0	-0.390	0.75	7.9	71.4	12.70						12.70	100.0	37
6.06	CPW2	16	12.2	1.42		97.0	-0.540	0.91	5.9	40.5	7.63	15.7	17.9	5.37	48.8	5.07	12.70	100.0	44
AVG	CPW	17	14.5	1.40		78.5	-0.465	0.83	6.9	56.0	10.16	15.7	17.9	5.37	48.8	5.07	12.70	100.0	41
STD		0.9	2.4	0.0		18.5	0.1	0.1	1.0	15.4	2.5						0.0	0.0	4
CV		6	16	2		24	-16	10	15	28	25						0	0	9
6.01	CPN1	21	7.0	1.04		143.3	-0.490	0.65	11.2	71.4	12.70						12.70	100.0	37
6.09	CPN2	16	5.9	1.00		94.4	-0.407	.73*	11.4	71.4	12.70						12.70	100.0	44
AVG	CPN	19	6.4	1.02		118.8	-0.449	0.65	11.3	71.4	12.70						12.70	100.0	41
STD		2.8	0.6	0.0		24.4	0.0	0.0	0.1	0.0	0.0						0.0	0.0	4
CV		15	9	2		21	-9	0	1	0	0						0	0	9
6.07	NTW1	100	23.2	1.41		91.1	-0.350	.12*	14.8	71.4	12.70						12.70	100.0	44
5.26	NTW2	100	24.0	1.42		3445	-1.420												37
AVG	NTW	100	23.6	1.42		1768	-0.885		14.8	71.4	12.70						12.70	100.0	41
STD		0.0	0.4	0.0		1677	0.5												4
CV		0	2	0		95	-60												9
6.03	NTN1	100	25.5	1.41		193.4	-0.710	0.97	4.8	47.3	9.34	14.3	23.6	5.93	47.7	3.36	12.70	100.0	44
6.1	NTN2	100	16.2	1.23		388.7	-0.58	1.00*	19.1	71.4	12.7						12.70	100.0	44
AVG	NTN	100	20.8	1.32		291	-0.645	0.97	12.0	59.4	11.02	14.3	23.6	5.93	47.7	3.36	12.70	100.0	44
STD		0.0	4.6	0.1		98	0.1		7.1	12.0	1.7						0.0	0.0	0
CV		0	22	7		34	-10		60	20	15						0	0	0

Table E-4 (L2) (cont'd).

FIELD #2, OSHTEMO SL, 1988

		%								(min)					(min)	(min)			(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	$\%D_a$	CUMWT
7.11	MBW1	0	7.5	1.46		105.9	-0.666	0.92	3.3	29.2	4.63	15.5	10.1	4.97	52.3	7.55	12.19	96.0	162
7.19	MBW2	0	14.6	1.29		120.3	-0.724	0.98	2.8	28.3	4.40	15.3	9.5	4.98	52.6	7.37	11.77	92.7	185
7.26	MBW3	10	17.1	1.43		76.5	-0.555	0.96	4.3	29.1	4.60	15.5	10.4	4.64	52.7	7.86	12.46	98.1	216
8.01	MBW4	3	7.2	1.37		96.3	-0.545	0.80	5.7	39.1	7.24	15.9	16.7	5.37	49.0	5.46	12.70	100.0	229
8.08	MBW5	5	13.4	1.44		85.2	-0.712	0.95	2.1	22.4	2.97	13.8	7.0	3.99	56.0	6.70	9.67	76.2	282
AVG	MBW	4	11.9	1.40		96.8	-0.640	0.92	3.6	29.6	4.77	15.2	10.7	4.79	52.5	6.99	11.76	92.6	215
STD		3.7	4.0	0.1		15.4	0.1	0.1	1.2	5.3	1.4	0.7	3.2	0.5	2.2	0.9	1.1	8.6	41
CV		103	33	4		16	-12	7	34	18	29	5	30	10	4	12	9	9	19
7.12	MBN1	0	13.4	1.23		106.0	-0.587	0.89	5.0	37.0	6.69	16.0	14.9	5.46	49.3	6.01	12.70	100.0	162
7.19	MBN2	5	18.2	1.40		128.0	-0.774	0.99	2.3	26.7	3.99	15.0	8.7	4.82	53.4	7.14	11.13	87.7	185
7.26	MBN3	3	12.0	1.00		90.1	-0.604	0.91	3.9	29.7	4.75	15.5	10.5	4.87	52.2	7.73	12.48	98.3	216
8.01	MBN4	10	10.0	1.30		126.9	-0.620	0.94	5.1	40.5	7.61	15.7	17.3	5.72	48.3	5.09	12.70	100.0	229
8.08	MBN5	10	9.2	1.21		115.2	-0.595	0.70	5.2	39.8	7.43	15.8	16.9	5.60	48.5	5.27	12.70	100.0	282
AVG	MBN	6	12.6	1.23		113.2	-0.636	0.89	4.3	34.7	6.10	15.6	13.7	5.29	50.3	6.25	12.34	97.2	215
STD		3.9	3.2	0.1		14.1	0.1	0.1	1.1	5.5	1.5	0.3	3.5	0.4	2.1	1.0	0.6	4.8	41
CV		70	25	11		12	-11	11	26	16	24	2	25	7	4	17	5	5	19
6.24	CPW1-1	61	20.1	1.19		97.0	-0.500	0.90	7.2	71.4	12.69						12.69	100.0	122
6.28	CPW1-2	80	10.7	1.13		154.1	-0.652	.78*	5.2	46.0	9.01	14.7	22.4	5.78	47.8	3.69	12.70	100.0	124
6.24	CPW1-3	84	19.1	1.07		84.8	-0.417	0.48	9.7	71.4	12.69						12.69	100.0	124
6.29	CPW1-4	39	11.6	1.35		141.4	-0.779	0.89	2.5	28.4	4.43	15.3	9.4	5.10	52.4	7.26	11.69	92.0	122
6.3	CPW1-5	61	7.0	1.00		139.2	-0.583	.65*	6.7	71.4	12.70						12.70	100.0	122
AVG	CPW1	65	13.7	1.15		123.3	-0.586	0.76	6.3	57.7	34.01	11.6	15.9	5.44	50.1	5.48	12.50	98.4	123
STD		16.1	5.1	0.1		27.2	0.1	0.2	2.4	17.7	3.3	0.3	6.5	0.3	2.3	1.8	0.4	3.2	1
CV		25	37	10		22	-21	26	38	31	10	3	41	6	5	33	3	3	1
7.15	CPW2-1	59	6.1	1.29		118.4	-0.581	.93*	5.8	45.2	8.81	14.9	22.1	5.51	48.3	3.89	12.70	100.0	162
7.21	CPW2-2	54	14.8	1.16		92.0	-0.465	0.48	8.2	71.4	12.70						12.70	100.0	189
7.28	CPW2-3	86	16.3	1.11		124.1	-0.468	.99*	10.9	71.4	12.70						12.70	100.0	229
8.03	CPW2-4	63	19.3	1.30		104.9	-0.765	0.96	2.0	23.6	3.24	14.2	7.4	4.27	55.2	6.77	10.01	78.8	241
8.11	CPW2-5	40	18.0	1.24		71.4	-0.493	0.55	5.5	32.8	5.58	15.9	12.7	4.78	51.3	7.12	12.70	100.0	294
AVG	CPW2	60	14.9	1.22		102.2	-0.554	0.66	6.5	48.9	8.61	15.0	14.1	4.85	51.6	5.93	12.16	95.8	223
STD		15.0	4.7	0.1		19.0	0.1	0.2	3.0	19.6	3.8	0.7	6.1	0.5	2.8	1.4	1.1	8.5	45
CV		25	31	6		19	-20	32	46	40	44	5	43	10	5	24	9	9	20

Table E-4 (L2) (cont'd).

FIELD #2, OSHTEMO SL, 1988 (CONT).

		%								(min)					(min)	(min)				(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	$\%D_e$	CUMWT	
6.27	CPN1-1	89	6.6	1.18		171.2	-0.546	.92*	10.0	71.4	12.7								12.70	100.0	122
6.29	CPN1-2	46	10.1	1.16		122.6	-0.595	0.92	5.6	43.8	8.47	15.2	16.7	8.02	44.3	4.23	12.70	100.0	124
6.3	CPN1-3	56	7.3	1.27		134.5	-0.568	0.85	7.0	71.4	12.7						12.70	100.0	124
6.27	CPN1-4	51	9.7	1.22		61.6	-0.303	.54*	12.8	71.4	12.7						12.70	100.0	122
6.28	CPN1-5	66	5.0	1.10		116.0	-0.390	.85*	15.3	71.4	12.7						12.70	100.0	122
AVG	CPN1	62	7.7	1.19		121.2	-0.480	0.88	10.2	65.9	11.85	15.2	16.7	8.02	44.3	4.23	12.70	100.0	123
STD		15.2	1.9	0.1		35.4	0.1	0.0	3.6	11.0	1.7						0.0	0.0	1
CV		25	25	5		29	-24	4	35	17	14						0	0	1
7.14	CPN2-1	84	7.2	1.04		116.9	-0.432	.76*	12.4	71.4	12.7						12.70	100.0	162
7.22	CPN2-2	89	10.3	1.09		110.8	-0.360	0.90	17.1	71.4	12.7						12.70	100.0	189
7.29	CPN2-3	60	16.9	1.09		64.7	-0.306	.75*	13.2	71.4	12.7						12.70	100.0	229
8.04	CPN2-4	54	11.9	1.02		64.0	-0.314	.57*	12.5	71.4	12.7						12.70	100.0	229
8.11	CPN2-5	53	16.0	1.13		101.1	-0.440	0.46	10.3	71.4	12.7						12.70	100.0	294
AVG	CPN2	68	12.4	1.07		91.5	-0.370	0.68	13.1	71.4	12.70						12.70	100.0	221
STD		15.4	3.6	0.0		22.7	0.1	0.2	2.2	0.0	0.0						0.0	0.0	45
CV		23	29	4		25	-15	33	17	0	0						0	0	20
7.14	NTW1	90	10.6	1.43		59.5	-0.204	.11*	20.6	71.4	12.7						12.70	100.0	162
7.21	NTW2	98	14.2	1.46		160.8	-0.619	.81*	6.5	71.4	12.7						12.70	100.0	189
7.27	NTW3	100	22.8	1.50		242.7	-0.698	.93*	6.5	71.4	12.7						12.70	100.0	229
8.02	NTW4	93	11.0	1.37		66.9	-0.370	0.33	9.8	71.4	12.7						12.69	100.0	241
8.1	NTW5	80	18.3	1.28		96.1	-0.469	0.84	8.4	71.4	12.7						12.69	100.0	294
AVG	NTW	92	15.4	1.41		125.2	-0.472	0.59	10.4	71.4	12.70						12.70	100.0	223
STD		7.1	4.6	0.1		68.7	0.2	0.3	5.3	0.0	0.0						0.0	0.0	45
CV		8	30	5		55	-37	44	51	0	0						0	0	20
7.12	NTN1	86	13.3	1.24		232.0	-0.747	0.71	4.8	51.6	10.31	12.8	39.1	2.43	58.9	2.39	12.70	100.0	162
7.21	NTN2	100	16.2	1.38		100.9	-0.487	0.47	8.0	71.4	12.70						12.70	100.0	189
7.27	NTN3	100	23.3	1.37		353.3	-0.753	.82*	7.1	71.4	12.70						12.70	100.0	216
8.02	NTN4	97	10.8	1.34		89.6	-0.33	.99*	16.1	71.4	12.70						12.70	100.0	229
8.1	NTN5	100	21.8	1.40		1385.	-0.93	.99*	11.1	71.4	12.70						12.70	100.0	294
AVG	NTN	97	17.1	1.35		432.3	-0.649	0.59	9.4	67.4	12.22	12.8	39.1	2.43	58.9	2.39	12.70	100.0	218
STD		5.4	4.8	0.1		486.4	0.2	0.1	3.9	7.9	1.0						0.0	0.0	45
CV		6	28	4		113	-33	20	42	12	8						0	0	20

Table E-4 (L2) (cont'd).

FIELD #3, MONTCALM SL, 1989

		%								(min)					(min)	(min)			(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	%D_a	CUMWT
7.31	MBW1	0	2.7	1.50	SL	120.7	-0.738	0.85	2.6	27.5	4.21	15.2	8.3	5.65	52.2	6.33	10.54	83.0	301
8.03	MBW2	3	11.5	1.47	SL	94.7	-0.755	0.99	1.9	22.4	2.96	13.8	6.4	4.51	55.5	5.72	8.68	68.4	332
7.25	MBW3	0	7.5	1.47	SL	119.8	-0.792	0.80	2.0	24.6	3.48	14.5	7.2	5.02	54.0	6.04	9.52	75.0	288
7.06	MBW5	1	7.7	1.49	SL	122.0	-0.755	0.79	2.4	26.8	4.01	15.0	8.0	5.49	52.7	6.27	10.28	80.9	216
6.26	MBW6	0	9.3	1.46	SL	SITE WETTED BY ACCIDENT													203
AVG	MBW	1	7.7	1.48	SL	114.3	-0.760	0.86	2.2	25.3	3.67	14.6	7.5	5.17	53.6	6.09	9.76	76.8	268
STD		1.3	2.9	0.0		11.3	0.0	0.1	0.3	2.0	0.5	0.5	0.7	0.4	1.3	0.2	0.7	5.7	50
CV		155	37	1		10	-3	9	14	8	13	4	10	9	2	4	7	7	19
7.06	MBN2	0	6.0	1.35	SL	135.7	-0.812	0.94	2.0	26.1	3.85	14.8	8.5	4.67	53.8	7.16	11.01	86.7	216
7.25	MBN3	3	5.9	1.28	SL	135.9	-0.863	0.96	1.5	23.6	3.24	14.2	6.9	4.79	54.7	5.91	9.15	72.1	288
7.31	MBN4	2	2.6	1.38	SL	133.2	-0.723	0.95	3.1	30.8	5.04	15.7	9.6	6.29	50.3	6.47	11.51	90.6	301
8.03	MBN5	3	10.9	1.28	SL	86.5	-0.524	0.97	5.7	37.0	6.68	16.0	13.5	6.52	47.9	6.02	12.70	100.0	332
6.26	MBN6	0	6.9	1.45	SL	143.7	-0.783	0.95	2.5	28.5	4.45	15.4	8.8	5.76	51.7	6.50	10.95	86.3	203
AVG	MBN	2	6.4	1.35	SL	127.0	-0.741	0.95	3.0	29.2	4.65	15.2	9.4	5.61	51.7	6.41	11.07	87.1	268
STD		1.5	2.7	0.1		20.6	0.1	0.0	1.5	4.6	1.2	0.6	2.2	0.8	2.4	0.4	1.1	9.0	50
CV		89	41	5		16	-16	1	49	16	25	4	23	13	5	7	10	10	19
8.03	DPW1	0	16.1	1.60	SL	106.1	-0.848	0.94	1.3	20.7	2.57	13.2	7.5	2.64	58.2	8.15	10.72	84.4	332
6.28	DPW2	3	12.4	1.53	SL	(162.4-1.165)													210
7.25	DPW3	3	10.1	1.43	SL	93.4	-0.632	0.77	3.5	28.5	4.46	15.4	8.7	5.85	51.6	6.39	10.85	85.4	288
7.10	DPW5	1	7.9	1.58	SL	100.6	-0.692	0.98	2.8	26.4	3.92	14.9	8.8	4.57	53.8	7.38	11.30	89.0	216
7.28	DPW6	0	11.1	1.54	SL	106.9	-0.765	0.93	2.0	23.9	3.31	14.2	7.3	4.47	54.9	6.58	9.89	77.9	301
AVG	DPW	1	11.5	1.54	SL	101.7	-0.734	0.90	2.4	24.9	3.57	14.4	8.1	4.38	54.6	7.12	10.69	84.2	269
STD		1.4	2.7	0.1		5.4	0.1	0.1	0.8	2.9	0.7	0.8	0.7	1.1	2.4	0.7	0.5	4.0	48
CV		102	24	4		5	-11	9	34	12	20	6	8	26	4	10	5	5	18
8.02	DPN1	5	14.9	1.40	SL	83.3	-0.727	0.92	1.9	21.5	2.76	13.5	6.8	3.61	56.8	6.89	9.64	75.9	332
7.10	DPN2	3	6.0	1.39	SL	93.9	-0.693	0.90	2.6	25.0	3.58	14.6	7.9	4.56	54.3	6.92	10.50	82.6	216
6.28	DPN4	7	12.9	1.43	SL	85.6	-0.706	0.92	2.2	22.7	3.04	13.9	6.6	4.60	55.2	5.78	8.82	69.5	210
7.24	DPN5	10	12.9	1.35	SL	71.5	-0.655	0.98	2.4	21.9	2.85	13.6	6.9	3.80	56.4	6.77	9.63	75.8	288
7.28	DPN6	12	8.9	1.33	SL	75.8	-0.752	0.97	1.5	19.3	2.28	12.6	5.6	3.61	57.7	5.59	7.87	61.9	301
AVG	DPN	7	11.11	1.38	SL	82.0	-0.707	0.94	2.1	22.1	2.90	13.6	6.8	4.04	56.1	6.39	9.29	73.2	269
STD		3.3	3.2	0.0		7.8	0.0	0.0	0.4	1.8	0.4	0.6	0.7	0.4	1.2	0.6	0.9	7.0	48
CV		46	29	3		10	-5	4	17	8	14	5	11	11	2	9	10	10	18

Table E-4 (L2) (cont'd).

FIELD #4, MONTCALM LS, 1989

		%								(min)					(min)	(min)			(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	%D_s	CUMWT
7.11	NTW1	83	2.0	1.38	S	107.7	-0.313	.68*	21.2	71.4	12.7						12.70	100.0	216
6.29	NTW2	67	7.1	1.39	S	131.2	-0.544	.81*	7.8	71.4	12.7						12.70	100.0	210
8.02	NTW3	82	15.3	1.44	S	112.3	-0.175	.11*	45.3	71.4	12.7						12.70	100.0	332
7.24	NTW4	88	11.7	1.47	S	110.3	-0.157	.07*	48.8	71.4	12.7						12.70	100.0	288
7.27	NTW5	72	7.6	1.44	LS	89.3	-0.352	.76*	14.4	71.4	12.7						12.70	100.0	301
AVG	NTW	78	8.7	1.42	S-	110.2	-0.308		27.5	71.4	12.70						12.70	100.0	269
STD		8.0	4.5	0.0	LS	13.3	0.1		16.6	0.0	0.0						0.0	0.0	48
CV		10	51	2		12	-45		60	0	0						0	0	18
7.27	NTN1	75	15.1	1.49	LS	1460.	-0.828	.74*	19.8	71.4	12.7						12.70	100.0	301
6.29	NTN3	72	6.2	1.40	LS	119.3	-0.371	.89*	17.4	71.4	12.7						12.70	100.0	210
7.24	NTN4	67	11.9	1.49	LS	62.2	-0.061	.09*	45.3	71.4	12.7						12.70	100.0	288
8.02	NTN5	73	17.5	1.43	LS	132.2	-0.389	.77*	17.5	71.4	12.7						12.70	100.0	332
7.11	NTN6	82	2.1	1.37	LS	ONLY 1 PONDED													216
AVG	NTN	74	10.5	1.44	LS	443.5	-0.412		25.0	71.4	12.70						12.70	100.0	269
STD		4.9	5.6	0.0		587.6	0.3		11.8	0.0	0.0						0.0	0.0	48
CV		7	54	3		132	-66		47	0	0						0	0	18

Table E-4 (L2) (cont'd).

FIELD #5, MONTCALM LS, 1989

		%								(min)					(min)	(min)			(mm)
DATE	SITE	RES	θ_i	BD	TXT	a	b	r^2	k	t_p	D_{tp}	r_{tp}	t_1	f	t_2	D_p	D_{tot}	%D_a	CUMWT
7.13	PMBW1	0	11.7	1.49	LS	104.1	-0.654	0.94	3.5	29.7	4.75	15.5	9.2	6.08	50.9	6.44	11.19	88.1	101
8.07	PMBW2	4	16.0	1.50	LS	65.3	-0.497	0.98	4.9	29.4	4.67	15.5	9.0	6.02	51.1	8.03	12.70	100.0	216
8.01	PMBW4	3	12.0	1.58	S	92.3	-0.490	.96*	7.2	71.4	12.70						12.70	100.0	110
6.30	PMBW5	0	12.8	1.58	LS	73.2	-0.449	0.84	7.1	44.4	8.61	15.1	17.2	8.05	44.2	4.09	12.70	100.0	95
7.26	PMBW6	34	10.8	1.60	LS	83.3	-0.472	.88*	7.2	71.4	12.70						12.70	100.0	103
AVG	PMBW	8	12.7	1.55	LS-	83.7	-0.512	0.92	6.0	49.2	8.69	15.4	11.8	6.72	48.7	6.19	12.40	97.6	125
STD		13.0	1.8	0.0	S	13.7	0.1	0.1	1.5	18.9	3.6	0.2	3.8	0.9	3.2	1.6	0.6	4.7	46
CV		159	14	3		16	-14	7	25	38	41	1	32	14	7	26	5	5	37
7.13	PMBN1	0	9.3	1.34	LS	81.5	-0.612	0.82	3.4	26.3	3.89	14.9	10.3	3.22	55.4	8.81	12.70	100.0	101
8.01	PMBN2	6	14.2	1.30	LS	96.0	-0.581	1.00	4.7	38.8	7.17	15.9	17.5	4.70	50.1	5.53	12.70	100.0	110
8.07	PMBN3	6	14.3	1.31	LS	132.7	-0.732	0.99	3.0	30.0	4.84	15.6	9.3	6.15	50.7	6.46	11.30	89.0	216
6.30	PMBN4	0	10.8	1.33	LS	123.8	-0.622	0.87	4.9	38.9	7.19	15.9	16.8	5.22	49.3	5.51	12.70	100.0	95
7.26	PMBN5	20	5.9	1.32	LS	159.8	-0.596	0.99	7.2	72.0	12.70						12.70	100.0	103
AVG	PMBN	6	10.9	1.32	LS	118.8	-0.629	0.93	4.6	41.2	7.16	15.6	13.5	4.82	51.4	6.58	12.42	97.8	125
STD		7.3	3.2	0.0		27.6	0.1	0.1	1.5	16.2	3.1	0.4	3.7	1.1	2.4	1.3	0.6	4.4	46
CV		115	29	1		23	-9	8	32	39	43	3	27	22	5	20	5	5	37
7.26	PPTW1	25	7.0	1.56	LS	121.8	-0.548	.89*	7.1	71.4	12.70						12.70	100.0	103
8.07	PPTW2	17	12.2	1.61	S	99.1	-0.621	0.97	3.9	30.9	5.08	15.7	12.6	3.89	53.1	7.62	12.70	100.0	216
7.05	PPTW4	0	14.7	1.58	LS	69.6	-0.453	0.71	6.6	37.7	6.87	16.0	12.9	7.40	46.7	5.83	12.70	100.0	100
8.01	PPTW5	9	17.0	1.64	LS	106.2	-0.799	0.79	1.7	22.4	2.96	13.8	7.8	3.29	56.8	7.82	10.78	84.9	110
7.14	PPTW6	0	14.2	1.58	LS	69.9	-0.465	0.91	6.2	35.7	6.35	16.0	12.5	6.62	48.2	6.35	12.70	100.0	101
AVG	PPTW	10	13.0	1.59	LS-	93.3	-0.577	0.85	5.1	39.6	6.79	15.4	11.4	5.30	51.2	6.90	12.32	97.0	126
STD		9.7	3.4	0.0	S	20.6	0.1	0.1	2.0	16.7	3.2	0.9	2.1	1.7	4.0	0.8	0.8	6.0	45
CV		95	26	2		22	-22	12	40	42	48	6	19	33	8	12	6	6	36
7.26	PPTN1	33	6.5	1.34	LS	137.8	-0.572	0.99	7.1	72.0	12.70						12.70	100.0	103
7.14	PPTN2	0	10.9	1.30	LS	70.2	-0.382	0.75	9.7	72.0	12.70						12.70	100.0	101
8.07	PPTN3	5	14.5	1.31	LS	91.2	-0.542	0.97	5.5	36.7	6.61	16.0	12.4	7.27	47.1	6.09	12.70	100.0	216
7.05	PPTN4	0	6.0	1.33	S	103.2	-0.515	0.94	7.1	72.0	12.70						12.70	100.0	100
8.01	PPTN5	15	16.1	1.32	S	116.1	-0.767	0.96	2.2	25.2	3.63	14.6	8.0	4.60	54.2	6.95	10.58	83.3	110
AVG	PPTN	11	10.8	1.32	LS-	103.7	-0.556	0.92	6.3	55.6	9.67	15.3	10.2	5.94	50.6	6.52	12.28	96.7	126
STD		12.6	4.1	0.0	S	22.8	0.1	0.1	2.5	20.4	3.8	0.7	2.2	1.3	3.5	0.4	0.8	6.7	45
CV		118	38	1		22	-22	10	39	37	40	4	22	22	7	7	7	7	36

Table E-5. (H1) COLLECTIVE. Appl. depth = 25.4mm, DRY data, high (57.4 mm/h) maximum rate.

#1, KALAMAZOO SL, 1988

	%									(min)				(min)		(min)			
	RES	θ_i	BD	a	b	r2	SEln(r)	n	K	H1RTP	Rtp	%Dtp	rtp	t1	f	t2	Rp	Rtot	%Ra
MBW	3	14.7	1.38	84.2	-0.652	0.92	0.166	12	2.9	7.3	2.26	9.1	34.5	2.1	5.85	34.6	8.26	10.53	41.4
MBN	6	9.1	1.03	292.5	-0.838	0.76	0.391	12	3.8	13.6	6.83	27.3	51.5	4.1	12.53	30.4	12.92	19.74	77.7
MB	4	11.9	1.20	117.3	-0.649	0.57	0.468	24	4.0	9.2	3.46	13.8	40.9	2.7	7.77	33.3	10.35	13.81	54.4
CPW	17	14.5	1.40	84.3	-0.508	0.80	0.161	12	6.0	8.5	3.00	12.0	38.6	2.5	6.69	33.8	10.44	13.44	52.9
CPN	19	6.4	1.02	98.9	-0.398	0.71	0.254	12	12.5	9.3	3.52	14.1	41.1	3.0	6.43	33.5	13.10	16.62	65.4
CP	18	10.5	1.21	76.3	-0.387	0.56	0.136	24	10.2	9.2	3.44	13.8	40.8	2.9	6.71	33.5	12.31	15.75	62.0
NTW	100	23.6	1.42	376.6	-0.844	0.56	0.444	12	4.7	16.0	8.96	35.8	55.1	5.1	14.69	29.0	13.73	22.69	89.3
NTN	100	20.8	1.32	104.4	-0.397	0.32	0.449	12	13.3	12.1	5.58	22.3	48.5	4.0	9.09	31.8	14.68	20.27	79.8
NT	100	22.2	1.37	189.6	-0.620	0.45	0.466	24	7.6	13.8	7.00	28.0	51.9	4.4	11.96	30.4	13.88	20.88	82.2

#2, OSHTEMO SL, 1988

MBW	4	11.9	1.40	87.8	-0.588	0.85	0.198	30	4.1	8.0	2.69	10.7	37.0	2.3	6.44	34.1	9.38	12.07	47.5
MBN	6	12.6	1.23	99.2	-0.557	0.87	0.197	29	5.5	9.1	3.38	13.5	40.5	2.7	7.40	33.4	10.73	14.11	55.6
MB	5	12.3	1.31	91.5	-0.562	0.83	0.214	59	4.9	8.5	2.99	12.0	38.6	2.5	6.85	33.8	10.07	13.06	51.4
CPW1	65	13.7	1.15	99.2	-0.496	0.72	0.294	29	7.5	9.9	3.89	15.6	42.7	3.0	7.86	33.0	11.92	15.81	62.2
CPN1	62	7.7	1.19	98.8	-0.402	0.66	0.664	28	12.3	11.4	5.01	20.0	46.8	3.7	8.57	32.2	14.12	19.13	75.3
CP1	62	12.1	1.18	94.9	-0.430	0.65	0.322	57	10.2	10.5	4.33	17.3	44.4	3.3	8.03	32.7	13.07	17.40	68.5
CPW2	60	14.9	1.22	77.9	-0.441	0.74	0.293	26	7.9	8.7	3.11	12.4	39.2	2.6	6.57	33.8	11.20	14.30	56.3
CPN2	68	12.4	1.07	82.7	-0.362	0.66	0.34	29	12.6	10.3	4.20	16.8	44.0	3.3	7.40	32.9	13.69	17.89	70.4
CP2	63	11.8	1.17	75.9	-0.370	0.66	0.334	56	11.1	9.4	3.56	14.2	41.3	3.0	6.74	33.4	12.70	16.26	64.0
NTW	92	15.4	1.41	116.6	-0.460	0.74	0.279	26	10.7	12.0	5.49	21.9	48.2	3.8	9.49	31.7	13.97	19.46	76.6
NTN	97	17.1	1.35	118.7	-0.411	0.69	0.32	26	14.0	13.3	6.62	26.5	51.1	4.5	10.16	31.0	15.25	21.87	86.1
NT	94	16.2	1.38	116.0	-0.414	0.67	0.315	52	13.5	12.9	6.30	25.2	50.4	4.3	9.90	31.2	15.02	21.32	84.0

#3, MONTCALM SL, 1989

MBW	1	7.7	1.48	104.7	-0.703	0.84	0.246	24	2.7	8.1	2.71	10.8	37.1	2.3	6.70	34.0	8.92	11.63	45.8
MBN	2	6.4	1.35	115.2	-0.680	0.92	0.196	30	3.4	8.8	3.18	12.7	39.5	2.5	7.41	33.5	9.79	12.97	51.1
MB	1	7.1	1.41	109.9	-0.686	0.88	0.225	54	3.1	9.3	3.48	13.9	41.0	2.6	7.95	33.2	10.08	13.56	53.4
DPW	1	11.5	1.54	107.8	-0.817	0.88	0.237	30	1.5	7.4	2.32	9.3	34.8	2.0	6.13	34.5	7.87	10.19	40.1
DPN	7	11.1	1.38	79.5	-0.680	0.91	0.18	30	2.3	6.9	2.01	8.0	32.8	1.9	5.43	34.9	7.62	9.64	37.9
DP	4	11.3	1.46	89.9	-0.730	0.87	0.226	60	2.0	7.1	2.16	8.6	33.8	2.0	5.76	34.7	7.77	9.93	39.1

#4, MONTCALM LS, 1989

NTW	78	8.7	1.42	101.4	-0.296	0.39	0.395	22	21.8	14.7	7.78	31.1	53.4	5.5	9.56	30.7	17.04	24.82	97.7
NTN	74	10.5	1.44	101.1	-0.263	0.56	0.284	22	25.8	16.1	9.13	36.5	55.3	6.5	9.69	30.2	16.27	25.40	100.0
NT	76	9.6	1.43	102.5	-0.286	0.51	0.339	44	23.2	15.3	8.35	33.4	54.3	5.9	9.72	30.4	17.05	25.40	100.0

#5, MONTCALM LS, 1989

PMBW	8	12.7	1.55	73.0	-0.444	0.83	0.21	30	7.3	8.2	2.80	11.2	37.6	2.5	6.15	34.1	10.62	13.41	52.8
PMBN	6	10.9	1.32	100.2	-0.552	0.78	0.276	29	5.7	9.2	3.46	13.8	40.9	2.7	7.50	33.3	10.89	14.35	56.5
PMB	7	11.8	1.44	84.4	-0.491	0.79	0.251	59	6.6	8.7	3.12	12.5	39.3	2.6	6.80	33.7	10.78	13.90	54.7
PPTW	10	13.0	1.59	80.9	-0.512	0.74	0.289	30	5.7	8.2	2.80	11.2	37.6	2.4	6.42	34.0	10.07	12.88	50.7
PPTN	11	10.8	1.32	89.7	-0.494	0.83	0.21	30	6.9	9.1	3.38	13.5	40.5	2.7	7.17	33.5	11.18	14.56	57.3
PPT	10	11.9	1.46	85.4	-0.504	0.77	0.257	60	6.2	8.7	3.08	12.3	39.1	2.6	6.79	33.8	10.62	13.70	53.9

Table E-6. (H2) COLLECTIVE. Appl. depth - 12.7mm, DRY data, high (57.4 mm/h) maximum rate.

#1, KALAMAZOO SL, 1988

	%									(min)									
	RES	θ_i	BD	a	b	r2	SEln(r)	n	K	H2TP	Rtp	%Dtp	rtp	t1	f	t2	Rp	Rtot	%Ra
MBW	3	14.7	1.38	84.2	-0.652	0.92	0.166	12	2.9	5.0	2.00	15.7	43.1	1.4	6.23	16.3	5.28	7.28	57.3
MBN	6	9.1	1.03	292.5	-0.838	0.76	0.391	12	3.8	10.2	6.55	51.6	57.4	3.5	13.03	13.3	6.15	12.70	100.0
MB	4	11.9	1.20	117.3	-0.649	0.57	0.468	24	4.0	6.4	3.09	24.3	50.0	1.9	8.24	15.4	6.31	9.40	74.0
CPW	17	14.5	1.40	84.3	-0.508	0.80	0.161	12	6.0	5.7	2.48	19.6	46.5	1.7	6.84	16.0	6.18	8.66	68.2
CPN	19	6.4	1.02	98.9	-0.398	0.71	0.254	12	12.5	6.0	2.75	21.7	48.2	2.0	6.46	15.9	7.21	9.96	78.4
CP	18	10.5	1.21	76.3	-0.387	0.56	0.136	24	10.2	5.9	2.66	21.0	47.7	1.9	6.62	15.9	6.87	9.53	75.0
NTW	100	23.6	1.42	376.6	-0.844	0.56	0.444	12	4.7	12.9	9.03	71.1	52.8	5.4	14.39	12.4	3.67	12.70	100.0
NTN	100	20.8	1.32	104.4	-0.397	0.32	0.449	12	13.3	8.1	4.55	35.8	55.2	2.8	9.08	14.7	7.67	12.22	96.2
NT	100	22.2	1.37	189.6	-0.620	0.45	0.466	24	7.6	10.2	6.56	51.7	57.4	3.7	12.32	13.4	6.14	12.70	100.0

#2, OSHTEMO SL, 1988

MBW	4	11.9	1.40	87.8	-0.588	0.85	0.198	30	4.1	5.4	2.31	18.2	45.4	1.6	6.74	16.1	5.78	8.09	63.7
MBN	6	12.6	1.23	99.2	-0.557	0.87	0.197	29	5.5	6.2	2.89	22.7	48.9	1.9	7.68	15.6	6.38	9.27	73.0
MB	5	12.3	1.31	91.5	-0.562	0.83	0.214	59	4.9	5.8	2.55	20.1	47.0	1.7	7.12	15.9	6.08	8.64	68.0
CPW1	65	13.7	1.15	99.2	-0.496	0.72	0.294	29	7.5	6.6	3.25	25.6	50.7	2.1	8.03	15.4	6.82	10.07	79.3
CPN1	62	7.7	1.19	98.8	-0.402	0.66	0.664	28	12.3	7.5	4.04	31.8	53.8	2.5	8.55	15.0	7.55	11.59	91.3
CP1	62	12.1	1.18	94.9	-0.430	0.65	0.322	57	10.2	6.9	3.50	27.6	51.8	2.2	8.06	15.3	7.22	10.72	84.4
CPW2	60	14.9	1.22	77.9	-0.441	0.74	0.293	26	7.9	5.7	2.48	19.6	46.5	1.7	6.60	16.0	6.44	8.92	70.2
CPN2	68	12.4	1.07	82.7	-0.362	0.66	0.34	29	12.6	6.6	3.25	25.6	50.7	2.2	7.28	15.5	7.42	10.67	84.0
CP2	63	11.8	1.17	75.9	-0.370	0.66	0.334	56	11.1	6.0	2.74	21.5	48.1	1.9	6.63	15.9	7.02	9.76	76.8
NTW	92	15.4	1.41	116.6	-0.460	0.74	0.279	26	10.7	8.2	4.63	36.5	55.4	2.8	9.62	14.5	7.43	12.06	95.0
NTN	97	17.1	1.35	118.7	-0.411	0.69	0.32	26	14.0	9.2	5.64	44.4	57.0	3.4	10.21	14.1	7.06	12.70	100.0
NT	94	16.2	1.38	116.0	-0.414	0.67	0.315	52	13.5	8.9	5.31	41.8	56.7	3.2	9.95	14.2	7.39	12.70	100.0

#3, MONTCALM SL, 1989

MBW	1	7.7	1.48	104.7	-0.703	0.84	0.246	24	2.7	5.6	2.45	19.3	46.3	1.6	7.20	15.9	5.69	8.14	64.1
MBN	2	6.4	1.35	115.2	-0.680	0.92	0.196	30	3.4	6.1	2.86	22.6	48.8	1.8	7.92	15.6	6.09	8.95	70.5
MB	1	7.1	1.41	109.9	-0.686	0.88	0.225	54	3.1	5.9	2.67	21.0	47.7	1.7	7.59	15.8	5.92	8.59	67.7
DPW	1	11.5	1.54	107.8	-0.817	0.88	0.237	30	1.5	5.3	2.18	17.2	44.4	1.5	6.78	16.2	5.27	7.45	58.7
DPN	7	11.1	1.38	79.5	-0.680	0.91	0.18	30	2.3	4.7	1.79	14.1	41.3	1.3	5.83	16.5	4.97	6.76	53.2
DP	4	11.3	1.46	89.9	-0.730	0.87	0.226	60	2.0	5.0	1.96	15.4	42.8	1.4	6.24	16.4	5.11	7.08	55.7

#4, MONTCALM LS, 1989

NTW	78	8.7	1.42	101.4	-0.296	0.39	0.395	22	21.8	10.2	6.53	51.5	57.4	4.2	9.43	14.0	6.17	12.70	100.0
NTN	74	10.5	1.44	101.1	-0.263	0.56	0.284	22	25.8	19.9	12.70	100						12.70	100.0
NT	76	9.6	1.43	102.5	-0.286	0.51	0.339	44	23.2	11.3	7.56	59.5	56.5	5.0	9.67	13.7	5.14	12.70	100.0

#5, MONTCALM LS, 1989

PMBW	8	12.7	1.55	73.0	-0.444	0.83	0.21	30	7.3	5.3	2.22	17.5	44.8	1.6	6.17	16.2	6.15	8.38	66.0
PMBN	6	10.9	1.32	100.2	-0.552	0.78	0.276	29	5.7	6.3	2.95	23.3	49.3	1.9	7.77	15.6	6.45	9.40	74.0
PMB	7	11.8	1.44	84.4	-0.491	0.79	0.251	59	6.6	5.8	2.56	20.2	47.0	1.8	6.92	15.9	6.32	8.88	69.9
PPTW	10	13.0	1.59	80.9	-0.512	0.74	0.289	30	5.7	5.5	2.32	18.3	45.5	1.6	6.57	16.1	6.00	8.33	65.6
PPTN	11	10.8	1.32	89.7	-0.494	0.83	0.21	30	6.9	6.1	2.79	22.0	48.4	1.9	7.31	15.7	6.51	9.30	73.2
PPT	10	11.9	1.46	85.4	-0.504	0.77	0.257	60	6.2	5.7	2.55	20.0	46.9	1.7	6.94	15.9	6.26	8.80	69.3

Table E-7. (L1) COLLECTIVE. Appl. depth = 25.4mm, DRY data, low (16 mm/h) maximum rate.

#1, KALAMAZOO SL, 1988

	%										(min)								
	RES	θ_i	BD	a	b	r2	SEln(r)	n	K	L1TP	Rtp	%Dtp	rtp	t1	f	t2	Rp	Rtot	%Ra
MBW	3	14.7	1.38	84.2	-0.652	0.92	0.166	12	2.9	35.7	3.97	15.6	12.0	11.3	3.97	118.3	12.79	16.76	66.0
MBN	6	9.1	1.03	292.5	-0.838	0.76	0.391	12	3.8	55.9	8.63	34.0	15.2	19.4	6.52	106.3	15.41	24.04	94.6
MB	4	11.9	1.20	117.3	-0.649	0.57	0.468	24	4.0	45.9	6.18	24.3	14.0	15.5	5.05	112.4	15.20	21.38	84.2
CPW	17	14.5	1.40	84.3	-0.508	0.80	0.161	12	6.0	51.7	7.58	29.9	14.8	19.3	4.97	110.4	16.99	24.58	96.8
CPN	19	6.4	1.02	98.9	-0.398	0.71	0.254	12	12.5	80.3	15.04	59.2	15.8	47.5	2.88	110.1	10.36	25.40	100.0
CP	18	10.5	1.21	76.3	-0.387	0.56	0.136	24	10.2	83.0	15.75	62.0	15.6	45.1	4.65	105.0	9.65	25.40	100.0
NTW	100	23.6	1.42	376.6	-0.844	0.56	0.444	12	4.7	66.0	11.27	44.4	15.9	24.9	7.22	101.7	14.13	25.40	100.0
NTN	100	20.8	1.32	104.4	-0.397	0.32	0.449	12	13.3	142.8	25.40	100.0						25.40	100.0
NT	100	22.2	1.37	189.6	-0.620	0.45	0.466	24	7.6	78.0	14.46	56.9	15.9	35.9	6.41	100.7	10.94	25.40	100.0

#2, OSHTEMO SL, 1988

MBW	4	11.9	1.40	87.8	-0.588	0.85	0.198	30	4.1	42.7	5.46	21.5	13.4	14.4	4.55	114.5	15.02	20.48	80.6
MBN	6	12.6	1.23	99.2	-0.557	0.87	0.197	29	5.5	51.5	7.53	29.6	14.8	18.8	5.18	110.1	16.61	24.14	95.0
MB	5	12.3	1.31	91.5	-0.562	0.83	0.214	59	4.9	47.4	6.52	25.7	14.2	16.7	4.88	112.2	16.05	22.58	88.9
CPW1	65	13.7	1.15	99.2	-0.496	0.72	0.294	29	7.5	63.8	10.68	42.0	15.8	26.6	5.51	105.6	14.72	25.40	100.0
CPN1	62	7.7	1.19	98.8	-0.402	0.66	0.664	28	12.3	142.8	25.40	100.0						25.40	100.0
CP1	62	12.1	1.18	94.9	-0.430	0.65	0.322	57	10.2	142.8	25.40	100.0						25.40	100.0
CPW2	60	14.9	1.22	77.9	-0.441	0.74	0.293	26	7.9	60.9	9.92	39.1	15.7	25.4	5.06	107.3	15.48	25.40	100.0
CPN2	68	12.4	1.07	82.7	-0.362	0.66	0.34	29	12.6	142.8	25.40	100.0						25.40	100.0
CP2	63	11.8	1.17	75.9	-0.370	0.66	0.334	56	11.1	142.8	25.40	100.0						25.40	100.0
NTW	92	15.4	1.41	116.6	-0.460	0.74	0.279	26	10.7	142.8	25.40	100.0						25.40	100.0
NTN	97	17.1	1.35	118.7	-0.411	0.69	0.32	26	14.0	142.8	25.40	100.0						25.40	100.0
NT	94	16.2	1.38	116.0	-0.414	0.67	0.315	52	13.5	142.8	25.40	100.0						25.40	100.0

#3, MONTCALM SL, 1989

MBW	1	7.7	1.48	104.7	-0.703	0.84	0.246	24	2.7	37.4	4.30	16.9	12.4	11.7	4.27	117.2	12.93	17.23	67.8
MBN	2	6.4	1.35	115.2	-0.680	0.92	0.196	30	3.4	42.0	5.31	20.9	13.3	13.7	4.74	114.5	14.23	19.54	76.9
MB	1	7.1	1.41	109.9	-0.686	0.88	0.225	54	3.1	40.1	4.88	19.2	12.9	12.9	4.55	115.6	13.74	18.62	73.3
DPW	1	11.5	1.54	107.8	-0.817	0.88	0.237	30	1.5	30.7	3.01	11.9	10.8	9.0	3.58	121.1	10.30	13.31	52.4
DPN	7	11.1	1.38	79.5	-0.680	0.91	0.18	30	2.3	32.4	3.33	13.1	11.2	9.9	3.62	120.3	11.59	14.92	58.7
DP	4	11.3	1.46	89.9	-0.730	0.87	0.226	60	2.0	32.0	3.25	12.8	11.1	9.6	3.64	120.5	11.16	14.40	56.7

#4, MONTCALM LS, 1989

NTW	78	8.7	1.42	101.4	-0.296	0.39	0.395	22	21.8	142.8	25.40	100.0						25.40	100.0
NTN	74	10.5	1.44	101.1	-0.263	0.56	0.284	22	25.8	142.8	25.40	100.0						25.40	100.0
NT	76	9.6	1.43	102.5	-0.286	0.51	0.339	44	23.2	142.8	25.40	100.0						25.40	100.0

#5, MONTCALM LS, 1989

PMBW	8	12.7	1.55	73.0	-0.444	0.83	0.21	30	7.3	56.0	8.65	34.0	15.3	22.3	4.87	109.1	16.75	25.40	100.0
PMBN	6	10.9	1.32	100.2	-0.552	0.78	0.276	29	5.7	52.8	7.84	30.9	14.9	19.5	5.25	109.5	16.76	24.60	96.8
PMB	7	11.8	1.44	84.4	-0.491	0.79	0.251	59	6.6	54.8	8.35	32.9	15.1	21.2	5.08	109.1	17.05	25.40	100.0
PPTW	10	13.0	1.59	80.9	-0.512	0.74	0.289	30	5.7	49.2	6.96	27.4	14.5	18.0	4.81	111.6	16.69	23.66	93.1
PPTN	11	10.8	1.32	89.7	-0.494	0.83	0.21	30	6.9	57.7	9.09	35.8	15.4	22.8	5.25	107.9	16.31	25.40	100.0
PPT	10	11.9	1.46	85.4	-0.504	0.77	0.257	60	6.2	53.1	7.91	31.2	14.9	20.1	5.04	109.8	17.13	25.04	98.6

Table E-8. (L2) COLLECTIVE. Appl. depth = 12.7mm, DRY data, low (16mm/h) maximum rate.

#1, KALAMAZOO SL, 1988

	% RES	θ_i	BD	a	b	r2	SEln(r)	n	K	(min) L2TP	Rtp	%Dtp	rtp	t1	f	t2	Rp	Rtot	%Ra
MBW	3	14.7	1.38	84.2	-0.652	0.92	0.166	12	2.9	25.0	3.58	28.2	14.6	8.2	4.33	54.6	7.26	10.84	85.4
MBN	6	9.1	1.03	292.5	-0.838	0.76	0.391	12	3.8	44.5	8.66	68.2	15.0	19.8	6.46	46.6	4.04	12.70	100.0
MB	4	11.9	1.20	117.3	-0.649	0.57	0.468	24	4.0	33.5	5.76	45.3	15.9	12.4	5.41	50.3	6.94	12.70	100.0
CPW	17	14.5	1.40	84.3	-0.508	0.80	0.161	12	6.0	38.4	7.07	55.6	15.9	16.4	5.17	49.4	5.63	12.70	100.0
CPN	19	6.4	1.02	98.9	-0.398	0.71	0.254	12	12.5	71.4	12.70	100.0						12.70	100.0
CP	18	10.5	1.21	76.3	-0.387	0.56	0.136	24	10.2	71.4	12.70	100.0						12.70	100.0
NTW	100	23.6	1.42	376.6	-0.844	0.56	0.444	12	4.7	71.4	12.70	100.0						12.70	100.0
NTN	100	20.8	1.32	104.4	-0.397	0.32	0.449	12	13.3	71.4	12.70	100.0						12.70	100.0
NT	100	22.2	1.37	189.6	-0.620	0.45	0.466	24	7.6	71.4	12.70	100.0						12.70	100.0

FIELD #2, OSHTEMO SL, 1988

	% RES	θ_i	BD	a	b	r2	SEln(r)	n	K	(min) L2TP	Rtp	%Dtp	rtp	t1	f	t2	Rp	Rtot	%Ra
MBW	4	11.9	1.40	87.8	-0.588	0.85	0.198	30	4.1	30.2	4.88	38.4	15.6	10.8	4.87	52.1	7.79	12.67	99.7
MBN	6	12.6	1.23	99.2	-0.557	0.87	0.197	29	5.5	38.5	7.09	55.8	15.9	16.2	5.40	49.1	5.61	12.70	100.0
MB	5	12.3	1.31	91.5	-0.562	0.83	0.214	59	4.9	34.2	5.94	46.8	16.0	13.2	5.18	50.4	6.76	12.70	100.0
CPW1	65	13.7	1.15	99.2	-0.496	0.72	0.294	29	7.5	71.4	12.70	100.0						12.70	100.0
CPN1	62	7.7	1.19	98.8	-0.402	0.66	0.664	28	12.3	71.4	12.70	100.0						12.70	100.0
CP1	62	12.1	1.18	94.9	-0.430	0.65	0.322	57	10.2	71.4	12.70	100.0						12.70	100.0
CPW2	60	14.9	1.22	77.9	-0.441	0.74	0.293	26	7.9	71.4	12.70	100.0						12.70	100.0
CPN2	68	12.4	1.07	82.7	-0.362	0.66	0.34	29	12.6	71.4	12.70	100.0						12.70	100.0
CP2	63	11.8	1.17	75.9	-0.370	0.66	0.334	56	11.1	71.4	12.70	100.0						12.70	100.0
NTW	92	15.4	1.41	116.6	-0.460	0.74	0.279	26	10.7	71.4	12.70	100.0						12.70	100.0
NTN	97	17.1	1.35	118.7	-0.411	0.69	0.32	26	14.0	71.4	12.70	100.0						12.70	100.0
NT	94	16.2	1.38	116.0	-0.414	0.67	0.315	52	13.5	71.4	12.70	100.0						12.70	100.0

#3, MONTCALM SL, 1989

	% RES	θ_i	BD	a	b	r2	SEln(r)	n	K	(min) L2TP	Rtp	%Dtp	rtp	t1	f	t2	Rp	Rtot	%Ra
MBW	1	7.7	1.48	104.7	-0.703	0.84	0.246	24	2.7	26.6	3.97	31.3	15.0	8.8	4.68	53.6	7.30	11.27	88.7
MBN	2	6.4	1.35	115.2	-0.680	0.92	0.196	30	3.4	30.3	4.92	38.7	15.6	10.6	5.15	51.7	7.54	12.46	98.1
MB	1	7.1	1.41	109.9	-0.686	0.88	0.225	54	3.1	28.7	4.51	35.5	15.4	9.8	4.95	52.5	7.48	11.99	94.4
DPW	1	11.5	1.54	107.8	-0.817	0.88	0.237	30	1.5	21.9	2.86	22.5	13.6	6.7	4.03	56.1	6.38	9.24	72.7
DPN	7	11.1	1.38	79.5	-0.680	0.91	0.18	30	2.3	22.6	3.02	23.8	13.9	7.1	3.98	55.9	6.82	9.84	77.5
DP	4	11.3	1.46	89.9	-0.730	0.87	0.226	60	2.0	22.5	3.00	23.6	13.8	7.0	4.03	55.9	6.68	9.68	76.2

#4, MONTCALM LS, 1989

	% RES	θ_i	BD	a	b	r2	SEln(r)	n	K	(min) L2TP	Rtp	%Dtp	rtp	t1	f	t2	Rp	Rtot	%Ra
NTW	78	8.7	1.42	101.4	-0.296	0.39	0.395	22	21.8	71.4	12.70	100.0						12.70	100.0
NTN	74	10.5	1.44	101.1	-0.263	0.56	0.284	22	25.8	71.4	12.70	100.0						12.70	100.0
NT	76	9.6	1.43	102.5	-0.286	0.51	0.339	44	23.2	71.4	12.70	100.0						12.70	100.0

#5, MONTCALM LS, 1989

	% RES	θ_i	BD	a	b	r2	SEln(r)	n	K	(min) L2TP	Rtp	%Dtp	rtp	t1	f	t2	Rp	Rtot	%Ra
PMBW	8	12.7	1.55	73.0	-0.444	0.83	0.21	30	7.3	71.4	12.70	100.0						12.70	100.0
PMBN	6	10.9	1.32	100.2	-0.552	0.78	0.276	29	5.7	40.0	7.49	59.0	15.8	17.4	5.42	48.8	5.21	12.70	100.0
PMB	7	11.8	1.44	84.4	-0.491	0.79	0.251	59	6.6	42.9	8.23	64.8	15.4	20.5	5.12	49.0	4.47	12.70	100.0
PPTW	10	13.0	1.59	80.9	-0.512	0.74	0.289	30	5.7	35.6	6.32	49.8	16.0	14.4	5.06	50.2	6.38	12.70	100.0
PPTN	11	10.8	1.32	89.7	-0.494	0.83	0.21	30	6.9	71.4	12.70	100.0						12.70	100.0
PPT	10	11.9	1.46	85.4	-0.504	0.77	0.257	60	6.2	40.1	7.51	59.2	15.8	17.8	5.19	49.1	5.19	12.70	100.0

Table E-9. (H1) COLLECTIVE. Appl. depth - 25.4mm, WET data, high (57.4mm/h) maximum rate.

FIELD #1, KALAMAZOO SL, 1988

NO WET TESTS DONE

FIELD #2, OSHTEMO SL, 1988

	% RES	BD	TXTR	a	b	r^2	k	t_p (min)	D_{tp}	r_{tp}	t_1	f (min)	t_2	D_p (min)	D_{tot}	$\%D_a$
MBW	4	1.40		46.33	-0.520	0.70	3.1	5.4	1.28	26.9	1.5	3.78	35.9	6.44	7.72	30.4
MBN	6	1.23		47.74	-0.550	0.73	2.7	5.4	1.27	26.9	1.5	3.82	35.9	6.28	7.55	29.7
CPW1	65	1.15		81.84	-0.629	0.44	3.1	7.4	2.28	34.5	2.1	5.84	34.6	8.38	10.66	42.0
CPW2	60	1.22		50.14	-0.469	0.40	4.4	6.0	1.54	29.2	1.7	4.20	35.6	7.52	9.06	35.7
CPN1	62	1.19		56.53	-0.226	0.30	17.5	8.8	3.19	39.6	3.1	5.03	34.1	14.33	17.53	69.0
CPN2	68	1.07		55.97	-0.274	0.41	13.5	8.1	2.74	37.3	2.7	5.04	34.4	12.63	15.37	60.5
NTW	92	1.41		60.87	-0.390	0.51	8.0	7.9	2.60	36.5	2.4	5.70	34.3	10.62	13.22	52.0
NTN	97	1.35		60.27	-0.240	0.20	17.3	8.3	2.87	38.0	2.9	4.58	34.4	14.01	16.88	66.5

FIELD #3, MONTCALM SL, 1989

	% RES	BD	TXTR	a	b	r^2	k	t_p (min)	D_{tp}	r_{tp}	t_1	f (min)	t_2	D_p (min)	D_{tot}	$\%D_a$
MBW	1	1.48	SL	36.7	-0.601	0.61	1.6	4.4	0.85	22.4	1.1	3.09	36.6	3.98	4.83	19.0
MBN	2	1.35	SL	44.2	-0.563	0.57	2.4	5.1	1.13	25.5	1.3	3.80	36.1	4.76	5.89	23.2
DPW	1	1.54	SL	41.8	-0.722	0.75	1.0	4.5	0.88	22.8	1.2	3.17	36.5	4.06	4.95	19.5
DPN	7	1.38	SL	33.2	-0.577	0.70	1.7	4.1	0.77	21.4	1.1	2.86	36.8	3.71	4.48	17.6

FIELD #4, MONTCALM LS, 1989

	% RES	BD	TXTR	a	b	r^2	k	t_p (min)	D_{tp}	r_{tp}	t_1	f (min)	t_2	D_p (min)	D_{tot}	$\%D_a$
NTW	78	1.42	LS-S	94.1	-0.249	0.13	25.8	15.2	8.30	54.2	6.0	9.00	30.6	17.10	25.40	100.0
NTN	74	1.44	LS	81.6	-0.420	0.48	9.2	9.3	3.51	41.1	2.9	6.99	33.4	12.06	15.56	61.3

FIELD #5, MONTCALM LS, 1989

	% RES	BD	TXTR	a	b	r^2	k	t_p (min)	D_{tp}	r_{tp}	t_1	f (min)	t_2	D_p (min)	D_{tot}	$\%D_a$
PMBW	8	1.55	LS-S	48.8	-0.561	0.74	2.7	5.4	1.29	27.1	1.5	3.87	35.9	6.28	7.57	29.8
PMBN	6	1.32	LS	46.4	-0.503	0.76	3.4	5.5	1.31	27.3	1.5	3.82	35.9	6.64	7.95	31.3
PPTW	10	1.59	LS-S	40.1	-0.543	0.69	2.4	4.8	1.02	24.4	1.3	3.26	36.4	5.50	6.52	25.7
PPTN	11	1.32	LS-S	46.1	-0.493	0.70	3.6	5.5	1.32	27.3	1.5	3.81	35.9	6.71	8.03	31.6

Table E-10. (H2) COLLECTIVE. Appl. depth = 12.7mm, WET data, high (57.4mm/h) maximum rate.

FIELD #1, KALAMAZOO SL, 1988

NO WET TESTS DONE

FIELD #2, OSHTEMO SL, 1988

	% RES	BD	TXTR	a	b	r^2	k	t_p (min)	D_{tp}	r_{tp}	t_1	f (min)	t_2	D_p (min)	D_{tot}	$\%D_a$
MBW	4	1.40		46.33	-0.520	0.70	3.1	3.5	1.04	33.2	1.0	3.87	17.4	4.02	5.07	39.9
MBN	6	1.23		47.74	-0.550	0.73	2.7	3.6	1.06	33.5	1.0	3.95	17.4	3.98	5.04	39.7
CPW1	65	1.15		81.84	-0.629	0.44	3.1	5.0	1.98	42.9	1.4	6.16	16.4	5.31	7.29	57.4
CPW2	60	1.22		50.14	-0.469	0.40	4.4	3.8	1.23	35.6	1.1	4.23	17.2	4.55	5.78	45.5
CPN1	62	1.19		56.53	-0.226	0.30	17.5	5.2	2.15	44.2	1.8	4.66	16.5	7.55	9.70	76.4
CPN2	68	1.07		55.97	-0.274	0.41	13.5	4.9	1.92	42.4	1.6	4.74	16.6	6.82	8.73	68.8
NTW	92	1.41		60.87	-0.390	0.51	8.0	4.8	1.82	41.6	1.5	5.22	16.6	5.90	7.72	60.8
NTN	97	1.35		60.27	-0.240	0.20	17.3	5.5	2.37	45.8	1.9	5.08	16.3	7.65	10.01	78.9

FIELD #3, MONTCALM SL, 1989

	% RES	BD	TXTR	a	b	r^2	k	t_p (min)	D_{tp}	r_{tp}	t_1	f (min)	t_2	D_p (min)	D_{tot}	$\%D_a$
MBW	1	1.48	SL	36.7	-0.601	0.61	1.6	2.9	0.72	28.3	0.8	3.05	17.8	3.09	3.81	30.0
MBN	2	1.35	SL	44.2	-0.563	0.57	2.4	3.3	0.94	31.8	0.9	3.64	17.5	3.69	4.63	36.4
DPW	1	1.54	SL	41.8	-0.722	0.75	1.0	3.0	0.79	29.5	0.8	3.32	17.7	3.11	3.90	30.7
DPN	7	1.38	SL	33.2	-0.577	0.70	1.7	2.7	0.64	26.8	0.7	2.78	17.9	2.91	3.54	27.9

FIELD #4, MONTCALM LS, 1989

	% RES	BD	TXTR	a	b	r^2	k	t_p (min)	D_{tp}	r_{tp}	t_1	f (min)	t_2	D_p (min)	D_{tot}	$\%D_a$
NTW	78	1.42	LS-S	94.1	-0.249	0.13	25.8	10.7	7.08	57.1	4.8	8.85	14.0	5.62	12.70	100.0
NTN	74	1.44	LS	81.6	-0.420	0.48	9.2	6.0	2.76	48.2	1.9	6.94	15.8	6.79	9.55	75.2

FIELD #5, MONTCALM LS, 1989

	% RES	BD	TXTR	a	b	r^2	k	t_p (min)	D_{tp}	r_{tp}	t_1	f (min)	t_2	D_p (min)	D_{tot}	$\%D_a$
PMBW	8	1.55	LS-S	48.8	-0.561	0.74	2.7	3.6	1.07	33.6	1.0	3.99	17.3	3.99	5.06	39.8
PMBN	6	1.32	LS	46.4	-0.503	0.76	3.4	3.5	1.05	33.4	1.0	3.86	17.4	4.09	5.14	40.5
PPTW	10	1.59	LS-S	40.1	-0.543	0.69	2.4	3.1	0.84	30.2	0.9	3.34	17.7	3.49	4.33	34.1
PPTN	11	1.32	LS-S	46.1	-0.493	0.70	3.6	3.5	1.05	33.4	1.0	3.85	17.4	4.12	5.17	40.7

Table E-11. (L1) COLLECTIVE. Appl. depth = 25.4mm, WET data, low (16 mm/h) maximum rate.

FIELD #1, KALAMAZOO SL, 1988

NO WET TESTS DONE

FIELD #2, OSHTEMO SL, 1988

	% RES	BD	TXTR	a	b	r^2	k	(min) t_p	D_{tp}	r_{tp}	t_1	(min) f	t_2	(min) D_p	D_{tot}	$\%D_a$
MBW	4	1.40		46.33	-0.520	0.70	3.1	30.5	2.98	10.7	9.7	3.07	122.0	12.12	15.09	59.4
MBN	6	1.23		47.74	-0.550	0.73	2.7	29.3	2.76	10.4	9.2	3.00	122.7	11.43	14.20	55.9
CPW1	65	1.15		81.84	-0.629	0.44	3.1	36.8	4.19	12.2	11.8	4.04	117.8	13.26	17.45	68.7
CPW2	60	1.22		50.14	-0.469	0.40	4.4	36.5	4.13	12.2	12.4	3.55	118.7	14.51	18.65	73.4
CPN1	62	1.19		56.53	-0.226	0.30	17.5	143.0	25.40						25.40	100.0
CPN2	68	1.07		55.97	-0.274	0.41	13.5	143.0	25.40						25.40	100.0
NTW	92	1.41		60.87	-0.390	0.51	8.0	56.6	8.79	15.3	23.4	4.54	109.6	16.61	25.40	100.0
NTN	97	1.35		60.27	-0.240	0.20	17.3	143.0	25.40						25.40	100.0

FIELD #3, MONTCALM SL, 1989

	% RES	BD	TXTR	a	b	r^2	k	(min) t_p	D_{tp}	r_{tp}	t_1	(min) f	t_2	(min) D_p	D_{tot}	$\%D_a$
MBW	1	1.48	SL	36.7	-0.601	0.61	1.6	22.1	1.64	8.4	6.5	2.22	127.2	8.27	9.90	39.0
MBN	2	1.35	SL	44.2	-0.563	0.57	2.4	27.0	2.37	9.8	8.3	2.76	124.1	10.47	12.84	50.5
DPW	1	1.54	SL	41.8	-0.722	0.75	1.0	19.9	1.34	7.7	5.6	2.04	128.5	6.74	8.08	31.8
DPN	7	1.38	SL	33.2	-0.577	0.70	1.7	21.5	1.55	8.2	6.3	2.11	127.7	8.15	9.70	38.2

FIELD #4, MONTCALM LS, 1989

	% RES	BD	TXTR	a	b	r^2	k	(min) t_p	D_{tp}	r_{tp}	t_1	(min) f	t_2	(min) D_p	D_{tot}	$\%D_a$
NTW	78	1.42	LS-S	94.1	-0.249	0.13	25.8	142.8	25.40						25.40	100.0
NTN	74	1.44	LS	81.6	-0.420	0.48	9.2	142.8	25.40						25.40	100.0

FIELD #5, MONTCALM LS, 1989

	% RES	BD	TXTR	a	b	r^2	k	(min) t_p	D_{tp}	r_{tp}	t_1	(min) f	t_2	(min) D_p	D_{tot}	$\%D_a$
PMBW	8	1.55	LS-S	48.8	-0.561	0.74	2.7	29.1	2.74	10.4	9.1	3.01	122.7	11.29	14.03	55.2
PMBN	6	1.32	LS	46.4	-0.503	0.76	3.4	31.7	3.19	11.0	10.3	3.16	121.4	12.68	15.88	62.5
PPTW	10	1.59	LS-S	40.1	-0.543	0.69	2.4	26.1	2.24	9.6	8.0	2.62	124.7	10.30	12.53	49.3
PPTN	11	1.32	LS-S	46.1	-0.493	0.70	3.6	32.2	3.29	11.2	10.5	3.19	121.1	12.96	16.25	64.0

Table E-12. (L2) COLLECTIVE. Appl. depth - 12.7mm, WET data, low (16mm/h) maximum rate.

FIELD #1, KALAMAZOO SL, 1988

NO WET TESTS DONE

FIELD #2, OSHTEMO SL, 1988

	% RES	BD	TXTR	a	b	r^2	k	(min) t_p	D_{tp}	r_{tp}	t_1	(min) f	t_2	(min) D_p	D_{tot}	$\%D_a$
MBW	4	1.40		46.33	-0.520	0.70	3.1	20.3	2.49	13.0	6.5	3.27	57.6	6.90	9.39	74.0
MBN	6	1.23		47.74	-0.550	0.73	2.7	19.6	2.34	12.7	6.2	3.21	58.0	6.62	8.97	70.6
CPW1	65	1.15		81.84	-0.629	0.44	3.1	25.7	3.75	14.7	8.5	4.38	54.2	7.41	11.16	87.9
CPW2	60	1.22		50.14	-0.469	0.40	4.4	24.4	3.43	14.4	8.4	3.76	55.4	7.84	11.27	88.7
CPN1	62	1.19		56.53	-0.226	0.30	17.5	71.4	12.69					0.00	12.69	100.0
CPN2	68	1.07		55.97	-0.274	0.41	13.5	71.4	12.69					0.00	12.69	100.0
NTW	92	1.41		60.87	-0.390	0.51	8.0	71.4	12.69					0.00	12.69	100.0
NTN	97	1.35		60.27	-0.240	0.20	17.3	71.4	12.69					0.00	12.69	100.0

FIELD #3, MONTCALM SL, 1989

	% RES	BD	TXTR	a	b	r^2	k	(min) t_p	D_{tp}	r_{tp}	t_1	(min) f	t_2	(min) D_p	D_{tot}	$\%D_a$
MBW	1	1.48	SL	36.7	-0.601	0.61	1.6	14.8	1.41	10.5	4.4	2.39	61.0	5.07	6.47	51.0
MBN	2	1.35	SL	44.2	-0.563	0.57	2.4	18.0	2.02	12.1	5.6	2.95	58.9	6.17	8.19	64.5
DPW	1	1.54	SL	41.8	-0.722	0.75	1.0	13.6	1.21	9.9	3.9	2.26	61.6	4.38	5.60	44.1
DPN	7	1.38	SL	33.2	-0.577	0.70	1.7	14.3	1.32	10.2	4.2	2.27	61.3	4.97	6.28	49.5

FIELD #4, MONTCALM LS, 1989

	% RES	BD	TXTR	a	b	r^2	k	(min) t_p	D_{tp}	r_{tp}	t_1	(min) f	t_2	(min) D_p	D_{tot}	$\%D_a$
NTW	78	1.42	LS-S	94.1	-0.249	0.13	25.8	72.0	12.70						12.70	100.0
NTN	74	1.44	LS	81.6	-0.420	0.48	9.2	72.0	12.70						12.70	100.0

FIELD #5, MONTCALM LS, 1989

	% RES	BD	TXTR	a	b	r^2	k	(min) t_p	D_{tp}	r_{tp}	t_1	(min) f	t_2	(min) D_p	D_{tot}	$\%D_a$
PMBW	8	1.55	LS-S	48.8	-0.561	0.74	2.7	19.6	2.33	12.7	6.1	3.22	58.0	6.57	8.90	70.1
PMBN	6	1.32	LS	46.4	-0.503	0.76	3.4	21.1	2.66	13.3	6.9	3.35	57.2	7.14	9.80	77.2
PPTW	10	1.59	LS-S	40.1	-0.543	0.69	2.4	17.3	1.88	11.8	5.3	2.79	59.4	6.05	7.93	62.4
PPTN	11	1.32	LS-S	46.1	-0.493	0.70	3.6	21.4	2.73	13.4	7.0	3.38	57.1	7.25	9.98	78.6

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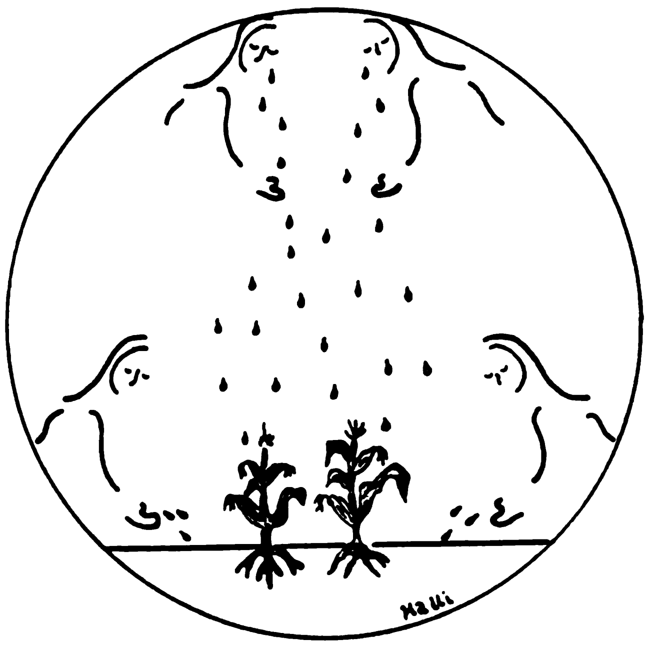
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