INFILTRATION AND EVAPORATION FROM A POINT SOURCE WATER APPLICATION

by

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ABSTRACT

Two separate field studies were conducted at the University of Arizona Campus Agricultural center in Tucson in the summer of 1985. The purpose of the first study was to use Infrared Theomometry, Micro Lysimeter, and Neutron Surface Meter Methods to estimate bare-soil water evaporation surrounding a point source emitter. The purpose of the second study was to estimate soil water infiltration from a point source using a theoretical model. In the model it is assumed that the water content ahead the front after infiltration commences is the same as the antecedent moisture content, and the moisture content behind the front is given by a quasi-linear solution that assumes an exponential relationship between the unsaturated hydraulic conductivity and the pressure head. The results from the first study showed good agreement among methods as indicated by high correlations. Also the results for the second experiment indicated that the model can be used to estimate infiltration from a point source, but special attention should be given to emitter flow rate.

CHPATER 1

INTRODUCTION

Bare-soil water evaporation and infiltration from point source water applications are two important components of the water cycle in a field under drip irrigation. Studies on soil water evaporation either on cropped or uncropped fields use methods that are traditional to estimate evaporation over large areas. Such methods include meteorological methods (Gay and Hartman, 1981), remote sensing, water balance methods, and lysimeters that range in size from 0.5 to 2.0 meter deep and areal extent on the order of 0.1 to $10m^2$.

None of the above methods are appropriate to use in estimating soil water evaporation from the wetted area that results from using drip emitters. Mass transfer theory can be used to estimate soil evaporation (Brutsaert, 1982) but this method assumes saturation over the entire wet soil surface. This requirement is certainly not met in the case of transient drying soil.

Models to estimate soil infiltration from a point source have been described quite extensively in the literature. However, these model are usually unrealistic when applied to field conditions. They assume soil uniformity most of the time.

The objectives of this study are two fold. Firstly, a comparative study is done among three different methods for estimating bare-soil water evaporation. The first method is the Infrared Thermometry method (Ben-Asher, Matthias and Warrick, 1983). This method is fairly simple to apply. Average daily wind speed and mid-day surface temperature are the only parameters needed to calculate cumulative evaporation flux density $(12h)^{-1}$. The second method is the new Micro-lysimeter method (Boast and Robertson, 1982). This method estimates evaporation by consecutive weight difference of micro-lysimeter. The third method applies a surface neutron scattering to measure temporal changes in soil water content.

The second objective is to use a simple model (Warrick and Lomen, 1986) to estimate infiltration from point source. The model is based on reasonable physical assumptions. The water content ahead of the front is the antecedent moisture content and the one behind the front is that of large time solution given by a quasi-linear solution.

CHAPTER 2

LITERATURE REVIEW

2.1. Soil Water Evaporation

The process of soil water evaporation has been studied quite thoroughly, and the general agreement is that evaporation of soil water into the atmosphere, under constant evaporative conditions, can be divided into three distinct stages.

The first stage or constant-rate stage is controlled by the available energy, which determines the rate of water loss from the surface soil. Soil surface conditions including reflectivity, can also influence evaporation rate insofar as these can modify the effect of meteorological conditions on the surface. The duration of this stage depends on the prevailing evaporative demand

The second stage or falling rate stage is the profile controlled stage. The evaporation rate falls considerably below the potential rate. The evaporation rate depends on the rate at which the profile can transport moisture to the evaporating layer. At this stage the moisture gradient toward the surface decreases gradually as does the ability of the soil profile to conduct moisture upward. Consequently, the soil hydraulic properties and available moisture dictate the evaporation rate. Philip (1957) reached a similar conclusion when he suggested that evaporation rate at stage 2 is independent of the evaporative demand. However, Cove and Bloodworth (1966) reported that evaporation rate depends on the evaporative demand. Hillel (1971), on the other hand, reported that the evaporation rate in the falling rate stage will depend either on the atmospheric evaporativity or on the soil's ability to transport water upward, whichever is the limiting factor.

Black, Gardner and Thurtell (1969) concluded by the solution of the flow equation, that the cumulative evaporation from the falling rate stage is a sole function of the hydraulic properties. Gardner and Hillel (1962) also concluded the first and second stage can be described by the solution of the isothermal flow equation. They reported good agreement between calculated and measured cumulative evaporation.

The third stage is the residual slow-rate stage. There is no distinct separation between stage 2 and stage 3, but according to Hillel (1982) the transition occurs when the surface soil is so dry that liquid water ceases to flow through it. At this point there is only vapor flow, and soil diffusivity and adsorption forces are the controlling forces.

Hide (1954) studied the factors that control evaporation in the boundary layer between the evaporating surface and the atmosphere. He pointed out two important factors affecting evaporation in the boundary layer: the vapor pressure difference and resistance to vapor flow. For a moist soil, he suggested, the resistance to vapor transport depends on the thickness of the laminar layer adjacent to the soil surface. He also pointed out that as the soil dries further at the surface, the resistance exceeds that due to the laminar layer at the soil surface.

2.1.1. Combination Approach to Measurements of Evaporation

Combination formulas, developed to estimate soil water evaporation, take advantages of relating temperature, net radiation, wind speed, etc. into a unique expression. These formulas should give good results, but it happens that assumptions have to be made in order for the formulas to have physical meaning. Fuchs and Tanner (1967) analyzed a combination formula against a detailed energy balance and Bowen ratio method for soil water evaporation measurements. The model used measured surface temperature. The assumptions are that water vapor, heat and momentum transfer coefficients in the atmospheric boundary layer are similar, and that the coefficients can be found from measurements of wind speed at a given height.

Van Bavel (1966) recognized that, with some modifications, potential evaporation could be calculated using a combination formula developed by Penman (1948). The modification consisted in replacing the empirical wind function proposed by Penman with a wind function based upon the standard wind profile theory for adiabatic conditions.

2.1.2 Application of Remote Sensing Surface Temperature in Evaporation Measurements

Remotely sensed thermal infrared data are becoming increasingly more feasible for use in determining soil water evaporation over large areas (Reginato et al. 1976).

Price (1980) presented analytical expressions that related mean bare-soil water evaporation rate to thermal parameters measured by remote sensing techniques. He was able to solve for average daily evaporation rate using flux expressions from Sellers (1965) to calculate absorbed solar and emitted long wave, and from Brunt (1932) to calculate absorbed long wave radiation. He concluded that surface soil temperature depends primarily on surface evaporation rate and albedo, provided the other factors such as wind speed, solar radiation, air temperature, etc., remain the same.

Idso et al. (1975) recognized the negative effect of data scattering in the thermal inertia approach to remote sensing of soil moisture measurement. To overcome this problem they suggested a normalization procedure that relates the difference between maximum and minimum temperatures to a standard surface heat flux. They pointed out that the surface heat flux is not known in most cases. As a result, they decided to use air temperature instead, because surface heat flux fluctuation is in phase with air temperature change.

A model described by Ben-Asher et al. (1983) calculates bare-soil water evaporation rate using average daily wind speed, and mid-day soil temperature difference between a steady-state dry soil, and a transient-state drying soil. The temperature measurement can be made by a hand-held infrared thermometer or remote sensing techniques.

The final mathematical expression for this model was reached by assuming after Fox (1968), that the sum of the integrated short wave radiation and soil heat flux of dry(o) and drying(d) surfaces is much smaller than the latent heat flux density. As a result of this assumption, soil water evaporation can be described based only on differences in radiation temperature through long-wave radiation(L), and sensible heat flux density. These two differences are given by the following expressions

$$Ho - Hd = \rho cp(To - Td)r^{-1} \tag{1}$$

$$Lo - Ld = 4\ \varepsilon\ \sigma\bar{T}^{3}(To - Td) \tag{2}$$

where To and Td are radiation temperatures of the dry and drying soil respectively; ρ is air density $(1.21\ kg\ m^{-3})$; cp is specific heat of air at constant pressure $(1000\ JKg^{-1}K^{-1})$; r is the aerodynamic resistance to heat transport (Sm^{-1}); σ is the Stefan-Boltzman constant $(5.67 \cdot 10^{-8} Wm^{-2}K^{-4})$; ε is the emissivity (.95) and $\bar{T}$ is the instantaneous average of To and Td measured at mid-day.

The integration of the sum of these two expressions between times t1 and t2 is equal to the total latent heat flux density (total evaporation Kg m^{-2}) during that time interval. The mathematical expression is written by,

$$\int_{t_1}^{t_2} \lambda E dt = \int_{t_1}^{t_2} (c p \rho r^{-1} + 4\ \varepsilon\ \sigma \bar{T}^3)(To - Td) dt \qquad (3)$$

where, λ is the latent heat of evaporization $(2.4 \cdot 10^6 JKg^{-1})$; E is the instantaneous mass flux of evaporation $(Kg\ S^{-1})$; and t1 and t2 are the beginning and ending times of evaporation, respectively. If the temperature difference (To - Td) is expressed in terms of an assumed sinusoidal daily cycle, the result of the integration of the above equation is

$$\int_{t_1}^{t_2} \lambda E dt = [6(\rho c_p r^{-1} + 4\ \varepsilon\ \sigma \bar{T}^3)(1 + \sqrt{2/\pi})](\Delta T) \qquad (4)$$

If the aerodynamic resistance to heat transport is calculated using the empirical equation, r = 0.035U (r has units of hr m-1 and U has units of m/s) equation (4) may be written as:

$$\int_{t_1}^{t_2} \lambda E dt = S \Delta T \qquad (5)$$

$$S = 8.7(\rho c_p r^{-1} + 4\ \varepsilon\ \sigma \bar{T}^3). \qquad (6)$$

2.1.3. Microlysimeter Approach to Measure Soil Water Evaporation

Small lysimeters have been used extensively in the lab and in the field to study the water evaporation phenomenon.

Abramova and Dokuchayev (1967) studied solid bottom evaporators versus screen bottom ones. They concluded that screen bottom evaporators should be used if one is interested in the amount of water lost to the atmosphere. On the other hand, solid bottom evaporators are more feasible to use if the interest is in the change of water in the profile. They also concluded that the length of microlysimeters (evaporators) should be chosen according to the depth of the 'true' evaporating layer.

Shawcroft and Gardner (1983) concluded that a relationship between microlysimeter evaporation and soil water content should be established before microlysimeter evaporation is used as a definite measure of the amount of water lost. The surface water content is then used in the relationship to infer microlysimeter evaporation.

Walker (1983) observed that microlysimeters made of plastic material are better to use in evaporation studies than metal ones, because of the highly conductive nature of the latter.

Boast (1986) listed several factors that might influence the behavior of the microlysimeter in relation to the surrounding soil:

(1) imposition of a plane of zero flow or water table at the bottom of the lysimeter;

(2) disturbance of soil inside the microlysimeter during installation and

(3) conduction of heat by the lateral walls.

Boast and Robertson (1983) analysed the question of how long a microlysimeter of a given length should be used before it no longer represents soil water evaporation of the surrounding soil. To carry out the analysis, they assumed that microlysimeters of any length evaporates for a given time as the surrounding soil. Thereafter, they compared shorter microlysimeter evaporation to longer ones until there was a deviation. The deviation indicated that the shorter microlysimeter no longer represented the evaporation rate taking place in the surrounding soil.

2.1.4. Neutron Scattering Technique to Estimate Water Evaporation

A detailed study was done by McGowan and Williams (1980) to analyse the errors associated with neutron probe measurement of water content and soil water evaporation. They listed two types of errors: systematic and random errors. The systematic errors that were identified include calibration, soil damage to access tube installation, and damage of surface soil and vegetation. The random errors most important are random count error, relocation, and soil variability. They recognized the need for the replication of measurements to overcome, to a certain extent, the soil variability and the resolution problem. They also concluded that random and relocation errors can be used to estimate the minimum interval between measurements.

Another neutron meter commercially available is the Troxler Surface Moisture-Density Gauges (Model 3411B). This neutron meter was developed to measure density and moisture content of soil solid surfaces, although it can be used on other materials. This instrument contains a microprocessor which contains all calibration information and algorithm to compute and display all end results, thus eliminating one source of operator error. There is also the option of reading in SI or British units.

The practical application of this instrument depends very much on the surface from which measurements are to be taken. Consequently, site preparation is required, even though we might be introducing some sort of error by disturbing the surface. The method of site preparation depends on the surface and type of test.

Rosenthal, Arkin and Shouse (1985) used this instrument (Troxler, 3411B) to measure transpiration of sorghum plant. The plant was in a rectangle steel lysimeter. The lysimeter had one of the faces made of glass, however. The soil surface was covered to eliminate soil water evaporation. The transpiration was estimated by summing volumetric water content changes, measured with the neutron, in every 25cm interval along the glass face. Transpiration rate measured by a load cell was compared with the one measured by the neutron, and a good agreement was reported by Rosenthal et al. (1985).

2.2. Soil Water Infiltration

In trickle irrigation water is applied either to buried point sources or to surface point sources. This method of water application has some advantages. It wets only a small fraction of the soil volume, it reduces bare-soil water evaporation, and it increases yield (French, et al. 1985). However, according to Hillel (1985) there are some remaining problems that need further research. Among others, he pointed out the following areas:

(1) spatial and temporal variation of soil moisture under trickle irrigation;

(2) interrelations among different plants and the optimal soil volume needed for them to grow in;

(3) trickle discharge rate and soil infiltrability;

(4) water distribution in the soil profile following water application with trickle system.

In the past, several researchers have tried to model transient water infiltration from a trickle source by solving Richards' equation for infiltration. A first attempt to model infiltration from a point source was by Brandt et al. (1971). In their analysis, they assumed stable, homogeneous, and isotropic soil conditions. To solve the differential equation that governs the flow of water in soil, they made use of the diffusion-type water flow equation. A field test of the theory carried out by Bresler et al. (1971) showed good agreement between calculated and experimental results. But they pointed out some discrepancies in the theory at large and small trickle discharge rate. In particular, at large discharge rates the water moved more in the horizontal direction than expected.

Ben-Asher, Lomen and Warrick (1978) reported a comparative study between numerical and analytical solutions for water flow from a point source. The numerical solution was done in large scale computers, and for the analytical solution they used a matric flux potential (Gardner, 1958) to linearize the differential equation that describes the movement of water in soils. They pointed out that the numerical solution has an advantage over the analytical solution, because the numerical procedure can use any reasonable function that describes the hydraulic properties of the soil. On the other hand, the linearized form permits only unsaturated conductivity which is exponentially related with pressure head. An additional condition is that $dK/d\theta$ be a constant. But in terms of computational time the linearized form is in the order of 1/20 to 1/200 of that necessary for the solution of the numerical solution.

It has been observed that shortly after water application from a trickle source starts, the soil infiltrability is reached and a small circular water pond forms at the soil surface. Usually the shape of the pond results in a wetted hemispherical volume. Mathematical models that describe constant-flux infiltration from this hemispherical cavity have been presented by Raats (1971), Parlange (1973), and Warrick (1974). Clothier and Scotter (1982) reviewed these models and observed considerable difference between Warrick's model and experimental results from a three dimensional infiltration experiment. They cited the constant diffusivity (D) assumed in Warrick's model as the main reason for the discrepancy. But they observed acceptable agreement between Raats' theory and experimental results.

Soil moisture distribution under trickle irrigation is very important from the point of view of irrigation scheduling. As Hillel (1985) pointed out more studies need to be done to come up with "realistic models for predicting spatial and temporal variation of soil moisture under trickle irrigation for different crops, weather, and soil conditions". Fletcher, Armstrong and Wilson (1983) used a computer simulation model to simulate irrigation in stratified soils, and to predict soil moisture distribution under a trickle source. They reported good agreement with experimental results. They also reported that both experimental and the computer model suggested that the shape and size of the wetted zone depends more on the volume of water applied than on the rate of water application. A similar conclusion was by Roth (1983).

The models mentioned above require mathematical skills and large scale computers to get the desired solution. These two factors may inhibit the application of these models to field conditions. Lately, however, there has been an effort in simplifying these procedures even though accuracy and generality are not ignored. Ghanim, Himah and Kamand (1985) proposed a very simple procedure relating emitter spacing to the soil wetted radius using basic soil data. They compared their result with more "sophisticated" approaches, and in general there was no major differences. They based their analysis on soil intake families as classified by USDA. The model may not give realistic results under stratified soils, because they assumed a homogeneous soil in their derivation.

In another study Shani et al. (1986) presented a very simple and straightforward procedure (the dripper method) to estimate infiltration from a point source. They started their analysis by assuming that after the radius of a hemispherical cavity at the soil surface reaches a constant value "steady state can be assumed and steady-state solution of the two dimensional equation can be applied to solve for the flux from the ponded zone. They used the assumed hydraulic conductivity (K)-pressure head (h) relationship of Wooding (1968), and hydraulic conductivity (K)-pressure head (h) and pressure head (h)-water content (θ) relationships of Brooks and Corey (1964). It was shown that the radius of the hemispherical cavity depends on the "dripper" discharge rate and on the time interval. A further evidence of the practicality of this method is the fact that saturated hydraulic and matric flux potential can be estimated from measurements of ponded radius and water flux for several fluxes.

CHAPTER 3

MATERIALS AND METHODS

3.1. Soil Water Evaporation

3.1.1. Site Description and Procedure

A field study to estimate bare-soil water evaporation from a point source water application was carried out during July 1985 on bare-soil at the University of Arizona Campus Agricultural Center in Tucson. The soil in this area is a Gila sandy loam, and is classified as a "coarse-loamy, mixed, calcareous, thermic, typic Torrifluvent" in the upper 60 cm (Hassan, Warrick and Amoozegar-Fard 1983). Deeper layers are sandy and very coarse.

The weather conditions during the experiment were very good with clear skies, high temperature, low wind speed, and no rainfall (see Table 1). The experiment lasted five days, from June 29, to July 4, 1985.

The area of the experimental site was 36 square meters. This 6 by 6 m plot was divided into 3 blocks. Each block was subdivided into 3 equal areas of 2 by 2 meters. This gave rise to a randomly complete block design experiment. An analysis of variance was carried out to determine if soil variability had any influence in the results.

Tatle 1. Environmental conditions during the period of the experiment. Data are from 0540 till 1940 hour of the day at mid-day.

Date	Solar Radiation ($MJm^{-2}d^{-1}$)	Air Temperature (°C)		Wind Speed (m/s)		Pan Evaporation ($mm\ d^{-1}$)
		Max.	Min.	Max.	Min.	
7/30/85	16.5	42.5	20.1	3.2	.76	11.1
8/1/85	16.6	43.5	21.7	3.5	.56	13.1
8/2/85	16.8	44.3	20.4	3.3	.61	15.6
8/3/85	16.9	45.2	20.1	2.7	.45	14.3
8/4/85	16.8	44.9	28.3	3.5	.58	14.4

Three methods of soil water evaporation measurement (Infrared Thermometry-IRT(A), Microlysimeter-LYS(B), and Neutron Surface Meter-NS(C)) were randomly assigned to the 9 experimental sites (see Figure 1).

The experimental area was smoothed out using hand rake, and the 9 experimental units were irrigated by a drip/trickle system. The water was applied using 5 gallon buckets. Plastic tubings of 1 cm diameter were attached on the side of the buckets approximately 1 cm from the bottom. The flow rate from the buckets was regulated by screw clamps attached to the plastic tubings, which conveyed the water to the point source. The flow rate was regulated in such a way that it was not larger than the soil infiltrability. As a result, the final wetted areas surface were nearly circular. A total of about 22 liters of water was applied to each site. The water application lasted 22 hours.

Twelve microlysimeters (internal diameter 8 cm, length 30 cm) were put into 3 of the wetted areas after the soil was allowed to drain from 1400 to 700 h the next day. Two other microlysimeters of identical dimensions were installed outside the wetted areas to estimate cumulative soil water evaporation from the dry soil. The microlysimeters were manually pushed into the soil with the help of a metal extension cylinder constructed by Steve Evett so it would fit the outside diameter of the microlysimeters.

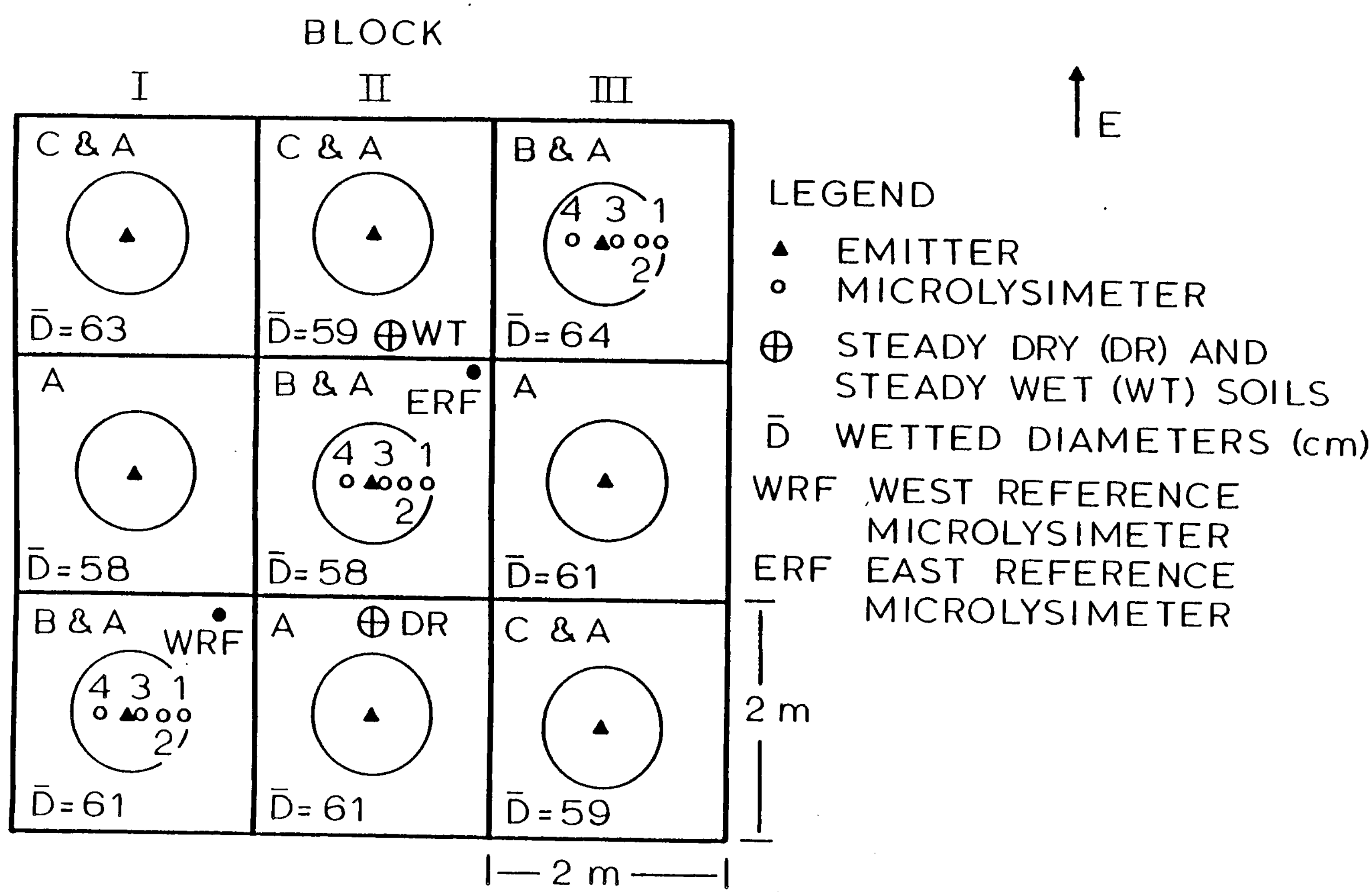

Figure 1. Experimental site and design showing the methods (A,B,C) and wetted surface diameters $\bar{D}$.

The soil filled microlysimeters were then removed from the soil, cleaned and sealed at the bottom using tape and plastic caps. These hydrologically isolated soil columns were weighed and put back into the preformed hole. The surface of each microlysimeter was maintained flush with the soil surface. The difference between two consecutive weighing divided by the cross-sectional area of the microlysimeter is the cumulative evaporation flux density during the time period (24 hours). A 1 gram change corresponded to approximately 0.20 mm of water evaporated.

The Infrared Thermometry Method (Ben-Asher et al. 1983) was used to estimate evaporation for the 12 daylight hours of every day during the study. Mid-day soil surface temperature was taken using an infrared thermometer (Everest Interscience, Model 110, 3° field of view). The thermometer was pointed to the target at an approximate 45 degree angle. The surface temperature readings of all the microlysimeters, the 6 undisturbed wet areas, and areas around the microlysimeters were automatically recorded by a CSI 21X Micrologger. Readings on each site were taken every second for about 12 seconds. The data reduction and statistical analysis was done with a DEC Rainbow microcomputer using the MSU Statistics Package.

The Neutron Surface Method was used to measure the change in soil water content. Measurements were taken on 3 experimental sites (NS) every day at the same time surface soil temperatures were taken. The neutron meter (Troxler, Model 3411-B) was calibrated for soil type (Gila soil) by developing a relationship between gravimetric soil moisture content and corresponding moisture count from the neutron meter. The use of the neutron meter required that special attention be given to site preparation at which measurements are to be taken. The site was leveled, smoothed, and packed slightly. The result of site preparation was the elimination of cavities at the surface. This preparation decreased the chance of scattered neutrons escaping from the detector. The neutron meter can measure volumetric and gravimetric moisture content, and density simultaneously.

3.1.2. Instrumentation

The surface temperature of all the nine experimental sites, the 14 microlysimeters, and the steady wet and steady dry soils were taken with a portable Everest Interscience Infrared Thermometer (Model 110, 3-degree field of view, and ± 0.5 °C accuracy). Two 3-gallon buckets were filled with soil and used as the steady-state dry and steady-state wet soils. These two buckets were maintained flush with the soil surface. Temperature readings were automatically recorded by a CSI 21X Micrologger. A weather station was mounted with a Licor Model LI 200S silicon pyranometer to measure incoming solar radiation, an anemometer positioned about 2 meters height to measure the wind speed, and thermocouples to measure air temperature. The output from these sensors were recorded by a second 21X micrologger every 10 seconds and averaged over 30 minute intervals.

The changes in masses in the microlysimeters were measured with an Ohaus balance (Central Scientific Co., 1 gram resolution).

3.2. Soil Water Infiltration

3.2.1. Theory

A model that simulates infiltration from a point source water application is described (Warrick and Lomen, 1986). We consider that infiltration into a uniform soil is described by Richards' equation (Philip, 1969) :

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (D \nabla \theta) - \frac{dK}{d\theta} \cdot \frac{\partial \theta}{\partial Z} \qquad (7)$$

where θ is the volumetric water content, t is time (units T), D is soil water diffusivity (units L^2/T), K is the hydraulic conductivity (units L/T), and Z is depth below the soil surface.

Equation (7) is a non-linear differential equation, whose solution can be generally given only by numerical methods. However, the steady-state form of equation (7) can be linearized into a simple linear equation by a matric flux potential after Gardner (1958)

$$\phi = \int_{h_0}^{h} K(h)dh \tag{8}$$

where h_0 is the lowest value of pressure head considered for a particular problem. In addition it is assumed that the conductivity is of the form

$$K = K_0 \exp(\alpha h) \tag{9}$$

where α and K_0 are empirical fitting constants.

In the model (Warrick and Lomen, 1986) it is further assumed that if infiltration at a point at the soil surface begins at time zero, then at any later time the water content in the front is given by

$$\begin{aligned} \theta &= \theta_i \qquad \text{(ahead of front)} \\ \theta &= \theta(\Phi) \qquad \text{(behind the front).} \end{aligned} \tag{10}$$

The water content behind the front is a function of the dimensionless, steady-state matric flux potential for infiltration from a point source presented by Raats (1971) as

$$\Phi = \frac{2}{\rho}\exp(Z - \rho) - 2\exp(2Z)E_1(Z + \rho) \tag{11}$$

where R is the nondimensional radial distance $(\alpha r/2)$, Z is the nondimensional depth $(\alpha z/2)$, $\rho^2 = R^2 + Z^2$, and E_1 is the exponential integral defined by Abramowitz and Stegun (1964, especially equation (5.5.1)).

Another condition in the model is that, if initially the soil moisture is very low then a relationship between Φ and h can be defined as

$$\Phi = (8\pi K_0/\alpha^2 q)\exp(\alpha h). \tag{12}$$

There is a common factor between equation (10) and equation (12). For a given Φ, h is calculated and then θ in equation (10) is estimated from

$$\theta = \theta(h) \tag{13}$$

for any specified water content pressure head relationship.

The final theoretical derivation in the model includes the assumption that if $v(t)$ is the wetted volume at time t, then continuity gives

$$qt = \int_{v(t)} (\theta - \theta_i)d\theta \tag{14}$$

where q is the water application rate (units L/t). This can also be written in a dimensionless form

$$(\alpha^3/8)(qt + \theta_i V) = \int_{V^*(t)} \theta dV^* \tag{15}$$

where V^* is the dimentionless volume given by

$$V^* = (8/\alpha^3). \tag{16}$$

The goal in this model is to estimate the optimal K_0 and α to calculate theoretical wetting fronts.

3.2.2. Procedure

Field data gathering was done in two occasions in the same location. The first data gathering was on July 13, 1985, and the second on January 26, 1986. This study was carried out at the University of Arizona Campus Agricultural Center in Tucson.

The procedure was the same and is quite simple. In this case all we needed were four 5-gallon-buckets with plastic tubings attached at approximately 1 cm from the bottom, a ruler, and core soil sampler. The soil in the area is a Gila loam and is classified as "coarse-loamy, mixed, calcareous, thermic, typic Torrifluvent" in the upper 60 cm (Hassan et al. 1983). Deeper layers are sandy and very coarse. We began by first smoothing out 4 spots. Then 4 buckets were filled with known volumes of water. The water was conveyed to the center of the spots through the plastic tubings, which had screw clamps to regulate the flow rate. In the first study the water application on all four spots was started at the same time, and after 4, 8, 12, and 16 liters of water were applied to the respective spots the water was stopped. In the second study the water application in the first spot was stopped after 3 hours, in the second spot after 5 hours, in the third spot after 9 hours, and the fourth spot after 24 hours. The rate of water application in the second study was considerably lower than the rate in the first study. About half an hour after each water application the surface diameters of the wetted areas were measured, and half of the wetted soil was removed and the maximum wetted depth and maximum wetted radius were measured. Also undisturbed soil samples from the wetted zones, taken at different depths, were brought to the laboratory, and moisture release curves determined using the pressure plate apparatus. The initial moisture content was also determined.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Soil Water Evaporation

The daily evaporation amounts as estimated by Microlysimeter (LYS) method, and the Infrared Thermometry (IRT) method and the daily change in the soil water content as estimated by the neutron surface (NS) meter (Model 3411-B) are presented in Table 2. The results show that during the experiment the daily average evaporation depend very much on the method used, and on the site characteristics. Within the wetted areas, for example Block I for the first day of the experiment, the daily average evaporation was higher for the Microlysimeter 3, located at the center of the wetted area, as estimated by the IRT method and the LYS method. The Microlysimeter method overestimated the evaporation, for the first day, over the IRT method by as much as 114% from Microlysimeter 3. The other Microlysimeters within the same area (IB) showed considerable approximation between the two methods. The reason for the discrepancy in the evaporation rates from Microlysimeter 3, as estimated by the two methods, is not known. This particular discrepancy will be attributed to random errors and not to method differences.

The daily evaporation rate from the IC and IA sites as estimated by the IRT method are very close to each other. The same

Table 2. Daily evaporation rate as determined by IRT method and LYS method, and daily change in soil water content estimated by Neutron surface meter (NS).

		mm/day											
		C	A	B									C
				LYS1		LYS2		LYS3		LYS4		ARLYS	
Julian Day	Block	IRT	IRT	IRT	LYS	IRT	LYS	IRT	LYS	IRT	LYS	IRT	NS
180	I	5.6	4.8	5.8	5.5	8.5	6.7	11	23.5	7.4	9.2	4.1	.305
	II	7.0	7.9	6.9	5.2	10.5	7.2	10.8	16.9	7.8	12.9	6.5	.271
	III	6.6	7.8	6.3	6.2	7.6	7.8	11.1	16.1	9.3	10.9	6.1	.270
181	I	3.2	3.7	3.4	5.3	4.4	3.7	7.2	7.8	4.4	4.7	1.4	.233
	II	3.4	3.7	4.0	3.8	7.3	3.2	8.8	9.2	5.0	5.8	3.2	.211
	III	3.6	3.7	3.2	1.8	5.0	5.6	6.3	5.8	5.5	6.7	2.7	.220
182	I	1.8	1.4	3.4	1.4	3.7	4.4	5.2	12.1	3.6	4.0	1.7	.204
	II	1.8	3.4	2.7	1.1	4.5	4.8	5.2	5.6	3.6	4.3	2.2	.177
	III	2.5	2.8	3.1	2.9	3.8	4.0	4.0	2.6	3.7	4.3	1.8	.191
183	I	1.3	0.5	2.8	1.2	3.1	4.0	5.0	4.0	3.2	1.3	1.8	.184
	II	2.0	0.7	3.0	2.4	4.3	4.0	4.8	3.6	3.1	4.0	2.1	.172
	III	2.1	2.2	3.7	4.3	4.0	4.1	4.6	3.3	4.0	5.8	2.1	.171

Table 2--Continued

		mm/day											
		C	A	B									C
Julian				LYS1		LYS2		LYS3		LYS4		ARLYS	
Day	Block	IRT	IRT	IRT	LYS	IRT	LYS	IRT	LYS	IRT	LYS	IRT	NS
184	I	1.8	1.3	3.0	1.3	3.8	4.4	5.2	4.4	4.0	2.8	1.6	.167
	II	2.3	2.3	3.2	2.7	4.3	4.4	5.5	2.2	4.1	4.6	3.1	.138
	III	2.1	2.0	2.9	2.2	3.8	2.5	4.9	2.0	4.0	1.7	1.5	.146

Note: A, B, and C represent the experimental sites in Figure 1. ARLYS means around microlysimeters.

can be said about IIC, IIA, IIIC, or IIIA. The little variation observed can be attributed to spatial variability of soil physical properties or to the positioning of the infrared thermometer during surface temperature readings. The evaporation rate around the Microlysimeters also indicated that there is considerable difference between evaporation rate estimated by the infrared thermometer on a disturbed surface (Microlysimeters) and on an undisturbed surface (site IB-ARLYS). An ANOVA indicated that the soil within the experimental area is homogeneous. Then it is logical to infer that the difference between these results are attributed to the fact that the Microlysimeters represent an isolated hydrological soil identity losing water only from the surface. Water movement from the surrounding soil into the Microlysimeter or vice versa is nonexistent and, there is a water reservoir in these Microlysimeters that will cause the evaporation rate from these surfaces to continue at a maximum rate longer than undisturbed soils. Gardner, Hillel and Benyamini (1970) , in their distribution analysis of post-irrigation of soil water, concluded that the ratio of the cumulative evaporation, without distribution, to cumulative evaporation with distribution is approximately 2.6. One way to check if our data is in accordance with Gardner's model is to divide the mean cumulative evaporation from the 4 Microlysimeters in site IB, as estimated by the Infrared Thermometry Method, to the cumulative evaporation from site IA, as estimated by the IRT method. Table 3 shows the cumulative evaporation amounts. The ratios in this particular case are approximately 2. Considering that there are uncertainties to our measurement techniques, it is not unreasonable to conclude that Gardner's model describes very well the evaporation phenomenon between these two evaporation sites.

The spatial and temporal variations of average daily evaporation as estimated by the Infrared Thermometry method, and the microlysimeter method from Site IIIB for the 4 Microlysimeters within the wetted area are presented in Figures 2 and 3 respectively. The results show conclusively that the Microlysimeter method overestimates bare-soil water evaporation over the infrared thermometry method during the energy limiting stage. The data also shows that during the second stage of drying the IRT method overestimates the evaporation rate over the LYS method. The reference Microlysimeters (Table 4) also indicate that in the dry soil the IRT method overestimated evaporation over the LYS method by as much as 152%. The explanation for this 152% difference might be found on the derivation of equation (3). Matthias et al. (1986) concluded that Ben-Asher's et al. (1983) assumption is correct, as far as the integral sum of the short wave solar radiation difference between a dry and a wet soil surface, plus the soil heat flux

Table 3. Cumulative evaporation (mm) from each microlysimeter estimated by IRT and LYS methods, and from undisturbed surfaces using IRT and NS methods.

	C	A	B												C
				LYS1		LYS2		LYS3		LYS4		AVER.		ARLYS	
Block	IRT	IRT	IRT	LYS	IRT	LYS	IRT	LYS	IRT	LYS	IRT	LYS	IRT	IRT	NS
I	13.7	11.7	15.0	14.7	19.1	23.2	33.6	51.8	22.6	22.2	25.2	27.9	10.7	11	70.1
II	16.5	17.0	19.8	15.2	30.9	23.6	35.1	37.5	23.6	31.6	31.6	26.9	17.1	17	78.9
III	16.9	18.5	19.2	17.4	24.2	24.0	30.9	29.8	26.5	29.6	28.8	25.2	14.2	14	71.8

Note: A, B, and C are the experimental sites.

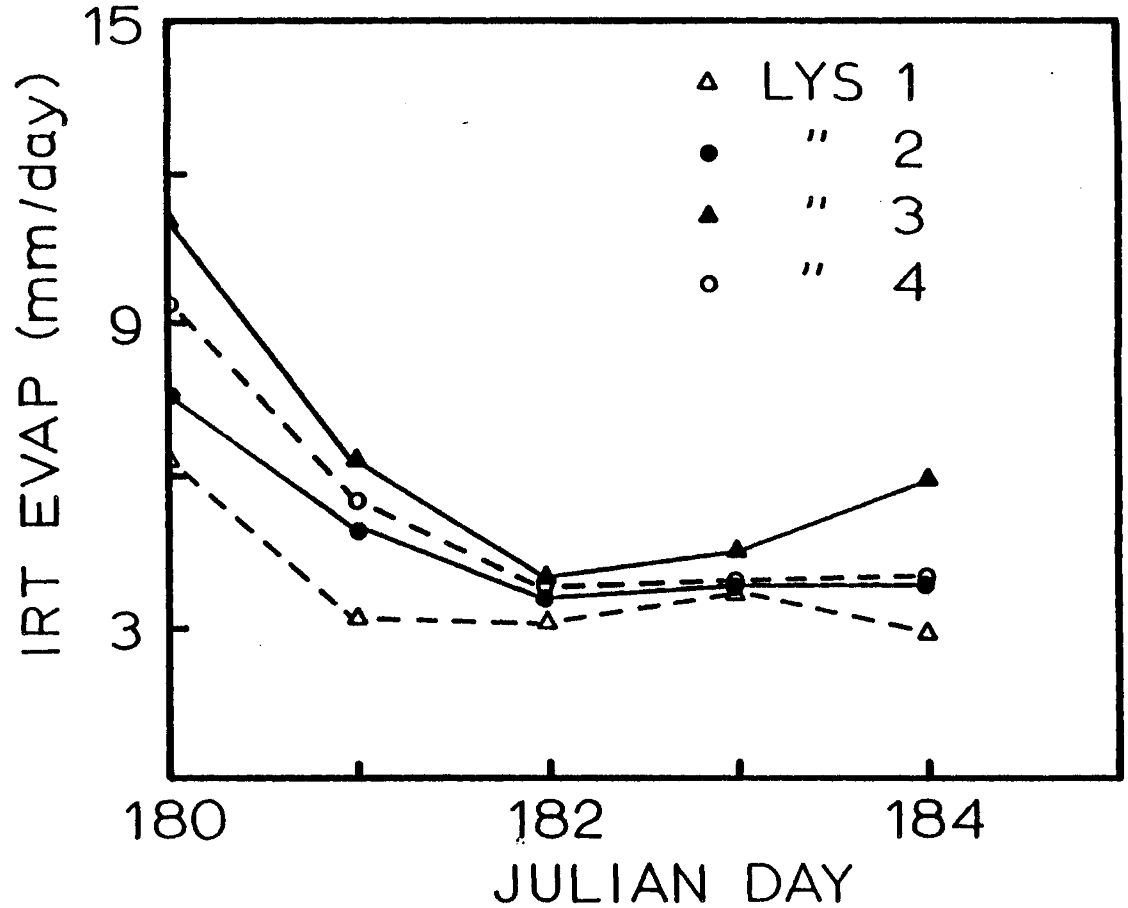

Figure 2. Spatial and temporal variation in evaporation measured by the IRT method.

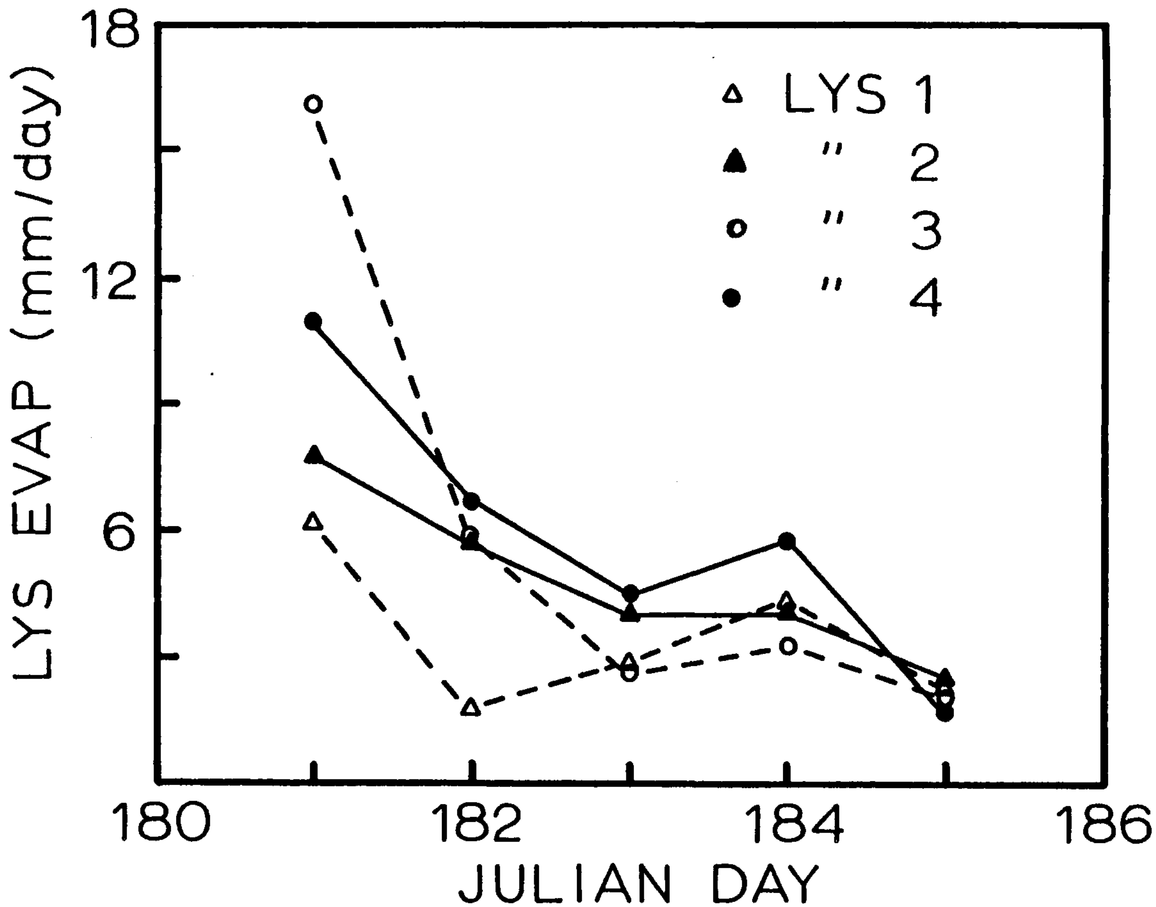

Figure 3. Spatial and temporal variation in evaporation measured by LYS method.

Table 4. Evaporation rate for the reference microlysimeters, and mid-day temperature data for the reference microlysimeters and the steady-dry and steady-wet soils.

	West Ref.			East Ref.			Dry Soil	Wet Soil
	Evap. (mm/d)		Av. T.	Evap. (mm/d)		Av. T.	Av. T.	Av. T.
Date	IRT	LYS	°C	IRT	LYS	°C	°C	°C
6/30/85	4.3	.50	49 ± 1.1	2.6	.60	55 ± .36	63 ± .35	29 ± 1.2
7/1/85	2.4	.60	57 ± .35	2.2	.40	57 ± .26	65 ± .30	31 ± 2.3
7/2/85	1.5	.60	56 ± 1.2	2.5	1.2	54 ± .33	62 ± .33	30 ± 1.0
7/3/85	1.3	.80	62 ± .60	2.0	1.2	60 ± .40	67 ± .80	34 ± 1.4
7/4/85	2.2	.40	61 ± .56	2.7	1.4	60 ± .50	67 ± .90	34 ± .50

difference between a dry and a wet soil being less than 16% of the integrated total latent heat flux. However, the data shows that in dry soil conditions these methods give unrelated results. This fact suggests that the problem with the Infrared Thermometry model is not likely caused by the assumptions but rather by the other parameters that go into equation (3), for instance the mid-day surface temperatures and average wind speed. Probably a weighting factor should be introduced into equation (3) to account for these possible influences of these parameters in the dry soil conditions.

The change in soil water content as estimated by the Neutron Surface Meter and the calibration curve (Figure 4) is also tabulated in Table 2. The data shows that there is a sharp decrease in the soil moisture content during the first 2 days. The amount of water evaporated estimated using this method is very high compared to the amount estimated using IRT and the LYS methods. It is even higher than the pan evaporation (Table 1). The neutron surface meter depends extensively on the evaporating surface. From observations made during the experiment, it is obvious that the neutron surface meter can give different results for the same surface just by changing its position. The calibration curve was drawn based on gravimetric soil water content from a soil that was not saturated at the beginning. It is imperative that a moisture count from a saturated soil be included in any future calibration curve.

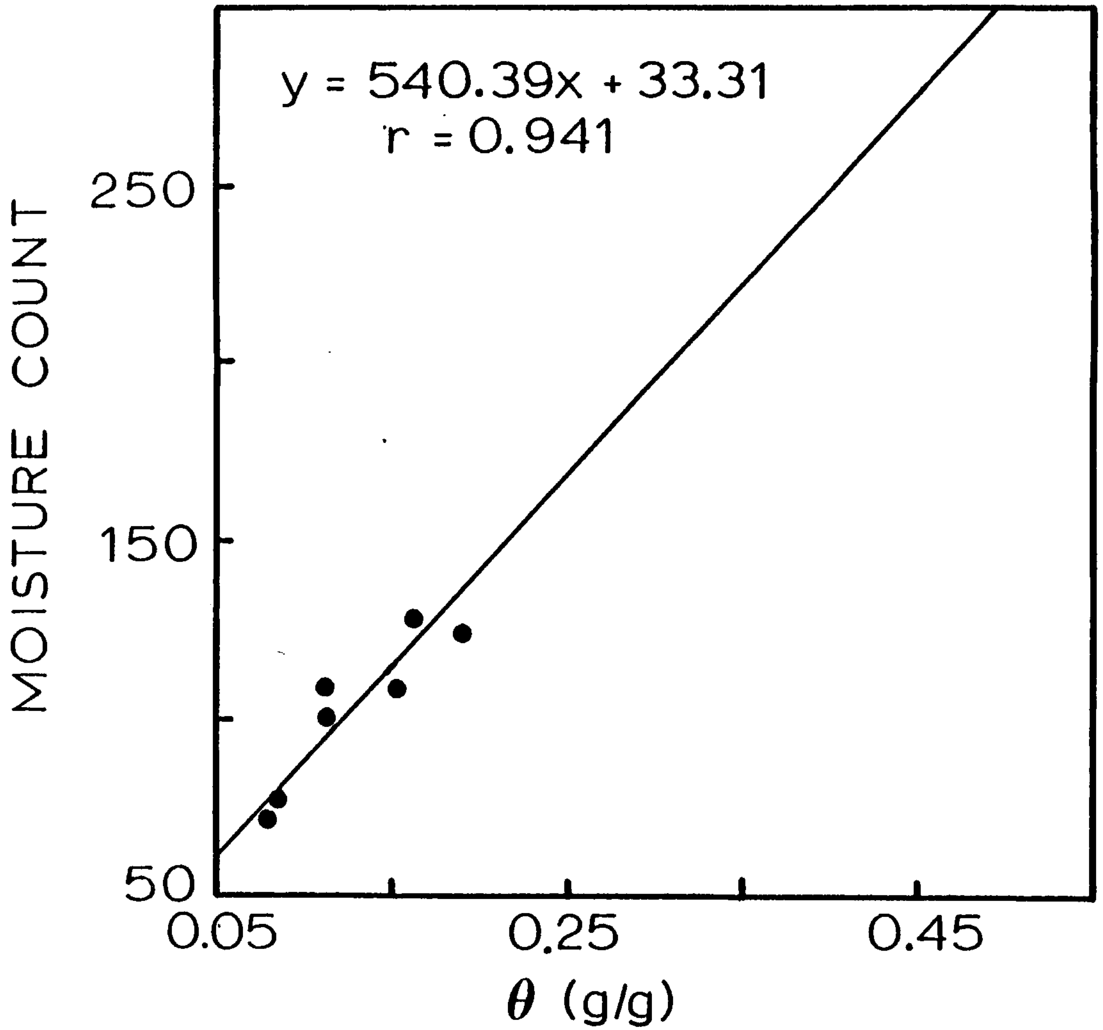

Figure 4. Calibration for Neutron Surface Meter.

Notwithstanding the differences between these three methods, Figures 5, 6, 7, 8, 9 show high correlation between these methods. Figure 6 shows once again that the IRT method tends to give increasingly higher evaporation rates as the soil dries out.

Table 3 presents the cumulative evaporation (mm) from all the sites, including all the microlysimeters within the wetted areas, and the mean cumulative average evaporation for the 4 Microlysimeters in each block. Figure 1 gives the average wetted diameters for the 9 experimental sites. For instance, the average cumulative evaporation for site IB as estimated by the IRT method is 25.2 mm, and the average wetted diameter is 61 cm. The volume of water evaporated from this area is approximately 7.3 liter. Assuming that the antecedent moisture content contributed 0.24 liter, then only 7.16 liter came from the 22 liter applied at the point source. The antecedent moisture used in this calculation was estimated by the LYS method. The IRT method estimated almost 12 mm for the antecedent soil moisture. We will assume that this value is in error. The undisturbed sites and around the Microlysimeters cumulative evaporation were lower than 1/3 of the total 22 liter of water applied. One reason might be due to the fact that the soil surface dried very rapidly in response to the high surface temperature observed during the experiment (Table 5). It has been observed that one way to decrease surface evaporation is

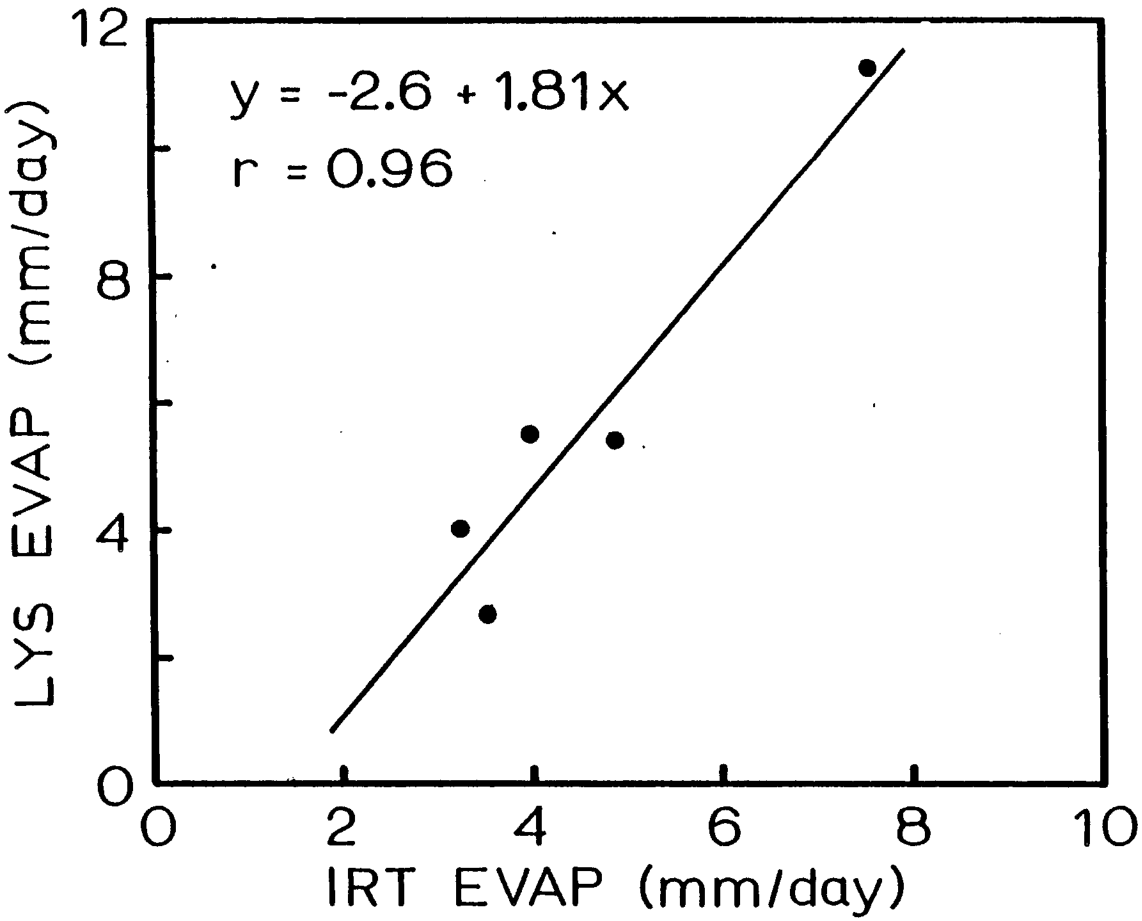

Figure 5. LYS evaporation rate vs IRT evaporation rate.

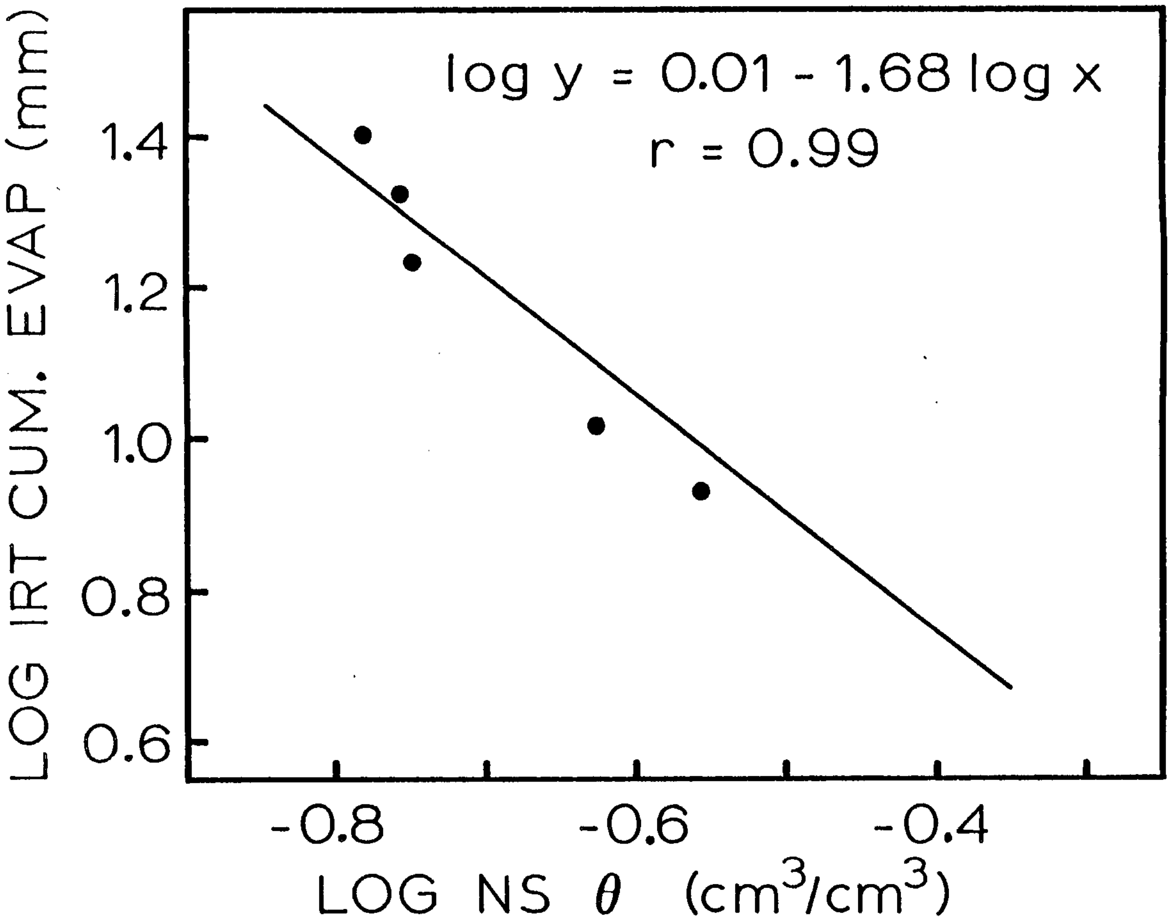

Figure 6. Log IRT cumulative evaporation vs. log soil water content measured by NS.

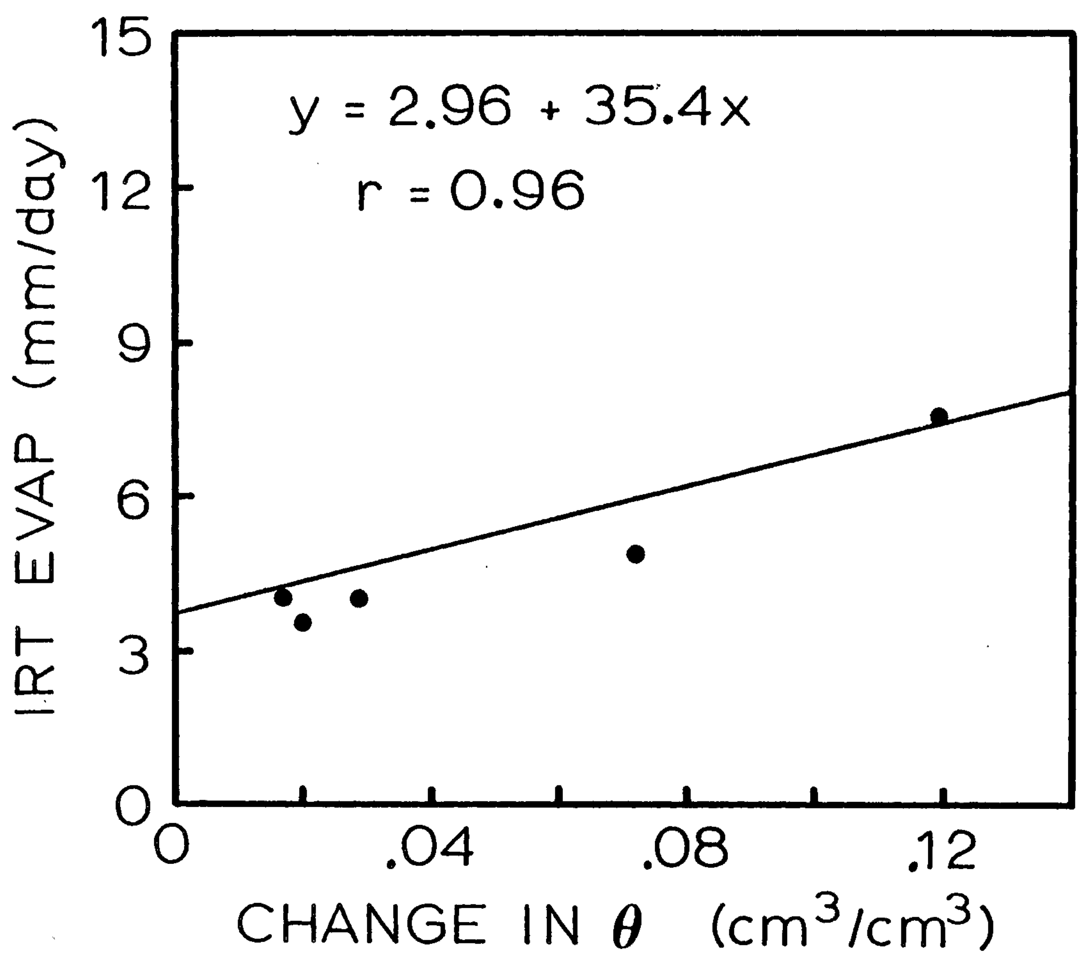

Figure 7. IRT evaproation rate vs. daily change in soil water content estimated by NS.

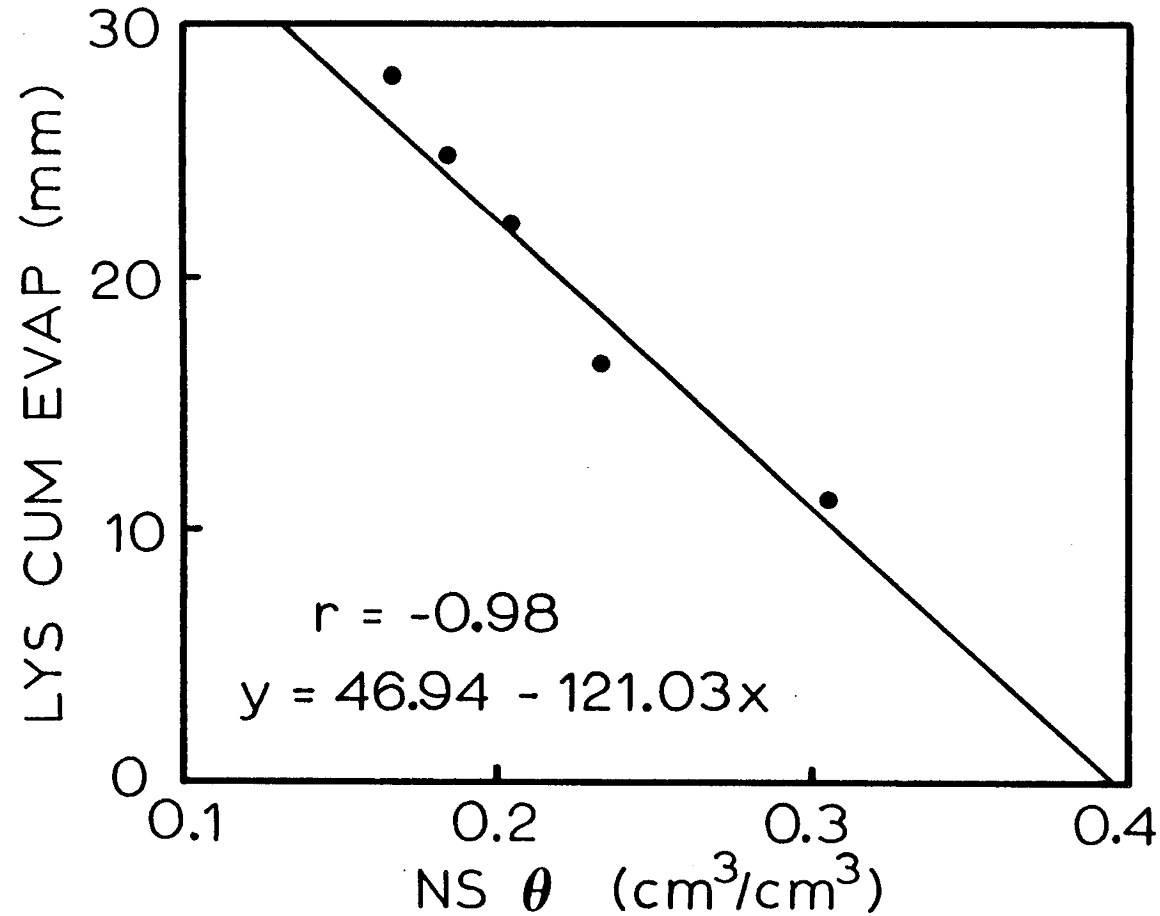

Figure 8. LYS evaporation vs. soil water content estimated by NS.

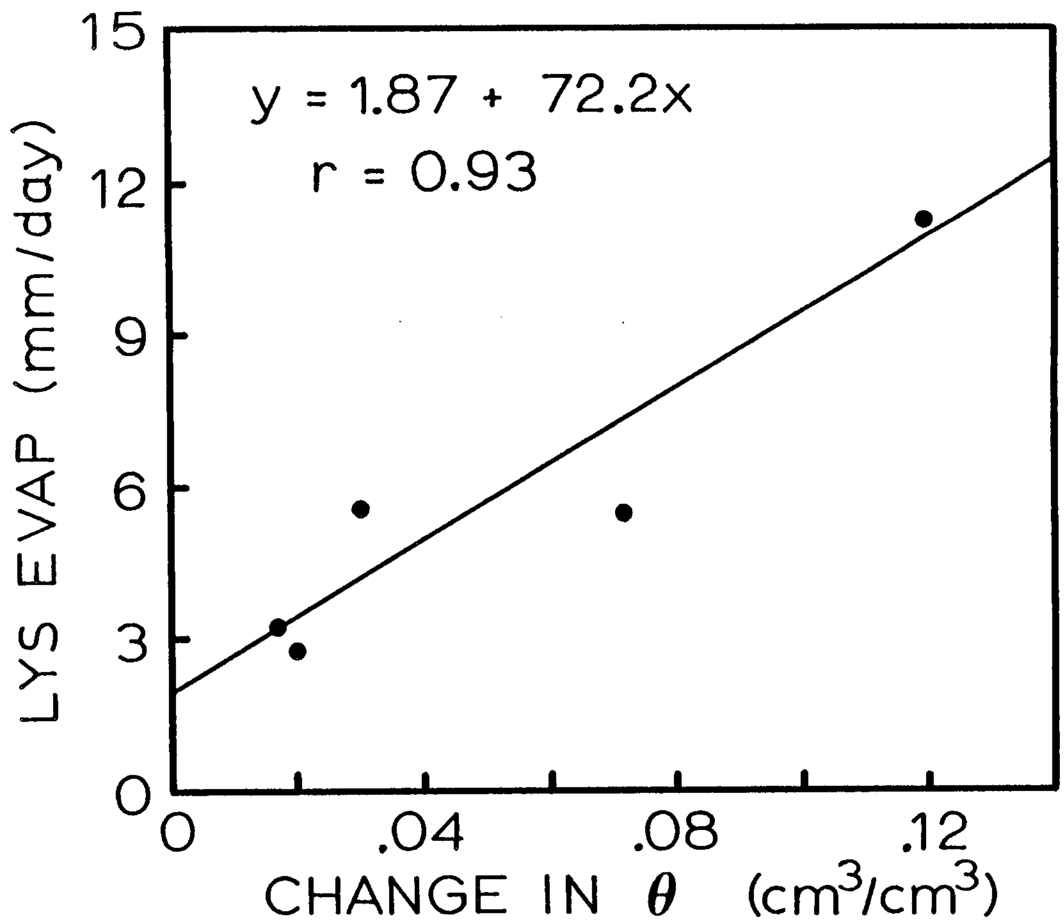

Figure 9. LYS evaporation rate vs. daily change in soil water content estimated by NS.

Table 5. Maximum temperature differences (°C) between the steady-dry soil and the drying surfaces.

		C	A	B					Ref. LYS	
Date	Block			LYS#1	LYS#2	LYS#3	LYS#4	ARLYS	WEST	EAST
7/29/85	I	17.0	14.9	17.8	26 2	34 3	22 4	12.6	12.9	8.0
	II	21.5	24.5	21.0	32.5	33.4	24.0	20.2		
	III	20.0	24.0	19.3	23.4	34.4	28.9	18.7		
8/1/85	I	10.4		12.7	14.0	23.1	14.1	4.4	7.7	7.0
	II	10.4	11.9	12.6	23.5	28.8	15.8	10.5		
	III	11.8	11.8	10.2	15.8	20.2	17.8	8.7		
8/2/85	I	5.6	4.4	10.8	11.7	16.3	11.3	5.4	4.7	7.7
	II	5.8	10.7	8.7	14.2	16.4	11.4	7.1		
	III	7.8	9.0	9.8	12.0	13.7	11.6	5.6		
8/3/85	I	4.7	1.7	9.7	10.8	17.5	11.2	6.4	4.6	6.6
	II	7.1	2.5	10.3	15.7	17.0	10.7	7.5		
	III	7.3	7.6	13.0	13.7	16.1	13.9	7.3		
8/4/85	I	5.3	3.8	8.5	11.0	14.8	11.5	4.6	6.3	7.8
	II	6.5	6.6	9.0	12.5	15.8	11.9	9		
	III	6.1	5.6	8.4	10.9	14.1	11.4	4.1		

to dry the soil surface very fast following water application. Also when the soil surface temperature is very high the flux of upward water flow stops because of the tendency of water vapor to flow towards the cooler layer below.

The neutron surface meter gave a cumulative evaporation of 70 mm in Block I(C-NS). This corresponds to a volume of 21.9 liters of water. In Block II the amount of 24.4 liters was estimated using this method. Of course this method estimate more than the cumulative evaporation. It should be pointed out that the neutron surface meter measures the total water change in the soil profile, whereas the IRT and LYS methods are conditioned to the Microlysimeters characteristics. Table 6 gives the gravimetric soil water content before and at the end of the experiment. According to these results a small fraction of the 22 liters of water remained in the soil profile at the end of the experiment. Assuming that these values truly represent the soil water status, it is not wrong to assume that the neutron surface meter can be used to estimate the changes in soil water content in the top 50 cm.

4.2. Soil Water Infiltration

Table 7 (Example 1) summarizes the data collected from the field. The comparison between maximum wetted depth and the maximum wetted radius for each time interval and volume of water applied, shows that the water moved faster in the horizontal direction than

Table 6. Gravimetric soil water content on a dry weight basis before and at the end of the experiment.

	Block								
	I			II			III		
Depth (cm)	A	B	C	A	B	C	A	B	C
15	.08. 17	.07 .16	.06 .16	.09 .16	.08 .17	.11 .16	.08 .19	.11 .17	.10 .17
30	.08 .14	.11 .15	.17 .17	.17 .19	.11 .12	.15 .15	.15 .16	.18 .17	.17 .19
40	.09 .12	.11 .13	.16 .13	.15 .13	.14 .15	.14 .17	.14 .16	.18 .15	.18 .15
60	.10 .07	.08 .08	.14 .07	.11 .14	.19 .17	.09 .08	.23	.10 .15	.16 .24

Note: The first number is the moisture content before the experiment and the second number is the gravimetric moisture content at the end of the experiment.

Table 7. Experimental results from point source infiltration.

Example 1

z_{max}(m)	r_{max}(max)	t(s)	Vol (1)	$Q(m^3s^{-1})$	D(cm)
0.16	0.225	4500	4	8.89E-7	42.4
0.21	0.275	9000	8	8.89E-7	53.5
0.22	0.305	13620	12	8.81E-7	60.2
0.27	0.35	18000	16	8.89E-7	65.5

Example 2

z_{max}(m)	r_{max}(max)	t(s)	Vol (1)	$Q(m^3s^{-1})$	D(cm)
0.14	0.14	10880	0.8	7.4E-8	25
0.21	0.155	18000	1.8	1.0E-7	29
0.27	0.213	28800	3.55	1.2E-7	39
0.33	0.27	86400	9.22	1.1E-7	50

it did in vertical direction. The initial moisture content (g/g) of the top 20 cm of soil was 0.0109 (g/g). The moisture gradient in the lateral direction can be compared to the moisture gradient in the vertical direction since the effect of the gravitational force can be neglected at the beginning of the water application. The soil at the experimental site was soft in the top 20-25 cm but beyond that the soil was compacted. This fact inhibited the moisture movement in the vertical direction. The radii of the wetted profiles were almost identical from the surface to the wetting front in all the sites. It is obvious than that the gravitational force had little effect in the water movement in the vertical direction in all the sites during the gathering of the data presented as Example 1 in Table 7.

The emitter flow rate was approximately 3.2 lh^{-1}, which was considered too high a flow rate for the experimental site. There was some ponding, and as a result the water moved more in the horizontal direction.

Another result that justifies the horizontal wetted distance is the time of water application. Usually in trickle irrigation the capillary and adsorptive forces are the dominant tension forces causing water to move away from the point source in both horizontal and vertical directions. The flow is unsaturated as long as the water is applied at low rates and no surface ponding occurs. The flow rate is adjusted to approximate the soil infiltrability. The soil in the experimental area is a sandy loam, but the inflow rate decreased sharply immediately after the start of water application. This resulted in water ponding at the surface for the duration of the experiment. Also the lateral movement continued until the experiment was over. There was not enough time for the horizontal water flow to reach the equilibrium state, and thus for the gravitational force and the suction at the wetting front to be the dominant forces in the water flow.

Example 2 (Table 7) shows experimental data gathered at a later time at the same location. This time the water application rate was very low compared to the flow rate in Example 7. In the first three hours the wetted soil volume was a semi-circle with both z_{max} and r_{max} equal to 0.14 meter. Two hours later the maximum depth had increased by 26% over the maximum radius. It should be obvious that the gravity began exerting some downward force on the water only after approximately 4 hours. But the water continued to move in the lateral direction, although at a slower rate. There was no ponding at the surface and the water movement can be considered unsaturated. The flow rate was not large enough to fill the larger pores (capillaries) and the water was held very strongly by adsorptive forces against the gravitational forces. Nonetheless, the water application time was long enough to allow the lateral water movement to lag behind the vertical water movement.

Figure 10 shows the plot of log z_{max} versus log r_{max} with the first data point falling on the 1:1 line and the rest falling below the line.

Table 7 shows the surface wetted diameters. If we assume that the wetted soil volume approximates a cylinder for the first moments of the infiltration process, then the wetted volume calculated assuming a cylinder shows that larger flow rates overestimates the wetted volume and small flow rates underestimates the wetted volume. Roth (1983) reached a similar conclusion. He calculated the wetted soil volume by dividing the effective amount of water applied to the soil by the difference between field capacity moisture content and the initial moisture content. He further supported his conclusion by stating that at large flow rates the larger pores tend to fill which contribute to a larger field capacity than the field capacity corresponding to a smaller flow rate.

Table 8 shows the results given by the model (Warrick and Lomen, 1986). The input parameters to the computer program includes the emitter flow rate, saturated volumetric moisture content, residual moisture content, the experimental z_{max} and r_{max} values, and a relationship for θ vs h. The relationship for θ vs h is accomplished by fitting two points from Figure 11 to the empirical form of Van Genuchten (1980)

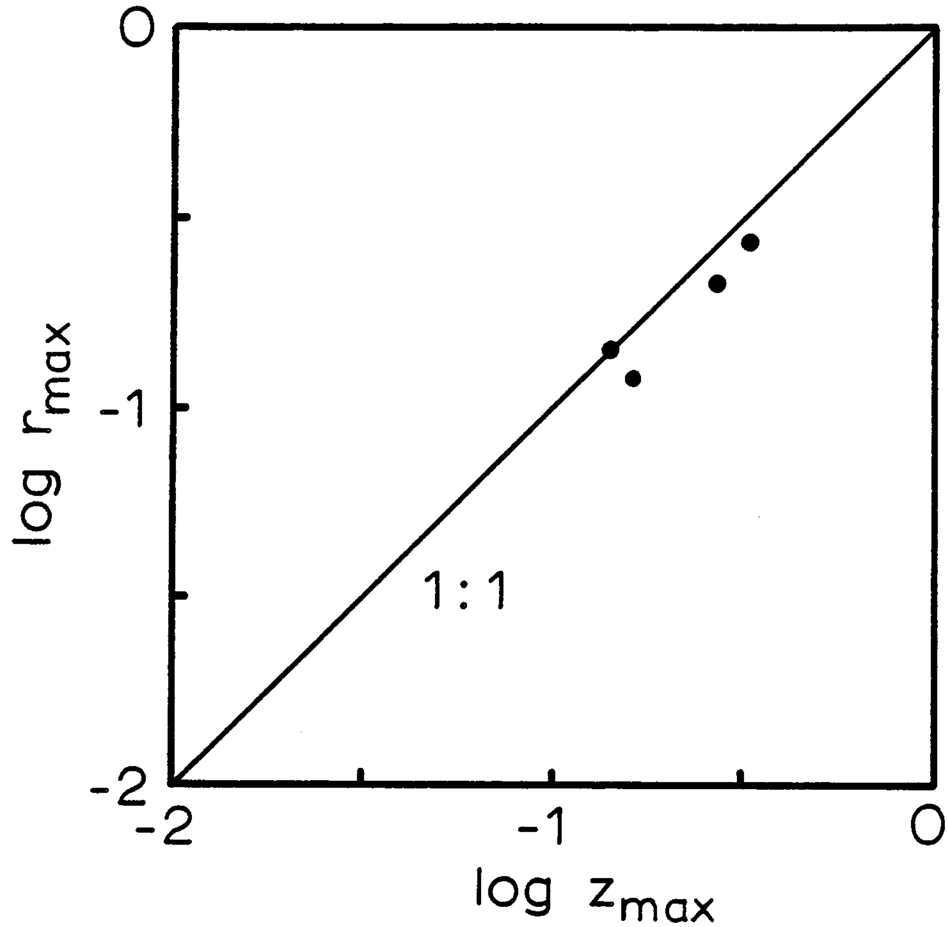

Figure 10. Log r_{max} vs. log z_{max}.

Table 8. Comparison between experimental and calculated times for fitted K_0 and α.

Example 1

z_{max}(m)	r_{max}(m)	t(h)	Predicted Times	
0.16	0.225	1.25	0.8	0.80
0.21	0.275	2.5	1.8	1.8
0.22	0.305	3.5	2.0	2.0
0.27	0.35	5.0	3.8	3.8
		$\alpha(m^{-1})$	0.18	0.20
		$K_0(ms^{-1})$	$8.7(10)^{-5}$	$2.3(10)^{-4}$
		SS	5.042	5.003

Example 2

z_{max}(m)	r_{max}(m)	t(h)	Predicted Times		
0.14	.14	3	2.7	2.7	2.7
0.21	.155	5	8.1	7.9	7.8
0.27	0.213		15.7	15.3	15.5
0.33	0.27	24	26.4	25.8	25.3
		$\alpha(m^{-1})$	1.4	1.5	1.6
		$K_0(m^{-1}s^{-1})$	$6.0(10)^{-3}$	$7.8(10)^{-3}$	$9.9(10)^{-3}$
		SS	4.755	4.408	4.11

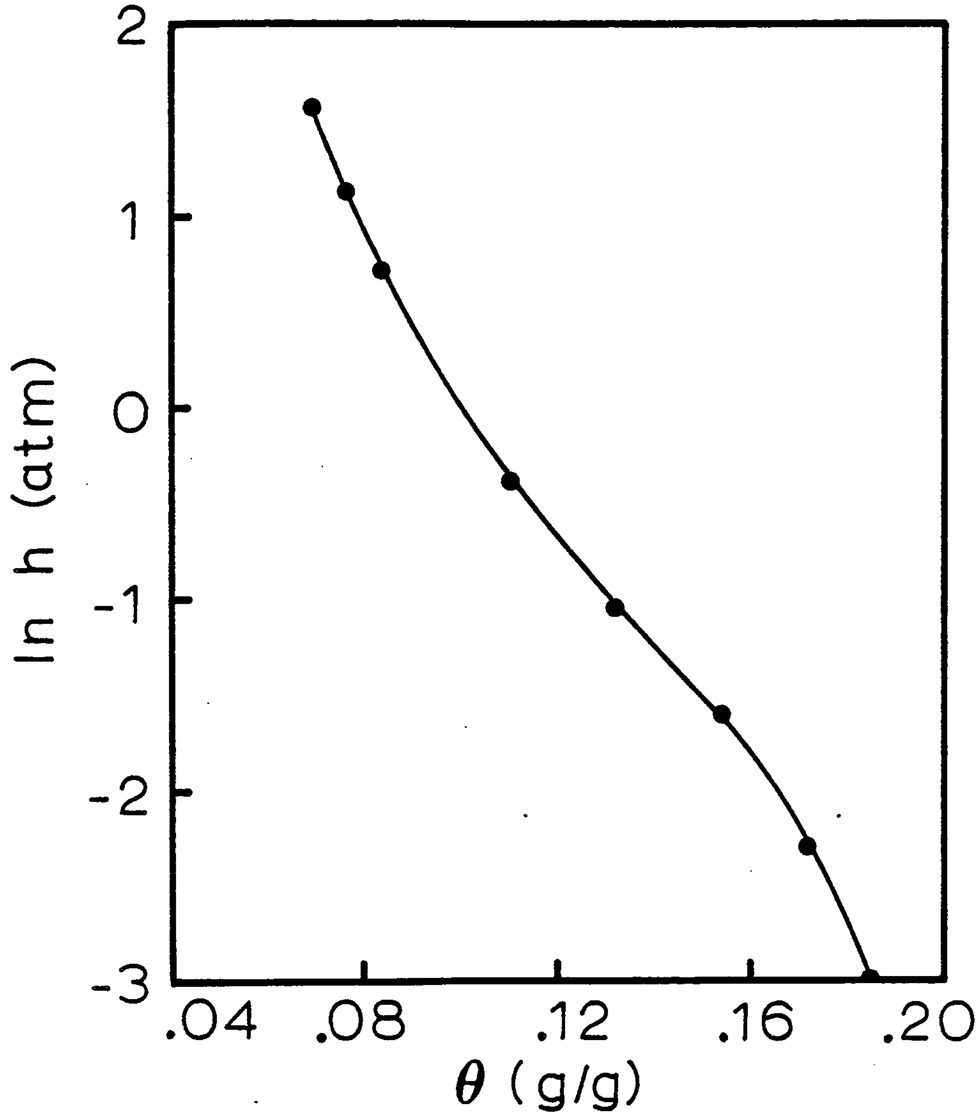

Figure 11. Moisture release curve generated from undisturbed soil sample using a 15 Bar Ceramic Pressure Plate (No. 13543).

$$\frac{\theta-\theta_r}{\theta_s-\theta_r} = [1 - |\alpha_v h|^m]^{-1/(1-m)}. \qquad (17)$$

Figure 11 was generated from undisturbed soil sample using a 15 Bar Ceramic pressure plate (No. 13543). The saturated volumetric moisture content (θ_s) was taken as 0.319 based on a bulk density of 1.77 Mgm^{-3}. The residual moisture content is an arbitrary value $(.02\ cm^3/cm^3)$. The two points from Figure 11 are $\theta = .268$, $h = -.517$ m and $\theta = .11$, $h = -31.6$ m. the best fitting coefficients were found to be 0.22 and 2.34 m for m and α_v respectively.

The α is determined only from the experimental z_{max} and r_{max}. It is estimated so that the sum of squares of the differences (SS) is minimized. The SS is given by

$$SS = \sum w_k (Y_k^* - Y_k)^2. \qquad (18)$$

The SS is calculated from $\alpha = 0.02$ to 50 m^{-1} in Example 1 and from $\alpha = 0.2$ to 50 m^{-1} in Example 2. Y_k^* is the value of log r_{max} from the following

$$\log R_{max} = -0.242 + 0.728 \log Z_{max} - 0.0795(\log Z_{max})^2 \qquad (19)$$

$$0.01 < Z_{max} < 50.$$

R_{max} is the dimensionless radius given by $(\alpha\, r_{max})/2$, Z_{max} is the dimensionless depth given by $(\alpha\, z_{max}/2)$ and Y_k is the experimental log r_{max} from Table 7. The index in equation (18) is taken as unity.

The values of K_0 are calculated also to minimize SS from equation (18). The index is taken as 2^k because it was felt that the larger times are more important when comparing predicted log t's to the experimental values. The values for Y_k^* are equal to log $t_{p,i}$ (predicted from equation (15)), and Y_k the log t for the 4 experimental results. The numerical values from equation (17) for K_0 and α were compared to choose the best α and K_0. The α and K_0 were then used in the following equation to estimate theoretical times

$$qt = (8/\alpha^3)\left[\sum_{J=1}^{n(k)} (.5)(\theta_{J+1} + \theta_J)\Delta V_J^k - \theta_i V_{n(k)+1}^*\right] \qquad (20)$$

$$\Delta V^* = V_{J+1}^* - V_j^* \qquad (21)$$

$$\log V^* = -0.121 + 2.46 \log Z_{max} - 0.169(\log Z_{max})^2. \qquad (22)$$

In Example 1 (Table 8) the predicted times are all less than experimental times. The regression equation between z_{max} and predicted times for $\alpha(m^{-1}) = 0.20$ is

$$\log z_{max} = -1.042 + 0.0965 \log t \tag{23}$$

with a $r = 0.5769$. This equation was used to calculate the wetting fronts using the real times. The model does not fit this data very well. The α is very small and this fact might have been the main reason why the correlation (r) coefficient is so insignificant. The z_{max} calculated by the above equation are 0.204, 0.218, 0.227, and 0.233 m^{-1}. The results shows considerable deviation from the experimental results.

The regression equation for Example 2 is

$$\log z = -2.37 + 0.382 \log t, \quad \alpha = 1.5\ m^{-1} \tag{24}$$

with a $r = 0.999$. The wetting fronts predicted from equation (24) using the real times are 0.148, 0.18, 0.215, and 0.347 m which are good approximation to the experimental values. However, the value (0.215 m) is 20% smaller than the experimental value. This is to be expected since there was considerable difference between the experimental time and the calculated time for this particular value.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1. Summary

The objectives of this study were

(1) to study the evaporation process from the surface of polyvinyl chloride microlysimeters using the Microlysimeter (LYS) Method and the Infrared Thermometric (IRT) Method and to compare the results from these two methods with the daily change in the soil water content as determined by Neutron scattering (NS) and

(2) to estimate water infiltration in the field from point source water application using a theoretical model.

The first objective was accomplished by dividing a 6 by 6 m plot into 9 equal experimental sites. The IRT method, LYS method, and NS method were randomly assigned to the 9 experimental sites. Twelve microlysimeters were installed in the wetted areas of the B-Sites, and two in the dry soil to measure the contribution to the total evaporation from the residual moisture content. The evaporation rates were measured by daily weight measurements of the microlysimeters, daily mid-day surface temperature of the microlysimeters and a nonevaporating reference dry microlysimeter, and the average daily wind speed. The soil water content was estimated from direct readings of moisture count from the neutron meter and a calibration curve developed for the Gila soil type.

Objective (2) was accomplished by comparing field data with results given by an infiltration model. The model consists of a series of equations that lead to the calculation of theoretical infiltration times. A regression equation is found by regressing the log of theoretical times with the log of experimental maximum infiltration depth. Maximum depth of any wetting front is then calculated from the regression equation using real infiltration times.

5.2. Conclusions

The evaporation experiment was quite conclusive in establishing the differences and similarities between the IRT method and the LYS method. The two methods predicted different evaporation rates and they were out of phase with each other in the energy controlled stage and in the third stage of soil water evaporation. When the soil is wet, the LYS method overestimates the evaporation rate over the IRT method, but the opposite is also true as the soil dries out. The cumulative evaporation measured by the IRT and LYS method were reasonably within experimental errors. But it should be pointed out that if the experiment was allowed to continue for 2 or more days the IRT method would begin to deviate from the LYS cumulative evaporation. The LYS method is based on microlysimeter weight differences taken every day around 0700. The IRT method is based on daily wind speed, and mid-day surface temperature. The LYS method gives an evaporation estimate which depends on the environmental conditions prevailing in the previous day. The IRT method, on the other hand, gives estimates which depends on two consecutive days. The difference in time at which measurements are taken my contribute to the difference in estimates from the two methods for a given day.

The evaporation from dry soil given by the LYS and IRT methods are highly different. In this study there was a difference of 152% of IRT evaporation over the LYS method.

The neutron meter estimates soil water changes from the top 50 cm of the soil profile. The neutron meter estimated over 70 mm of water depletion from the soil profile. This value is considerably higher than the estimates from the IRT and LYS methods. This is to be expected if the depth of influence of each method is taken in consideration. The LYS method depends on the length of the particular microlysimeters, and the IRT method depends on the top 2 cm of the soil surface. In spite of the high estimate by the neutron meter, it is proper to say that the neutron meter can be used to estimate soil water content change if a good calibration curve is developed for soil type, and measurements from very dry and very wet soils are included in the curve. However, the fact that special attention is put into site preparation can undermine the correctness and validity of measurements from this neutron meter.

The study indicates good correlation among LYS, IRT, and NS methods for the period of the experiment. Besides good correlations, it should be pointed out that the IRT method is easier to use than the LYS method, but the LYS method is more reliable in terms of practical use. The IRT method has a disadvantage in the use of a reference dry soil, by limiting its application only in dry conditions. The LYS method is very labor intensive, and consideration should be give in the case of sealed bottom microlysimeters versus solid bottom ones. The neutron meter is heavy, requires calibration, and site preparation. These facts may hamper the usefulness of the neutron meter in field conditions.

The infiltration experiment requires field data from a wetting front, a moisture release curve, residual and saturated moisture content, and an assumed relationship between hydraulic conductivity and pressure head. A computer program was used to calculate theoretical infiltration times. The two empirical constants α and K_0, were chosen to minimize the sum of squares. The results indicate a low correlation coefficient $(r = 0.58)$ for a flow of 3.2 lph, but the correlation approximated unity with a lower flow rate $(q = 0.26 \text{ lph})$ for the same soil. The calculated z using the regression equations, which resulted by regressing $\log z$ (experimental) and $\log t$ (predicted times), are good approximations of the real z (maximum depth). The differences can be attributed to the fact that the soil profile at the experimental site is very compacted beyond 15 cm depth. The results show that this model can be used in estimating the approximate wetted soil volume necessary for a given plant as long as the soil infiltrability is known.

The results of both studies showed that the methods used are reliable, but further study should be carried out to explain the reasons of why the infrared Thermometric Method overestimates soil water evaporation in dry soils as compared to the Microlysimeter Method, and to study the soil surface effects on the results from the neutron surface meter. Also the infiltration experiment showed that the theoretical model can be used to estimate infiltration, but it was felt that more field data ought to be used in the future in estimating K_0 and α.

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