EQUATIONS FOR RUNOFF FROM FURROW IRRIGATION

by

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# INTRODUCTION

The domain of irrigation is becoming ever larger. Each year a greater percentage of the arable land is placed under irrigation. Likewise, an increase in the demand for water suitable for irrigation is realized each year. At the same time, non-agricultural interests exert a similar increasing demand on the existing water supply.

In the past, the prevalent attitude appears to have been to disregard the need for water conservation. However, lowering water tables in many areas as well as increasing competition for existing water supplies have shown that the water supply is not unlimited. As the realization of a limited water supply becomes more apparent, refinement of present water conservation methods, as well as development of new methods, is dictated. In particular for irrigation, refinement and development of methods which not only meet agronomic requirements but also realize efficient water usage become increasingly more important.

While irrigation water can be applied by various methods, furrow irrigation is popular in many areas. Water is delivered at the head end of the furrow. As it advances down the furrow, some of the water infiltrates into the soil, some is temporarily stored on the soil surface, and the rest continues to move down the furrow. This process continues until the flow reaches the end of the furrow, at which time runoff begins. When inflow is terminated, runoff and surface storage begin to decrease, and continue to decrease until they also terminate.

According to Criddle, et al., (1), if a reasonably uniform distribution

of water is to be attained, the water should reach the end of the furrow in one-fourth the total irrigation time. Total irrigation time is defined as the time required to infiltrate the desired amount of water into the soil. Irrigation under the one-fourth time rule will give a reasonably uniform distribution of water and thus will reduce water loss to deep percolation, but at the same time will produce considerable runoff.

A method of reducing runoff from furrow irrigation known as cutback irrigation can be used. In cutback irrigation, when the water initially reaches the end of the furrow, inflow is reduced to more nearly conform to the intake rate of the soil. This method is a simple water conservation method, but one which is not often used because of the labor required to change the inflow. Automated surface irrigation promises to be a solution to the labor requirement (2). Automated cutback irrigation can be a method of reducing runoff from furrow irrigation, and thus can be a practical water conservation method.

Unless runoff water can be reused, it is wasted. Numerous investigators (3, 4) have studied the problems involved in the reuse of runoff (tailwater) for irrigation. The design of a tailwater reuse system often involves the design of a holding structure for the tailwater. Inherent in the design of the reuse system is a knowledge of the quantity of tailwater that will be realized from a given irrigated area. Thus, a satisfactory method of determining runoff is necessary in order that tailwater reuse systems can be properly designed.

Only recently has the idea of computer irrigation scheduling received notice as a practical water conservation method (5, 6). In computer irrigation scheduling, an account of the water added and the water used or lost in

an area is maintained with the aid of a computer in order to determine when to irrigate and how much water to apply. The water account is based on the equation (7):

$$P + I - S_D = \Delta D + \Delta M + \int E \, dt + U \tag{1}$$

where P = precipitation

I = irrigation water

$S_D$ = direct runoff

$\int E \, dt$ = evapotranspiration

$\Delta D$ = change in surface storage

$\Delta M$ = change in soil moisture storage

U = deep percolation loss

This equation requires a knowledge of the amount of runoff realized from an irrigation. Thus, the need for a method of accurately determining runoff is apparent if the concept of computer irrigation scheduling is to be useful as a water conservation method.

From observation of furrow irrigation, the fact that runoff varies as a function of time is apparent. Runoff commences after a period of irrigation time has elapsed. The runoff rate gradually increases, then reaches a steady state condition if the irrigation is continued long enough. When inflow is terminated, the runoff rate rapidly decreases to zero. The fact that runoff rate varies with time provides a method for determining runoff from furrow irrigation.

## PURPOSE OF STUDY

The purpose of this study was to obtain a simple method of determining the amount of water added to the soil in an area under irrigation. While remembering certain simplifications, the amount of water added to the soil is equal to the inflow minus the outflow, or runoff. Inflow can be easily measured at the head end of the furrow and is, in most cases, essentially constant. What remained to be determined was a satisfactory relationship for runoff. With this relationship determined, water application could easily be calculated. If the amount of soil water added during an irrigation could be determined, the chances of over or under irrigation would be reduced. Irrigation efficiency could also be evaluated if the amount of inflow and runoff were known.

The principal objective of this study was to develop an equation with time as an independent variable, to determine runoff from furrow irrigation. The equation sould be in a form that can easily be used without requiring the evaluation of the numerous factors that influence runoff rate.

# REVIEW OF LITERATURE

## Review of Previous Work

The flow pattern for furrow irrigation has been characterized as being non-uniform, unsteady, and spatially varied. It is subject to many factors, some of which change throughout the irrigation period. Among factors that influence the flow pattern are inflow, infiltration, and furrow characteristics such as slope, shape, and roughness.

Due to the complexity of mathematical derivations involving the factors that determine flow patterns of furrow irrigation, as well as the evaluation of the factors themselves, many investigators have based their considerations on the continuity equation. From the continuity equation, inflow equals infiltration plus outflow plus any water that is stored on the soil surface.

Davis (8) used the following form of the continuity equation in his development of an equation to estimate the rate of advance of water flowing in an irrigation furrow:

$$v_e = v_i + v_s \tag{2}$$

where $v_e$ = the volume of water entering the furrow

$v_i$ = the volume of water infiltrated into the soil

$v_s$ = the volume of water stored in the furrow.

This form of the continuity equation is applicable only until the water reaches the lower end of the furrow. In order to use the continuity equation for longer periods of irrigation during which runoff occurs, a term to describe the volume of runoff water must be included. With this consideration

the continuity equation becomes:

$$v_e = v_i + v_s + v_r \qquad (3)$$

where $v_r$ = the volume of runoff water.

Wu (9) presented a method for describing furrow irrigation using the concept of the overland flow hydrograph, a graphical solution to the continuity equation. This concept was based on the overland flow hydrograph for watershed runoff developed by Izzard (10). For a given section of furrow, if the period of constant inflow continues long enough, the outflow will develop a shape similar to the one shown in Fig. 1. Wu recognized four separate zones in the outflow hydrograph, each having its own flow characteristics.

## Zone I:  $(0\text{--}T_L)$

In Zone I, flow is advancing downstream, expressed by an advance function. Infiltration varies with time and distance from the head end of the furrow. Runoff is zero. Zone I extends from irrigation time equals zero to the time flow reaches the end of the furrow, $T_L$.

## Zone II:  $(T_L\text{--}T_E)$

The outflow (runoff) is expressed by the rising part of the hydrograph in Zone II. The whole section of the furrow is covered with water, and infiltration intensity varies with time and location along the furrow section. This zone describes flow from time $T_L$ to time $T_E$, the time at which outflow reaches a maximum rate.

## Zone III:  $(T_E\text{--}T_C)$

During Zone III, flow is in equilibrium, runoff rate is constant and at a maximum. Infiltration is constant for the whole furrow section and is at a

THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.
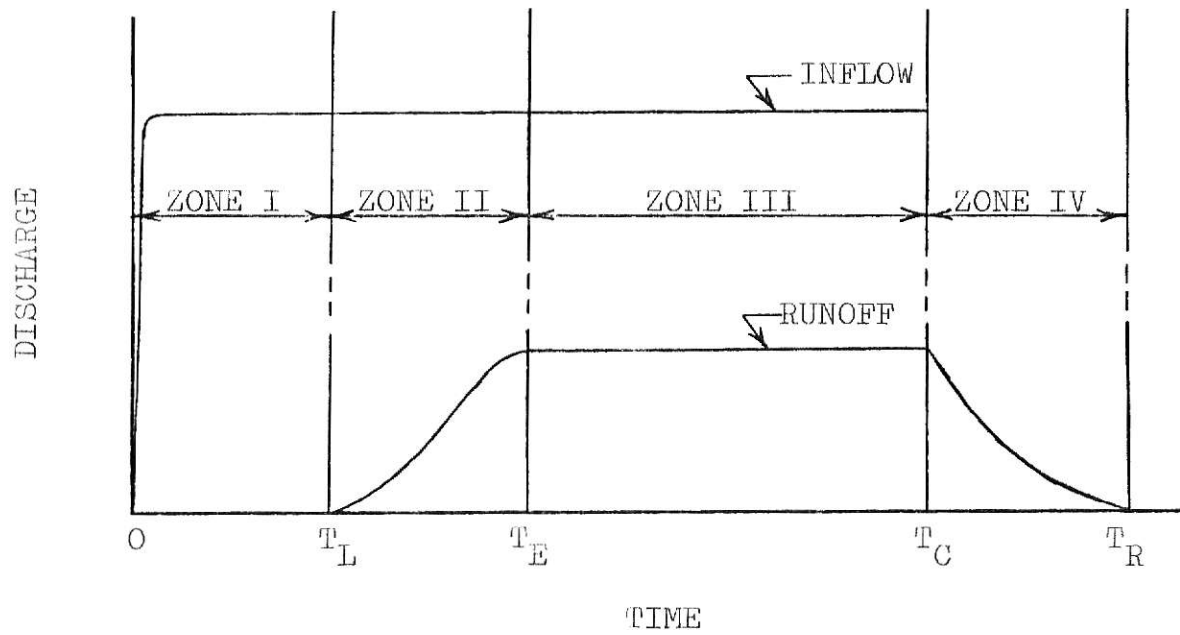
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Figure 1. Inflow and Outflow Hydrographs for a Given Furrow (9)
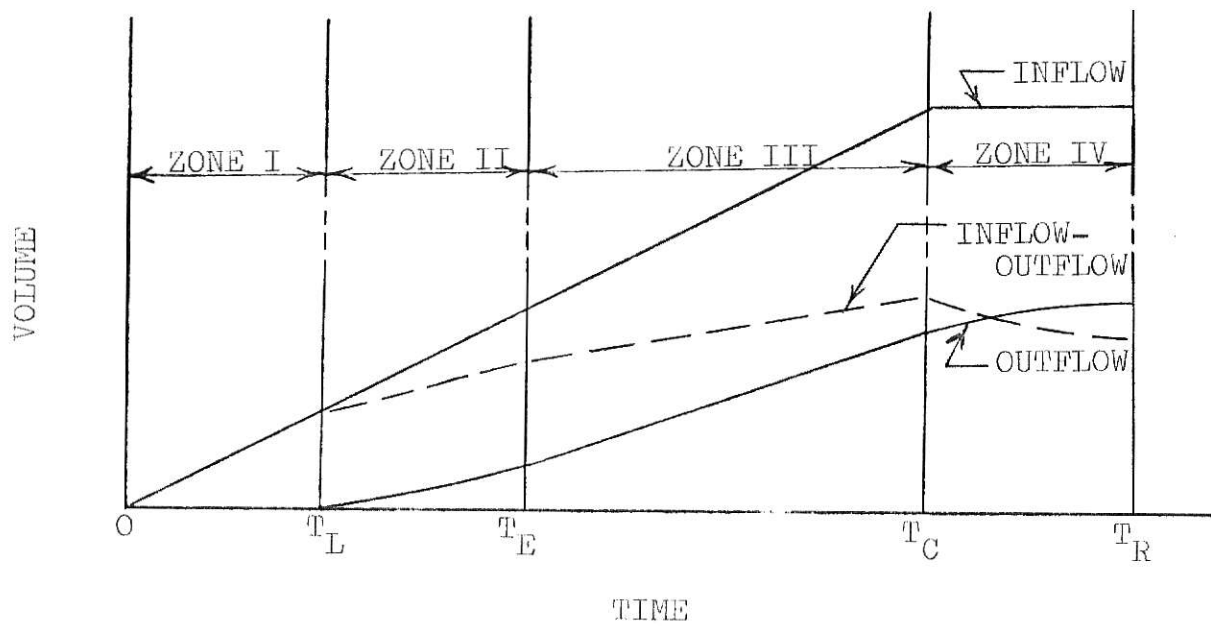


Figure 2. Mass Curves of Inflow and Outflow Hydrographs from
a Given Furrow (9)

minimum. Zone III extends from time $T_E$ to time $T_C$, the time inflow is terminated.

## Zone IV: $(T_C$ -- $T_R)$

In Zone IV, flow is expressed by recession flow. Infiltration is constant and the same as in Zone III. Zone IV continues until time $T_R$, the time runoff terminates.

Capitalized symbols were used to designate the time limits of the Zones, as these times represented constant values. In this thesis, constants are represented by capitalized symbols, and variables by lower case symbols.

Analysis of the mass curves of the inflow and outflow hydrographs, Fig. 2, as presented by Wu, can yield information on the total infiltration in a given furrow section. The inflow mass curve minus the outflow mass curve is the sum of the total infiltration and surface storage. If the amount of surface storage can be estimated or assumed and the inflow and outflow determined, the total infiltration can be found.

Wu suggested two methods for estimating the maximum surface storage. One method estimates the maximum storage from recession flow, considering the maximum storage as the sum of the volume of recession outflow and the infiltration during recession flow. Presentation of this method has been made by Allen et al. (11), but due to its complexity is not presented here.

Wu suggested the maximum storage can also be estimated from the shape of the furrow and the shape of the water surface profile. This method has been presented by Fok et al. (12). They show the average depth of water on the soil surface can be expressed by:

$$D_S = \frac{D_0}{1 + B} \tag{4}$$

where $D_S$ = the average depth of water on the soil surface

$D_0$ = the normal depth

B = an empirical constant in the advance function (13):

$$x = A t_a^B \tag{5}$$

in which x = the distance water has advanced at time $t_a$

$t_a$ = the advance time, in minutes

A and B = empirical constants obtained by evaluating data for the advance

equation.

Normal depth can be measured or can be determined from inflow, furrow slope, Chezy's or Manning's roughness coefficient, and the cross-sectional area of the furrow. The advance function can be determined by plotting on log-log paper the distance the water has advanced versus the time required for the water to advance the given distance. Storage volume, $V_S$, can be obtained by multiplying the average depth of water on the soil surface by the furrow length and the row spacing.

Davis (8) determined an equation for computing surface storage for use in calculating an advance equation. His equation was:

$$v_s = [C \, f(d) + E]x \tag{6}$$

where C = a factor that depends on the shape of the water surface and on the shape of the furrow

f(d) = some function of the depth of water flowing in the furrow channel

E = the puddle factor which represents the depth of water that would remain in the depressions along the length of the furrow if the furrow were first filled with water and then drained

x = the length of furrow the water has covered in its advance.

Recalling the continuity equation for long periods of irrigation, $v_e = v_i + v_s + v_r$; if the inflow rate is known and a satisfactory relationship for $v_s$ is used, only the term $v_i$ or $v_r$ remains to be determined in order to solve the equation. If the depth of water added to the soil by an irrigation is of primary interest, the equation could be better written:

$$D_I = \frac{V_I}{WL} = \frac{V_E - (V_S + V_R)}{WL} \tag{7}$$

where $D_I$ = the average depth of water added by an irrigation

  W  = the row spacing

  L  = the furrow length.

Only $V_R$ remains to be determined in order to find the amount of water added by an irrigation.

$V_R$ is the total volume of runoff water obtained from an irrigation. A method of calculating $V_R$ specified by the Soil Conservation Service Field Manual (14) is based on mean rate calculations. The time runoff started is observed and recorded. Runoff rates and their corresponding times are measured at intervals throughout the irrigation period. Mean runoff rates are determined between two successive runoff readings, then are multiplied by the corresponding time interval between the two readings. The runoff volumes obtained are then summed to give the total runoff volume realized from the irrigation.

This same basic approach has been used by other researchers in the determination of runoff volume. Clark (15) determined runoff volume by recording the upper head on one-inch free discharging Parshall flumes with water level recorders. Water from four furrows was channeled through each Parshall flume. Total runoff volume was calculated by mean rate calculations with the aid of a computer.

Pope (3) used the hydrograph concept to determine runoff. Measurement of the runoff was accomplished with an H flume and water level recorder. The pen trace on the strip chart formed a continuous record of time versus head on the H flume measuring device. Head readings were converted to flow rates at 15 minute intervals to obtain a hydrograph of flow rate versus time. Calculation of runoff volume was made with a digital computer, based on values obtained from the hydrograph.

Hydrographs obtained by Pope were based on runoff from a number of furrows rather than only on one or several furrows. These hydrographs did show, however, that runoff began after a period of irrigation time had elapsed, then gradually increased. They did not show a period of constant outflow. This was due to the length of irrigation time. That is, the irrigations did not last long enough for constant outflow to be established.

Other investigators have used the volumetric approach for measuring runoff (11). This method involves channeling the runoff into a large container and measuring the total accumulated volume of runoff that has occurred from the start of runoff until the time the measurement is made. This method can be used only for small plots. Calculation of runoff rates using this method still requires an averaging technique.

## Development from Theory

The continuity equation states that input must equal output. For irrigation, input considers only that water fed into the furrow during the irrigation process. This consideration eliminates water from precipitation. On the other hand, output is made up of several components. These components include the volume of water infiltrated into the soil profile, water stored on the

soil surface, water lost to evapotranspiration, water lost to deep percolation, and water lost to runoff. In equation form, this can be written:

$$V_E = V_I + V_S + V_{ET} + V_P + V_R \tag{8}$$

Evapotranspiration losses are difficult to measure and are relatively small compared to the other components. For the purposes of this study, evapotranspiration losses were disregarded. Deep percolation losses can be combined into the infiltration volume term. With this simplification, evaluation of deep percolation losses was not required.

During the irrigation process, the value of the surface storage term is significant. This term can be evaluated or estimated as set forth by Wu (9) or by a method that will be presented later. At the end of the total irrigation time surface storage vanishes, adding either to the value of runoff or becoming soil water. Thus, evaluation of components during the irrigation process should include evaluation of the surface storage term. Evaluation of the total irrigation process need not include a separate term for surface storage.

The value of components during the irrigation process can be calculated by using Equation 3. For theoretical evaluation of the term $v_r$, the concept of four separate zones in the overland flow hydrograph will be used. First, however, certain assumptions must be made. These assumptions are:

1. The furrow channel is prismatic and has a mild slope.

2. The inflow at the upper end of the furrow is constant during the entire irrigation process.

3. The advance function can be described by the equation:

$$x = A \, t_a^B$$

4.  The infiltration rate is uniform across the top width of the furrow cross-section. The infiltration is known and is the same for the entire furrow length. The effect of water depth on infiltration is negligible.

The total volume of water infiltrated into the soil can be evaluated by using infiltration functions presented by Israelson and Hansen (16):

$$i = K t_o^N \tag{9}$$

and

$$i = K t_o^N + I_C \tag{10}$$

where $i$ = infiltration rate, in inches per hour

   $t_o$ = opportunity time for infiltration, in minutes

   $K$ = an empirical constant

   $N$ = slope of the infiltration curve on log-log paper

   $I_C$ = the basic infiltration rate that will be approached if the irrigation period lasts long enough.

Equation 9 is used for short irrigation periods and Equation 10 is used for irrigation periods that last long enough for a constant infiltration rate to be established. For use in this analysis, Equation 10 will be used, but will be rewritten in the form of two equations. For time from the beginning of the irrigation until $T_E$, the time at which a constant infiltration rate is attained, the infiltration rate can be described by:

$$i = K t_o^N \tag{11}$$

For time $T_E$ to $T_C$, the infiltration rate is constant and can be expressed:

$$i = I_C \tag{12}$$

In order to evaluate the term $v_r$, the remaining terms of the continuity equation must be determined separately for each of the four zones.

Zone I:   $(0--T_L)$

In Zone I, Fig. 3, flow in the furrow channel is expressed by an advance equation.  Since flow in Zone I has not reached the end of the furrow, $v_r = 0$. The volume of inflow equals surface storage plus infiltration.

The depth of water that will have infiltrated into a small unit length ($\Delta x$) of the furrow after an opportunity time $t_o$, is given by integrating Equation 11 between the limits 0 and $t_o$:

$$d_i = {}_0\int^{t_o} i \; dt_o = {}_0\int^{t_o} Kt_o{}^N \; dt_o = \frac{K}{N+1} t_o{}^{N+1} \tag{13}$$

The opportunity time for infiltration at a given section of furrow x, whose advance time is $t_a$, and at a given time t, is given by:

$$t_o = t - t_a \tag{14}$$

The total volume of water infiltrated in the furrow at a given time t is expressed by integrating the depth of infiltrated water from furrow length 0 to x and multiplying by the furrow spacing W:

$$v_i = W \int_0^x \frac{K}{12(N+1)} (t-t_a)^{N+1} \; dx \tag{15}$$

If the advance function is described by the equation, $x = A \, t_a{}^B$, then, solving for $t_a$:

$$t_a = (x/A)^{1/B} \tag{16}$$

Substitution of Equation 16 into Equation 15 yields:

$$v_i = W \int_0^x \frac{K}{12(N+1)} [t-(x/A)^{1/B}]^{N+1} \; dx \tag{17}$$

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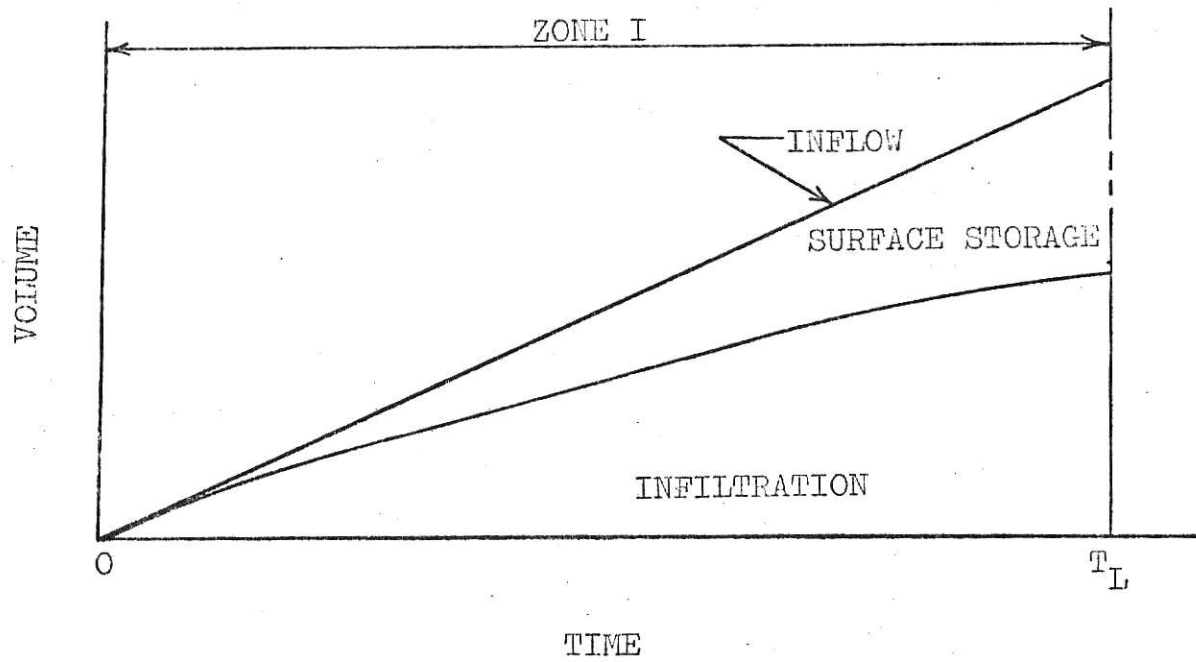


Figure 3.  Mass Flow Hydrograph for Zone I
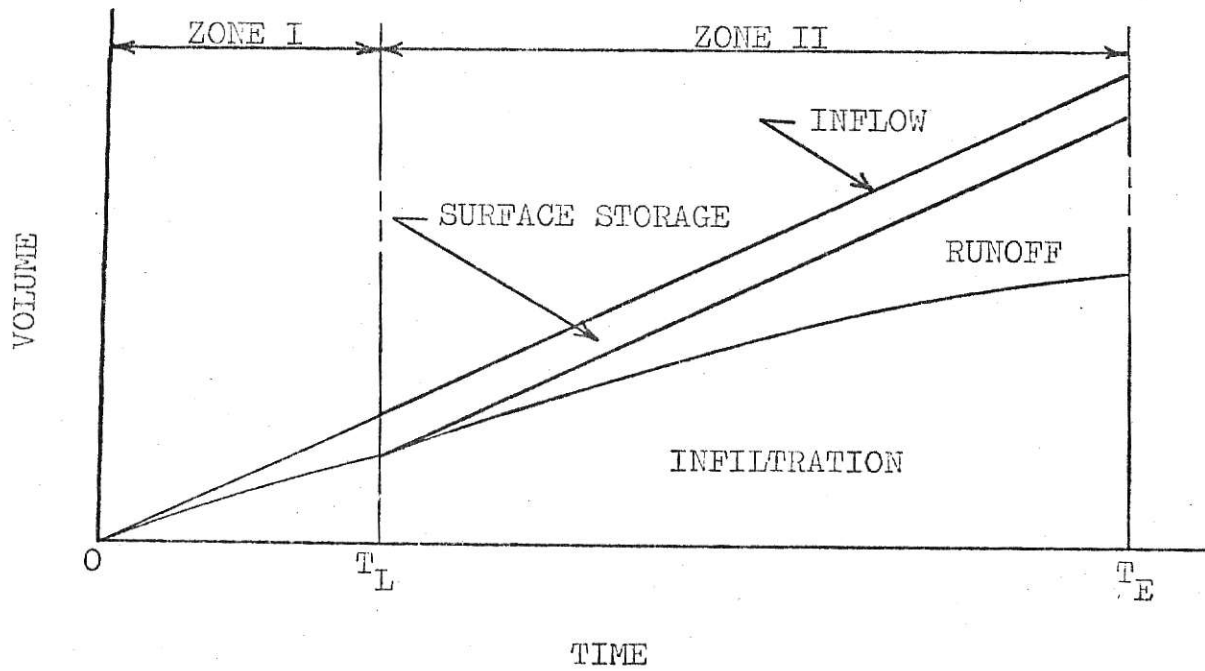


Figure 4.  Mass Flow Hydrograph for Zones I and II

Wu (9) has shown that since $t_a$ is smaller than t except at the tip of the water front, Equation 17 can be expanded by binomial expansion:

$$v_i = W \int_0^x \frac{K}{12(N+1)} [t^{N+1} - (N+1)(x/A)^{1/B} t^N \ldots] \, dx \qquad (18)$$

Using the first two terms as a close approximation and integrating from 0 to x, upon rearranging, Equation 18 becomes:

$$v_i = \frac{WKx}{12(N+1)} t^{N+1} - \frac{WKxt_a^B}{12(B+1)} t^N \qquad (19)$$

In Zone I, the advance time is the same as the irrigation time. Equation 19 can be written:

$$v_i = \frac{WKx}{12(N+1)} t^{N+1} \frac{[1 - B(N+1)]}{B+1} \qquad (20)$$

Since the absolute value of N is always between 0 and 1, and N is always a negative quantity, the value of the term $1 - B(N+1)/B+1$ can be shown to be positive and less than one. This is based on fact that the value of B can be calculated by the Equation (11):

$$B = e^{-0.6(N+1)} \qquad (21)$$

For simplification, let the term $1 - B(N+1)/B+1$ equal $C_1$. Since W and K are also constants and are positive, the term $WK/12(N+1)$ can be represented by a constant called $C_2$. Equation 20 can then be written:

$$v_i = C_1 C_2 x \, t^{N+1} \qquad (22)$$

or if $C_1 C_2 = C_3$:

$$v_i = xC_3 \, t^{N+1} \qquad (23)$$

The term N+1 is always less than one but greater than zero. Since, in

Zone I, $v_r = 0$, $v_s = v_e - v_i$. If x in Equation 23 is the distance from the tip of the water front to the head end of the furrow at time t, the value of $v_s$ at that time can be represented, as in Fig. 3, by the difference between the inflow curve and the infiltration curve. It can be seen that the volume of water stored on the surface in Zone I varies as a function of time.

## Zone II:  $(T_L--T_E)$

In Zone II, inflow equals surface storage plus infiltration plus runoff. At time $T_L$, the time at which flow reaches the end of the furrow, $V_S \simeq V_E - V_I$. Although $v_s$ in Zone II is still a function of time, change in the value of the total surface storage volume is small and therefore can be considered constant. The assumption that $v_s$ after time $T_L$ can be considered constant can be deduced from work done by other investigators (2, 17). For the purposes of this study, $v_s$ in Zone II will be considered constant and equal to the value of $V_E - V_I$ at time $T_L$.

In Zone II, the entire furrow length L is covered with water, but the infiltration intensity varies at each point along the furrow section. Since L is a fixed length and t is greater than $T_L$, the total volume of water infiltrated at time t can be obtained from Equation 19 by substitution of L and $T_L$ for x and $t_a$:

$$v_i = \frac{WKL}{12(N+1)} \, t^{N+1} - \frac{WKLT_L^B}{12(B+1)} \, t^N \tag{24}$$

where L  = the total length of the furrow, in feet

$T_L$ = the time required to wet the total furrow length, in minutes

In order to find the volume of runoff in Zone II, Equation 3 can be written:

$$v_r = v_e - v_i - v_s \tag{25}$$

As in Zone I, $v_e$ at time t can be expressed by a constant inflow rate Q, times the elapsed irrigation time t.

Recalling that $v_s$ in Zone II is considered a constant and equal to $V_E$ - $V_I$ at time $T_L$, Equation 25 can be rewritten:

$$v_r = Qt - C_4 t^{N+1} + C_5 t^N - V_S \tag{26}$$

where $C_4$ = WKL/12(N+1)

$C_5$ = $WKLT_L B/12(B+1)$

Equation 26 is shown graphically in Fig. 4.

Since N is always between 0 and -1, the term $Qt + C_3 t^N - V_S$ increases more rapidly than does the term $C_4 t^{N+1}$. This indicates that the volume of runoff increases at an increasing rate as time increases. If time after $T_L$ is designated $t_r$ for runoff time, and since $V_R = 0$ at time $T_L$, the volume of runoff can be expressed by an equation of the form:

$$v_r = C_6 t_r^M \tag{27}$$

where $C_6$ = a constant

$t_r$ = runoff time, in minutes

M   = an exponent.

The value of M is greater than zero due to the increase in runoff volume as runoff time increases. $C_6$ is greater than zero due to the fact that, at any time greater than $t_r$ = 0, the volume of runoff is greater than zero.

If Equation 27 is differentiated with respect to $t_r$, instantaneous runoff rates can be determined:

$$r = \frac{d(v_r)}{dt_r} = \frac{d(C_6 t_r^{M})}{dt_r} = \frac{C_6 t^{M-1}}{m-1} \qquad (28)$$

Equation 28 can be rewritten:

$$r = Rt_r^{S} \qquad (29)$$

where $R = C_6/M-1$

$S = M-1$

Figure 1 shows that the runoff rate in Zone II is always increasing. This dictates that S be greater than zero and thus, the value of M must be greater than one.   Likewise, R must be greater than zero.

## Zone III:   $(T_E--T_C)$

At time $T_E$, infiltration along the entire furrow section is constant. Surface storage during Zone III is in fact constant, and at a maximum, due to the constant and minimum infiltration rate along the entire furrow section. The increment of total infiltration, $\Delta v_i$, can be expressed as $\Delta v_i = WLI_c \Delta t$ since the infiltration rate is constant and equal to $I_c$.   Since both the infiltration rate and the inflow rate are constant and the surface storage is constant, the runoff rate must also be constant.   If the constant runoff rate in Zone III is denoted as $R_E$, the total accumulated volume of runoff from time $T_E$ to $T_C$ can be expressed as:

$$V_R = \int_{T_E}^{T_C} R_E \, dt = R_E(T_C - T_E) \qquad (30)$$

This can be shown graphically as in Fig. 5.
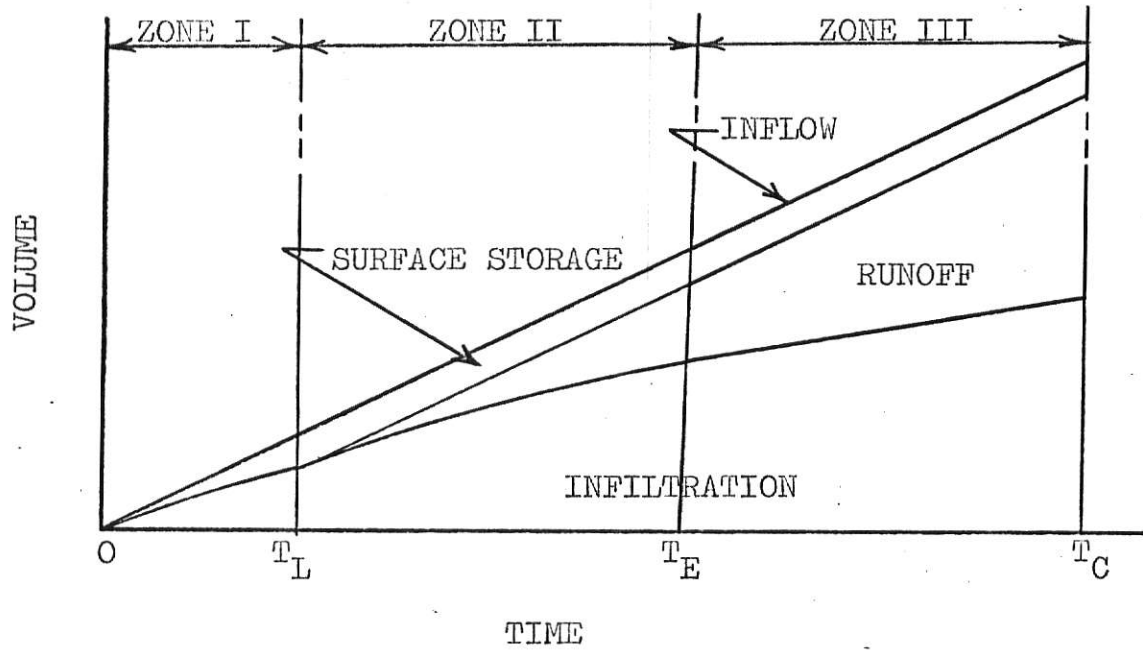
Figure 5.   Mass Flow Hydrograph for Zones I, II, and III
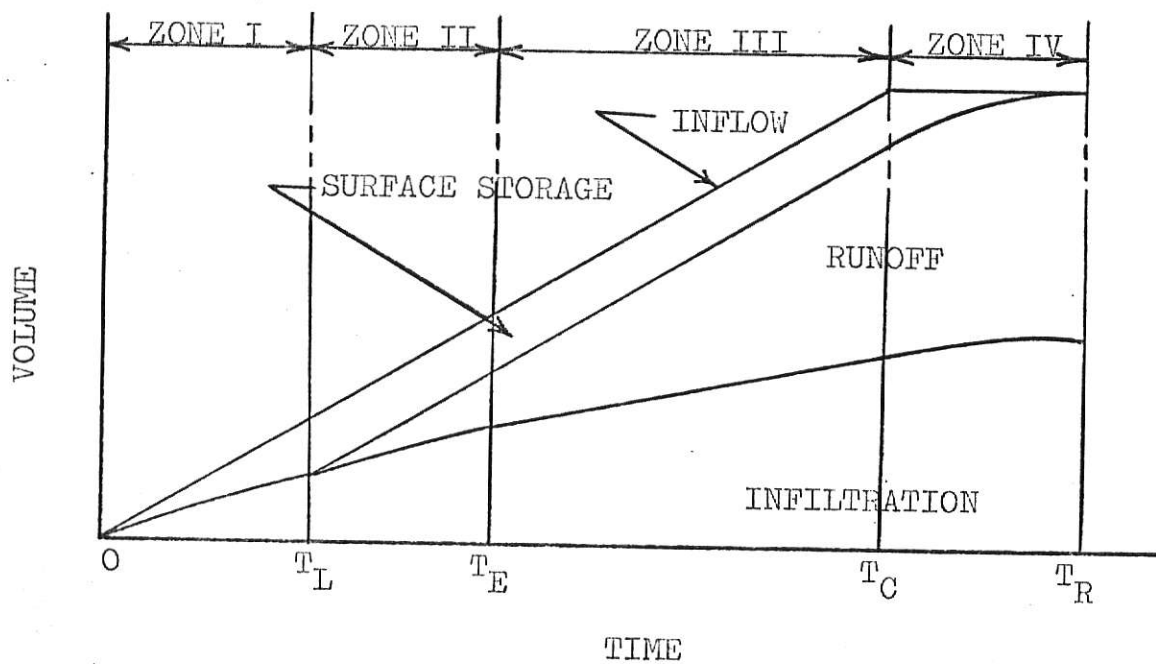


Figure 6.   Mass Flow Hydrograph for Zones I, II, III, and IV

Zone IV:   $(T_C - T_R)$

The increment of total infiltration, $\Delta v_i$, can be expressed as $\Delta v_i = c_r WLI_C \Delta t$, where $c_r$ is a coefficient with a value less than one that varies with time due to reduction of the wetted perimeter of flow during recession flow.  Since the infiltration rate is constant and equal to the infiltration rate in Zone III, and inflow is zero, the total accumulated volume of runoff from time $T_C$ to $T_R$ can be expressed as:

$$V_R = V_S - WLI_C \int_{T_C}^{T_R} c_r dt \tag{31}$$

where $V_S$ is the volume of surface storage in Zone III.

The volume of runoff from recession flow is small compared to the volume of runoff from Zones II and III (except for short total irrigation time).  The evaluation of $c_r$ is dependent on recession flow and was not within the scope of this study.  For these reasons, the volume of runoff from Zone IV will not be considered in this analysis and will not be further discussed.

Over the irrigation period, except for Zone IV, the volume of runoff can be described by the equations:

$$v_r = \frac{R \, t_r^{S+1}}{S+1} \tag{32}$$

for time from $t_r = 0$ to $t_r = T_{ER}$, and by:

$$v_r = \frac{RT_{ER}^{S+1}}{S+1} + R_E(t_r - T_{ER}) \tag{33}$$

for time $t_r = 0$ to $t_r = T_{CR}$.

$T_{ER}$ is the equilibrium time expressed in terms of runoff time; in

minutes, $T_{CR}$ is the inflow termination time expressed in runoff time.

Runoff rates during the irrigation period, except for Zone IV, can be described by Equation 29 for time $t_r = 0$ to $t_r = T_{ER}$, and by:

$$r = R_E \tag{34}$$

for time from $t_r = T_{ER}$ to $t_r = T_{CR}$.

INVESTIGATION

Equipment and Procedure

This study was comprised of two basic parts. The first part consisted of determining a relationship between runoff rate and time. To determine this relationship, it was necessary to gather detailed runoff data from selected plots. For the purpose of this study, the term "furrow" will designate an individual furrow. The term "plot" will be used to designate one or more furrows channeled into a single orifice plate. The second part of the study consisted of determining the amount of water that had been put on individual plots during an irrigation. Individual plot intake characteristics were also studied. To accomplish these objectives, it was necessary to obtain inflow and runoff data for all of the plots in the field.

The experiment field was located on the property of Pratt Feedlot Inc., at Pratt, Kansas. The field consisted of six plot series, with each series containing ten plots. Soil in the plots was determined to be of the Naron-Farnum Association (18) with a basic intake rate of 0.10 inches per hour. All six series were planted to corn with a furrow spacing of 30 inches. Furrow length on the first series ranged from 197 feet to 365 feet. Furrow length for the other series was 203 feet. Slope on all the series was less than 0.5 percent. A layout of the field is shown in Fig. 7.

Water was delivered to the furrows by gated pipe. A gate valve and a standpipe were located at the entrance of each gated pipe lateral. Inflow into each lateral was regulated by adjustment of the gate valve to maintain a
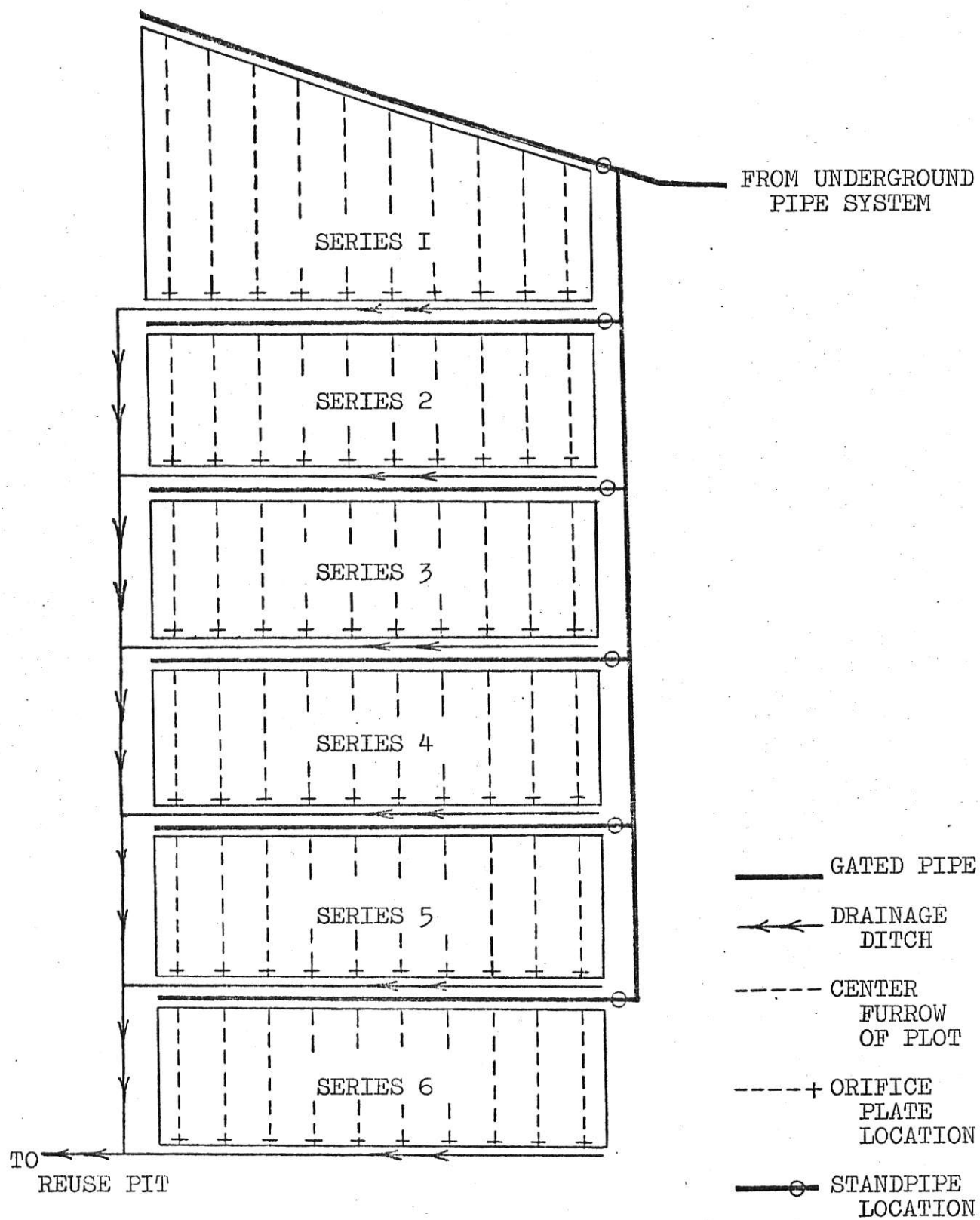
Figure 7. Layout of Experiment Field and Irrigation System

predetermined head in the standpipe. Gate settings were made prior to the start of the irrigation to deliver a predetermined inflow rate to each furrow.

Determination of inflow rates was made by using the orifice equation. First, the orifice equation was used to calculate a calibration coefficient for each gate on the gated lateral used during the irrigation. This calibration coefficient was then used in the orifice equation to calculate inflow rates for individual furrows.

For determination of the calibration coefficients, the time required to fill a one gallon container with water from the gate in question was measured. The head in the standpipe for the lateral on which the gate was located was also measured. These measurements were taken, in most cases, at least twice during the irrigation period. The value of the calibration coefficient was determined by the equation (19):

$$c_g = q/\sqrt{2Gh_g} \tag{35}$$

where $c_g$ = calibration coefficient considering both orifice edge roughness and orifice area

   $q$ = inflow rate, in gallons per minute, determined by dividing one by the time in minutes required to fill the one gallon container

   $G$ = force of gravity, 32.2 feet per second squared

   $h_g$ = head in the standpipe, in feet, measured from the center of the gated pipe lateral to the water level in the standpipe.

An average calibration coefficient was calculated if more than one set of calibration measurements were taken.

Standpipe head readings were measured at intervals during the entire irrigation process. Using the calculated average value for $c_g$, it was pos-

sible to calculate inflow rates throughout the irrigation period by again using the orifice equation and solving for q.

Runoff rates were measured in two different ways. The first consisted of using an orifice plate. The orifice plate, as shown in Fig. 8, was made from a one foot by three foot sheet of 16 gauge sheet metal. A one-inch diameter hole was drilled 0.62 feet from the top and centered on the plate. A slot, two inches deep and three inches long, centered over the orifice, was removed from the top edge of the plate. This was to provide an extra outlet in event of rainfall or if runoff exceeded the capacity of the orifice. This was a measure to keep the orifice plate from being washed out.

The orifice plate was driven into the ground so that it stood vertically at the lower end of the center furrow of the plot. It was driven into the ground until the one-inch hole was 0.2 feet from the bottom of the furrow channel. Dikes were built on the flanks of the orifice plates. The furrow section behind the plate was maintained in original condition as much as possible except for cuts in the furrow walls which were used to channel runoff water from more than one furrow into the orifice plate. During the irrigations, either one, three, four, or five furrows were channeled into one orifice plate. A drainage ditch was placed below the orifice plates which carried the runoff water from the area so that the orifices could flow unsubmerged. The layout for this method is shown in Fig. 9.

When using the orifice plates, runoff rates were determined by one of two methods. One method involved measuring the length of time required to fill a one gallon container with runoff water flowing through the orifice. This was considered to be an accurate method for determining runoff rates, and was used to obtain the detailed runoff data from selected plots.
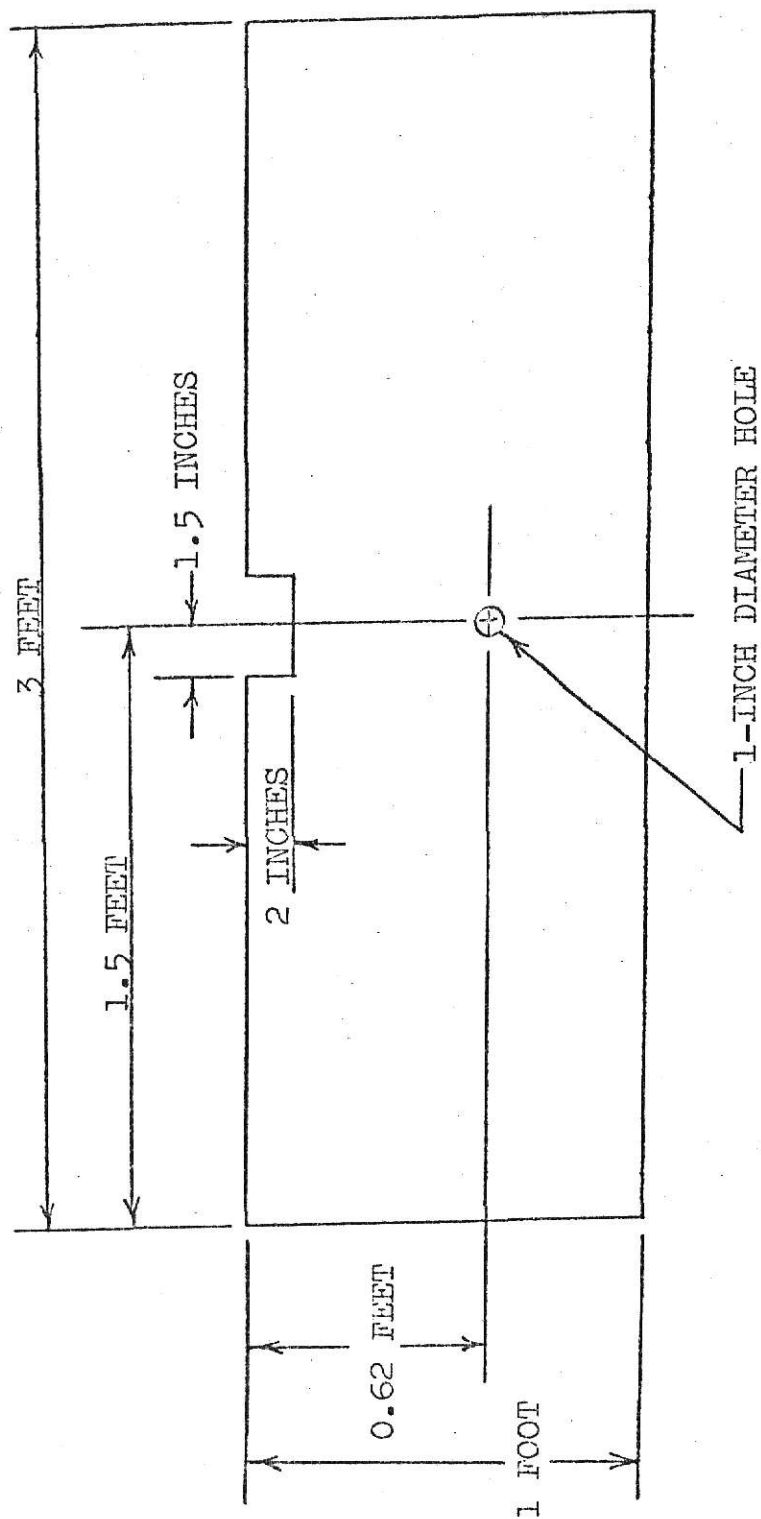
Figure 8. Orifice Plate Construction
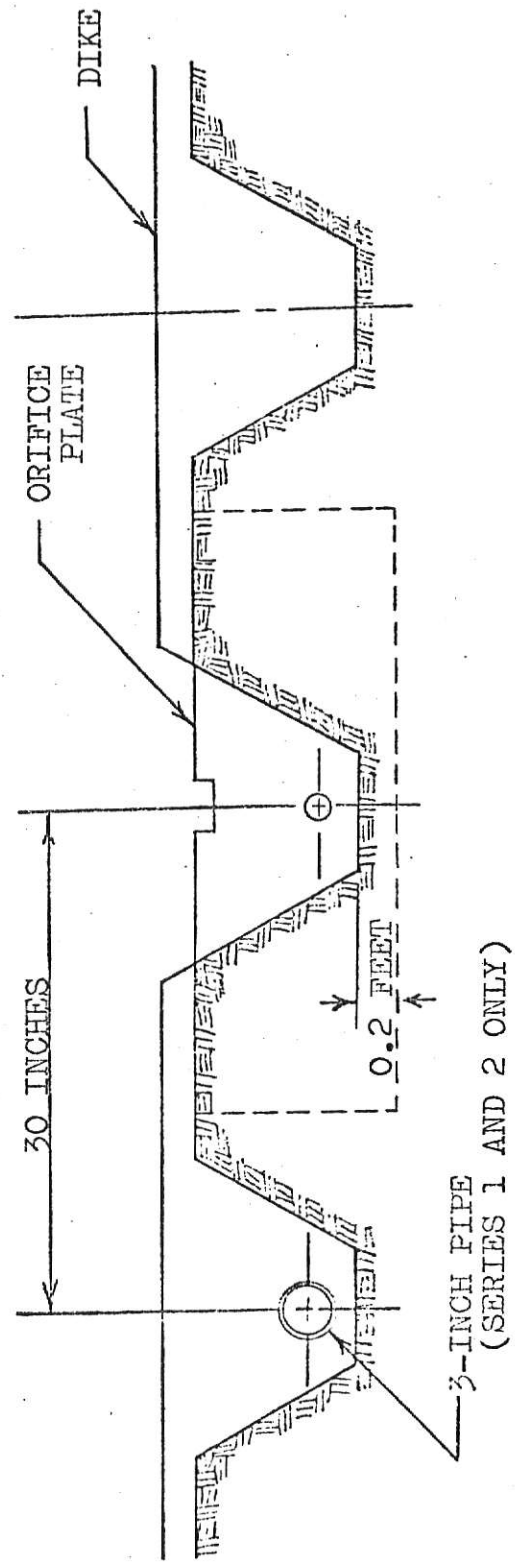
Figure 9. Typical Orifice Plate Installation as Viewed from Head End of Plot

The second method of measuring runoff rates with the orifice plates required measuring the distance from the top of the orifice plate to the water level behind the orifice plate. This measurement was later converted to a head measurement. Using the equation for flow through an orifice the runoff rate for a given head was determined (19):

$$q = c_o A_o \sqrt{2Gh_o} \ / \ 0.002228 \tag{36}$$

where $c_o$ = orifice coefficient

$A_o$ = orifice area, in square feet

$h_o$ = head on the orifice, measured from the center of the orifice, in feet.

The value of $c_o$ was determined in the laboratory after the irrigations were completed by subjecting the orifice to given heads and measuring the resultant outflow. Since the heads were small compared to the size of the orifice, the value of $c_o$ was not constant. When subjected to linear analysis, it was found that $c_o$ could be represented by an equation in which the value of $c_o$ varied as a function of the head. Each orifice plate was individually calibrated and an orifice calibration equation determined for each.

When water first flows through the orifice and until the head is above the top edge of the orifice, flow will not be orifice flow but will be weir flow. For weir flow, the flow rate can be determined by the equation (19):

$$q = c_w a_w \sqrt{2Gh_w} \ / \ 0.002228 \tag{37}$$

where $c_w$ = weir coefficient

$a_w$ = weir area, in square feet

$h_w$ = weir head, measured from the bottom of the orifice, in feet.

The value of $c_w$ was determined in the laboratory for various heads and was found not to be a constant. When subjected to linear analysis, $c_w$ was found to be an exponential function of the head measured from the bottom of the orifice. Each orifice plate was individually calibrated and a weir calibration equation determined for each plate.

Although drainage ditches were provided to allow free flow from the orifice plates, the drainage ditches for Series 5 and 6 did not perform so as to meet this requirement. During the latter part of the irrigations on these two series, water level in the drainage ditches remained sufficiently high as to cause some of the plots to flow as partially submerged and submerged orifice flow. Since partially submerged and submerged orifice flow were encountered, it was necessary to use different equations to calculate these types of flow. The times at which the water level began to remain high in the drainage ditches were sufficiently late in the irrigation periods so that no partially submerged weir flow measurements were encountered.

Submerged orifice flow can be calculated if the upper head behind the orifice plate and the lower head in front of the orifice plate have been measured. These values were measured and recorded during the course of irrigations where necessary. Submerged orifice flow was calculated by the equation (19):

$$q = c_o A_o \sqrt{2G(h_u - h_l)} \, / \, 0.002228 \tag{38}$$

where $c_o$ = orifice coefficient

$h_u$ = upper head, in feet

$h_l$ = lower head, in feet.

Partially submerged orifice flow can also be determined if the upper and lower heads are known. However, partially submerged orifice flow is made up

of two parts. Flow includes that from the part of the orifice above the lower head and that from the part of the orifice below the lower head. Flow from above the lower head can be calculated by the equation (19):

$$q_1 = c_o a_1 \sqrt{2G(h_u - h_1)} \; / \; 0.002228 \qquad (39)$$

where $q_1$ = flow rate from the part of the orifice above the lower head, in

gallons per minute,

$a_1$ = only that orifice area above the lower head, in feet squared.

Flow from the portion of the orifice below the lower head acts as submerged orifice flow and can be calculated by the equation (19):

$$q_2 = c_o a_2 \sqrt{2G[(h_u - h_1) + h_d]/2} \; / \; 0.02228 \qquad (40)$$

where $q_2$ = flow rate from the portion of the orifice below the lower head,

in gallons per minute

$a_2$ = only that orifice area below the lower head, in feet squared

$h_d$ = distance from the upper water level to the top edge of the

orifice, in feet.

Total flow rate from a partially submerged orifice then can be calculated by adding the flow from both portions:

$$q = q_1 + q_2 \qquad (41)$$

The second method used to measure runoff rates was a supplement to the orifice plates. In series 1 and 2, the runoff rate frequently exceeded the capacity of the orifice to discharge water. Therefore, a three inch pipe was inserted through the dike on one flank of the orifice plate. This pipe was plugged until the maximum capacity of the orifice was nearly exceeded. From that time and until the end of the irrigation, runoff readings were taken by

measuring the length of time required to fill a 2.54 gallon container with water flowing through the pipe.

Data from plots used for detailed runoff rate analysis were obtained from two different irrigations. Plots used for detailed analysis were chosen by their performance during previous irrigations. That is, from previous irrigations, it was known that certain plots maintained flow down the furrow channels without losing any water to, or gaining any water from, furrows next to them. This is a necessary consideration if an accurate water balance is to be maintained and accurate runoff readings are to be obtained. The test plots represented three different types of runoff conditions. Among conditions represented were: runoff from a single furrow, runoff from more than one furrow whose advance times were nearly equal, and runoff from more than one furrow whose advance times were not equal but were not drastically different. The plots used, together with irrigation number, irrigation date, average inflow, furrow length, runoff condition, and number of furrows channeled into each plate are shown in TABLE 1.

Initial runoff time was observed and recorded for the plots used for detailed analysis. Runoff readings were, in general, taken every 5 minutes for the first half hour of runoff, every 10 minutes for the second half hour, every 15 minutes for the next hour, every 30 minutes for the next two hours, and every hour for the next two hours. After that, and until inflow was terminated, runoff readings were taken at random times during the day.

For the remaining plots, those not selected for detailed analysis, initial runoff time was not always observed and recorded. Runoff readings were obtained by taking head readings on the orifice plates and by the pipe flow method (Series 1 and 2). Readings were taken at random intervals over

TABLE 1

PERTINENT INFORMATION FROM THE SEVEN PLOTS

SELECTED FOR DETAILED RUNOFF ANALYSIS

| Plot | Irrigation date | Irrigation number | Furrow length | Average[a] inflow | Runoff[b] condition | Number furrows feeding orifice plate |
|------|-----------------|-------------------|---------------|-------------------|---------------------|--------------------------------------|
| E-11 | Nov 11, 1970 | 8 | 197 | 3.39 | A | one |
| E-34 | Nov 11, 1970 | 8 | 203 | 3.88 | A | one |
| M-11 | Aug 6, 1970 | 4 | 203 | 6.30 | B | three |
| M-15 | Aug 6, 1970 | 4 | 203 | 6.17 | C | three |
| M-18 | Aug 6, 1970 | 4 | 203 | 6.83 | B | three |
| M-22 | Aug 12, 1970 | 4 | 203 | 7.14 | C | three |
| M-24 | Aug 12, 1970 | 4 | 203 | 6.74 | C | three |

[a] Average inflow from all furrows feeding orifice plate

[b] A--Runoff from one furrow

B--Runoff from more than one furrow whose advance times are nearly equal

C--Runoff from more than one furrow whose advance times were not equal but were not drastically different

the course of the irrigation period. An average of seven readings was taken for each plot during each irrigation.

## Data Analysis and Results

The data obtained from the seven plots selected for detailed runoff analysis were plotted on rectilinear coordinate paper with elapsed irrigation time on the abscissa and runoff rate on the ordinate. Resulting graphs of the plots representative of the three runoff conditions, that is, runoff from one furrow, runoff from more than one furrow whose advance times were nearly equal, and runoff from more than one furrow whose advance times were not equal but were not drastically different, are shown in Fig. 10, 12, and 14. These graphs display the characteristics of the overland flow hydrograph as presented by Wu (9). Runoff started after a period of time, then gradually increased until a maximum runoff rate was attained. Runoff then maintained the maximum rate until inflow was terminated. The curves did not show a definite inflection point to indicate the equilibrium time, $T_E$; that is, the curves did not show a definite time of transition from Zone II to Zone III.

Data were then subjected to linear analysis in an attempt to formulize the relationship between runoff rate and some characteristic time. It was found that, for runoff rates and their corresponding elapsed runoff time in Zone II, a linear relationship existed between the logarithmic values of the rates and times. This relationship can be expressed as an equation of the form:

$$r = Rt_r^S \tag{42}$$

where r = runoff rate, in gallons per minute

R = value of the y intercept at $t_r$ equals one minute

Figure 10.   Runoff Curve Determined by Measured Runoff
Rates from Plot E-34
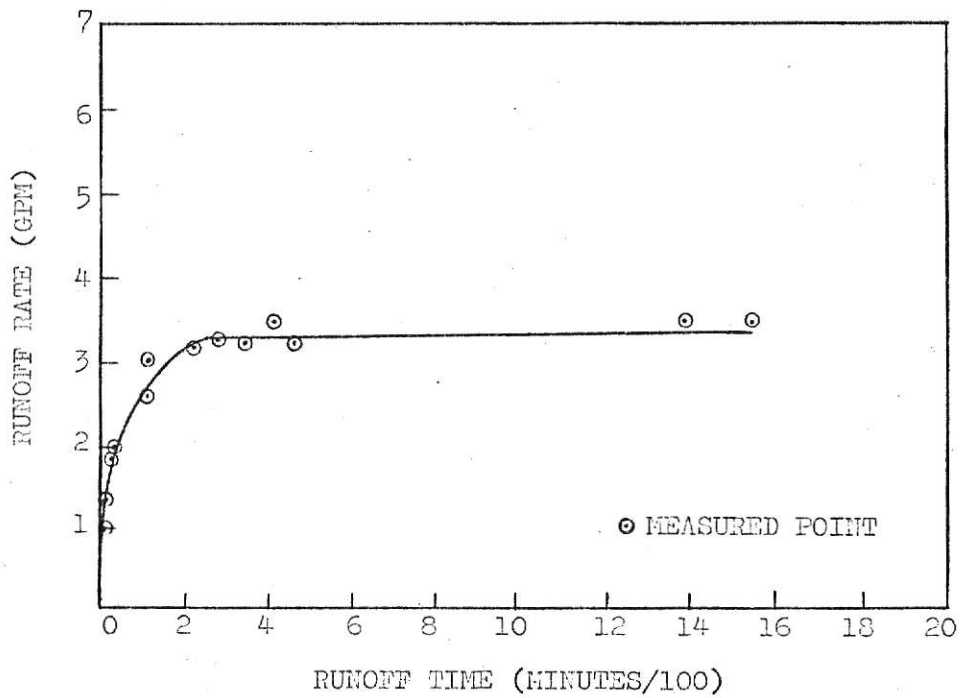


Figure 11.   Runoff Curve Determined by Empirical Equations
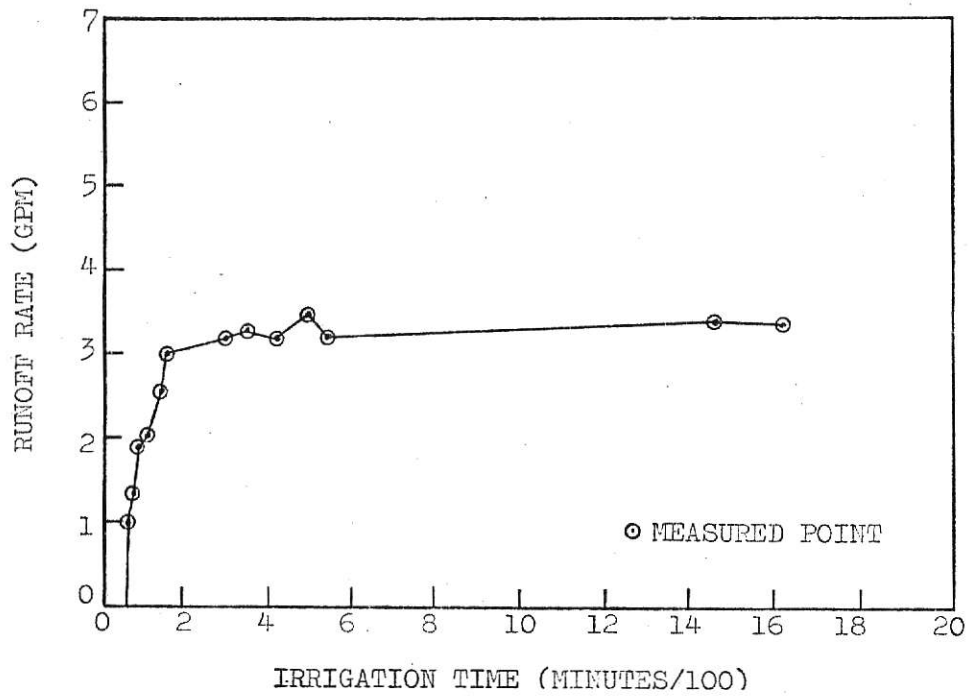for Plot E-34
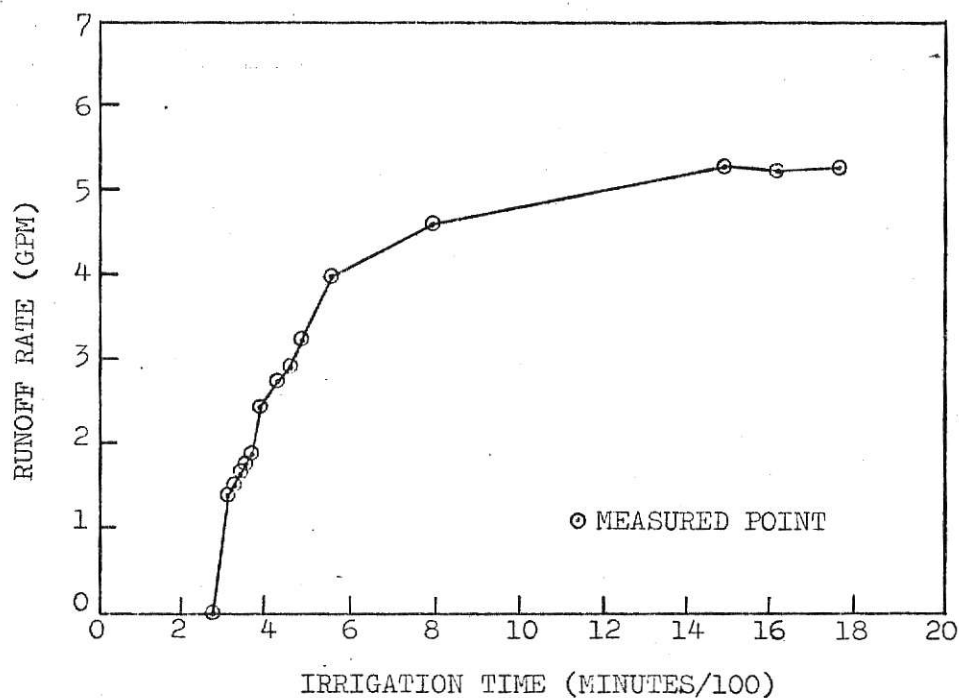
Figure 12. Runoff Curve Determined by Measured Runoff Rates from Plot M-18
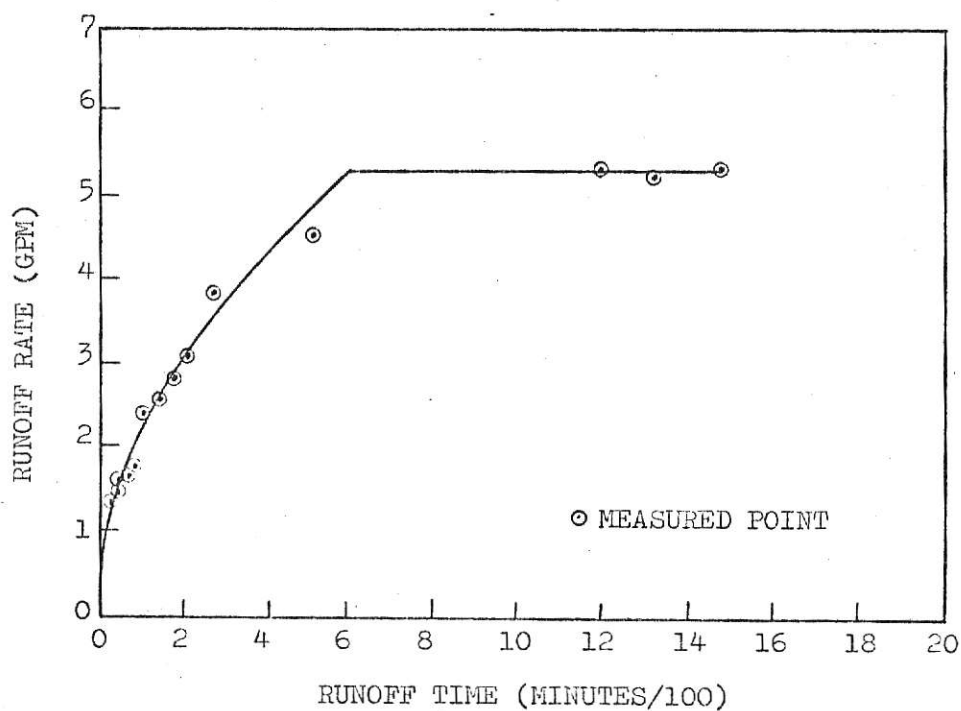


Figure 13. Runoff Curve Determined by Empirical Equations for Plot M-18
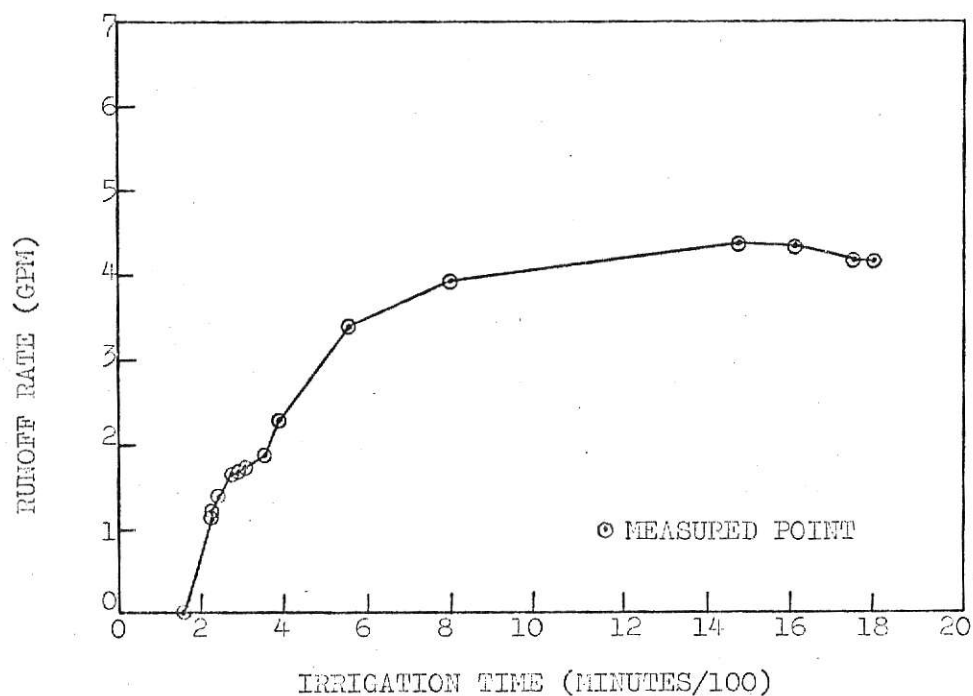
Figure 14.  Runoff Curve Determined by Measured Runoff
Rates from Plot M-15
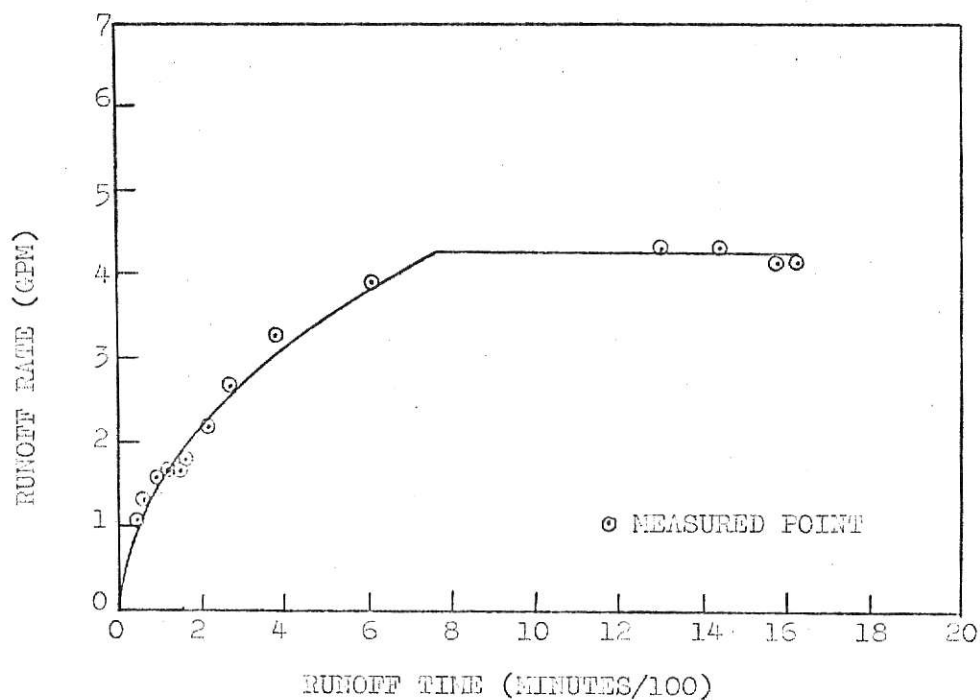


Figure 15.  Runoff Curve Determined by Empirical Equations
for Plot M-15

$t_r$ = elapsed runoff time, in minutes

$s$ = slope of the runoff rate curve if runoff rates and corres-
ponding times are plotted on log-log paper.

Using this relationship to characterize runoff rate as a function of runoff time, calculated correlation coefficients for the seven selected plots ranged from a low of 0.976 to a high of 0.996. From these calculated values of correlation coefficients it is suggested that an equation of the form, $r = Rt_r^S$, highly represents the relationship between runoff rate and corresponding elapsed runoff times for runoff occurring in Zone II.

When runoff values from Zone III were plotted with the runoff rates from Zone II on log-log paper, a horizontal line intercepting the line formed by the runoff rates from Zone II was formed. The point of intersection indicated the end of Zone II and the beginning of Zone III. By definition, the point representing the time at which the intersection occurred represents $T_{ER}$, the equilibrium time. Thus, the equation $r = Rt_r^S$ is bounded below by $t_r = 0$, and above by $t_r = T_{ER}$. Zone III can also be said to be bounded below by $T_{ER}$. This is in accordance with the concept of Wu (9). Runoff from the equilibrium time to the time inflow is terminated can be represented by Equation 34. Rectilinear coordinate graphs of measured values and values calculated by Equations 29 and 34 for the three representative plots are shown in Figs. 11, 13, and 15. Logarithmic graphs for the three plots are shown in Figs. 16, 17, and 18.

The accumulated runoff volume that has occurred from the start of runoff to some time in Zone II can be determined by integration of Equation 29 between the limits $t_r$ equal zero and the time in question:
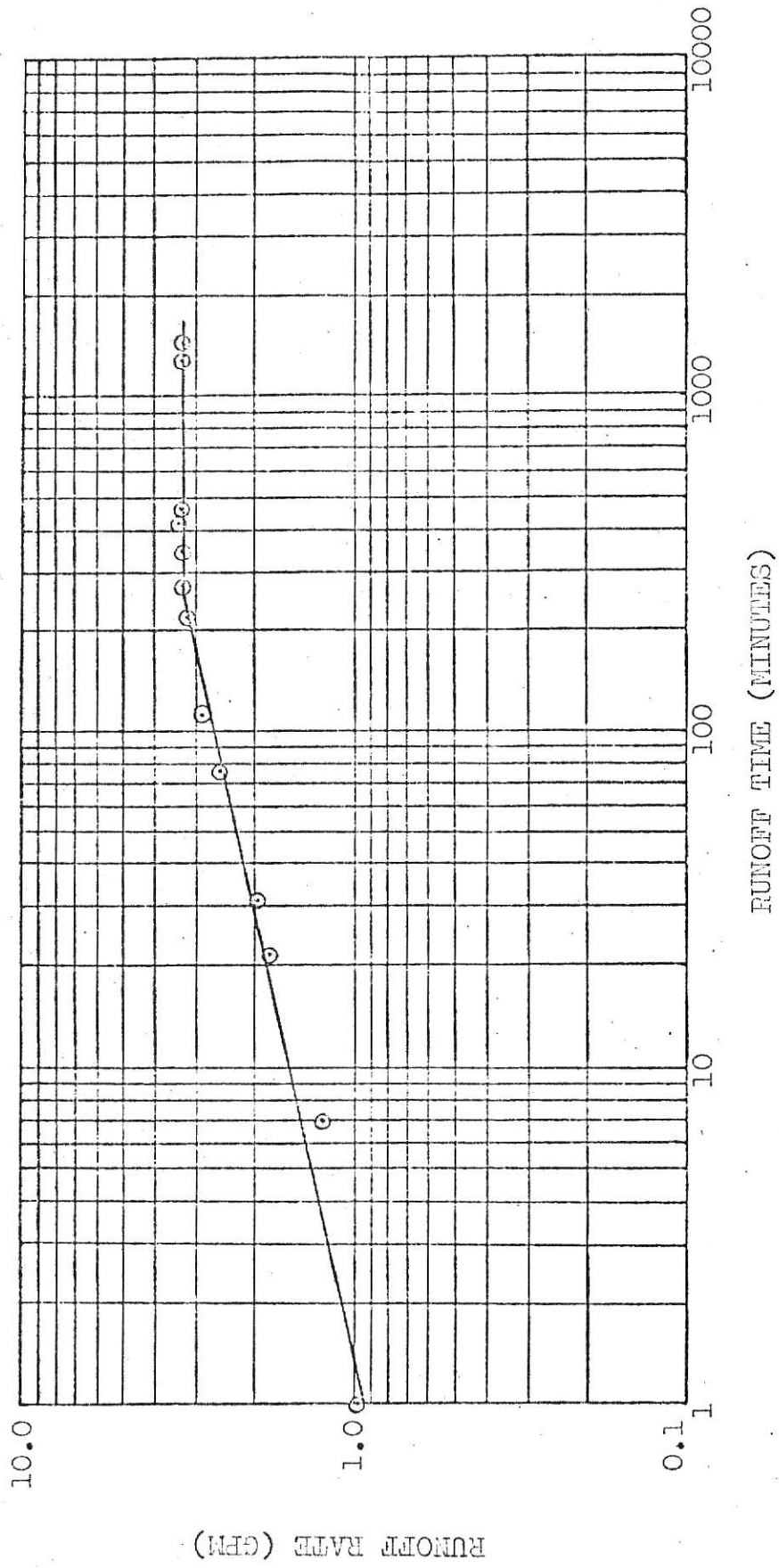
Figure 16.  Logarithmic Curve for Runoff from Plot E-34
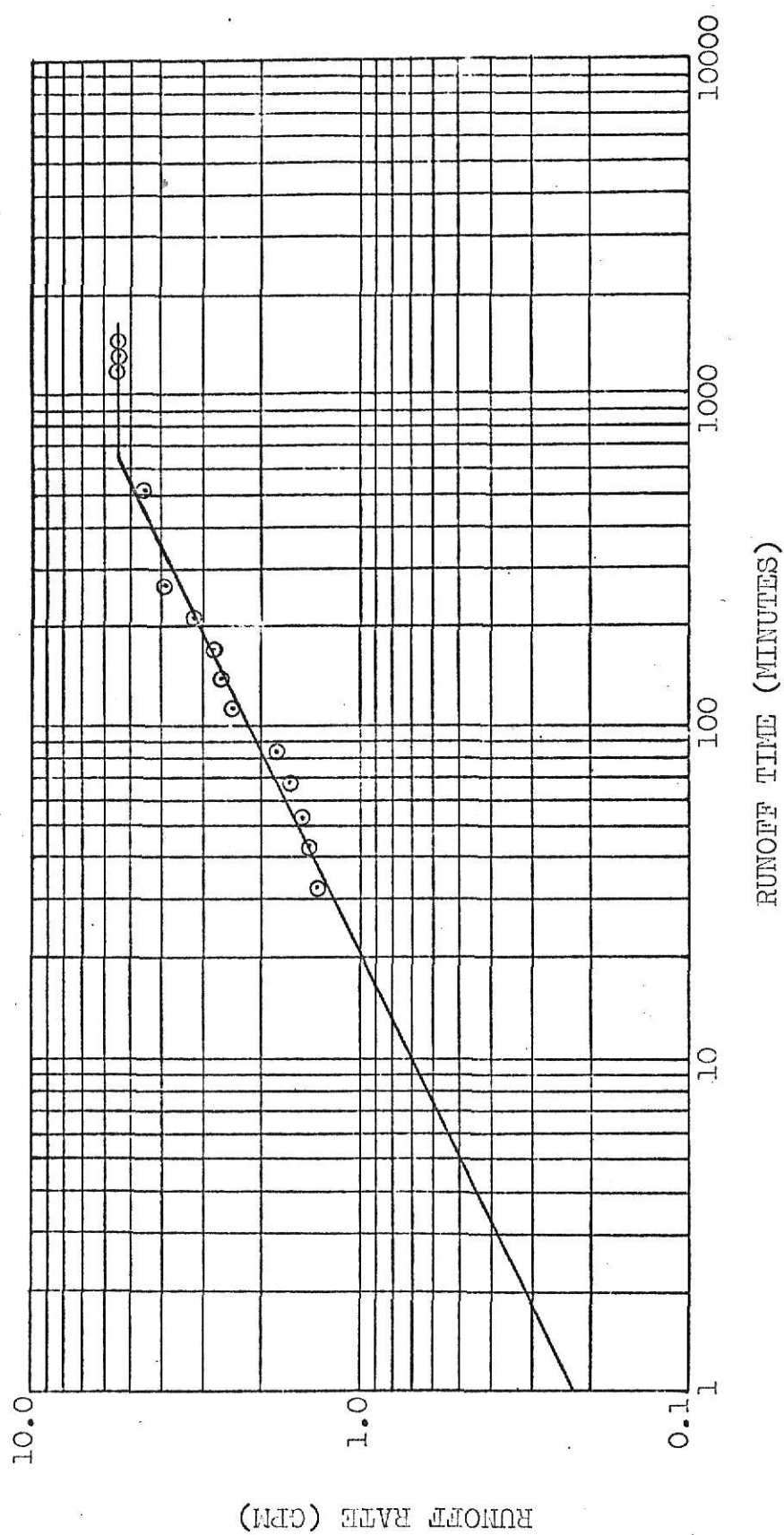
Figure 17. Logarithmic Curve for Runoff from Plot M-18
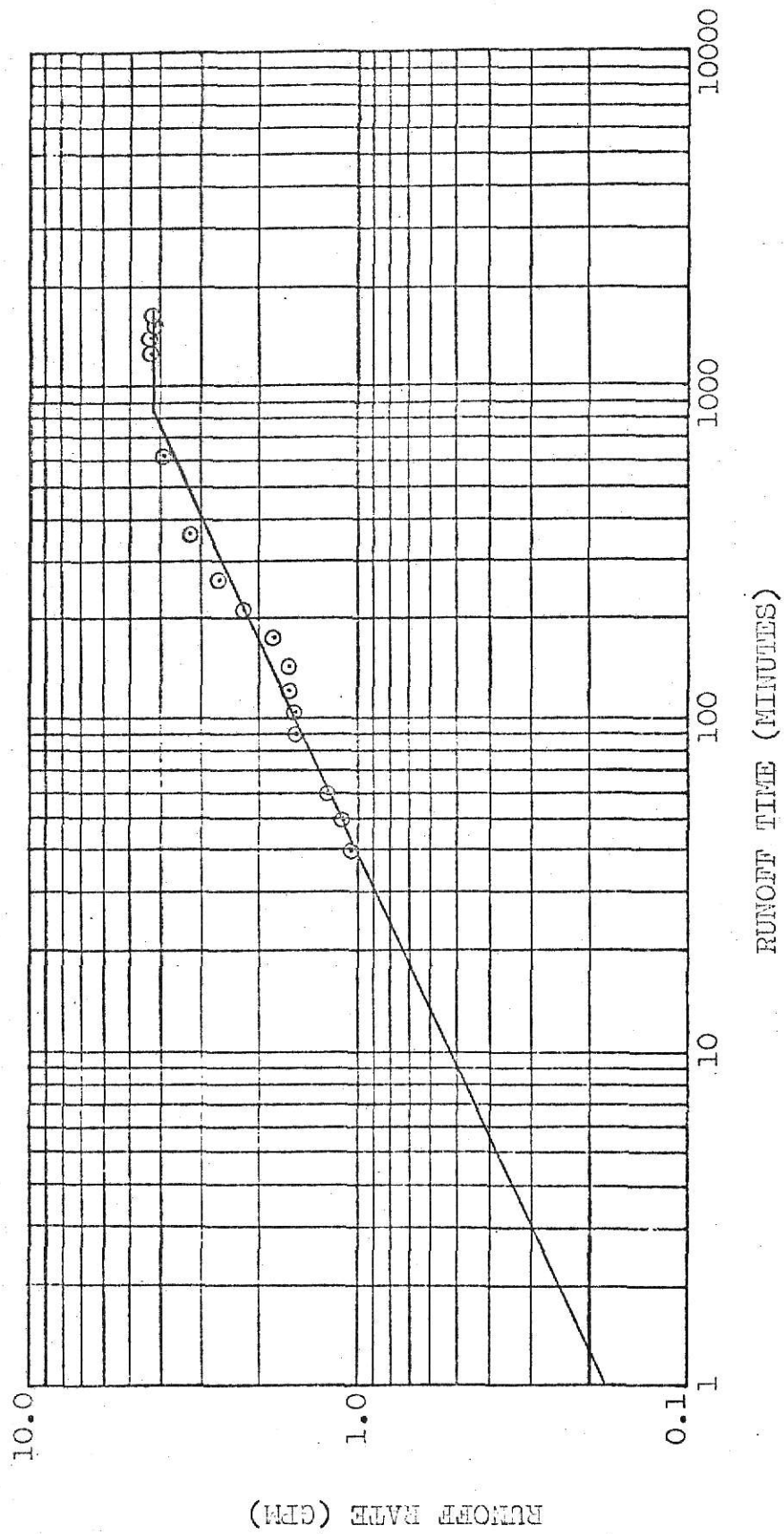
Figure 18. Logarithmic Curve for Runoff from Plot M-15

$$v_r = \int_0^{t_r} r\, dt_r = \int_0^{t_r} Rt_r^S\, dt_r = \frac{R}{S+1}\, t_r^{S+1} \tag{43}$$

Accumulated runoff volume from time $T_{ER}$ to a given time in Zone III can be determined by integrating Equation 34 between the limits $t_r = T_{ER}$ and the given time:

$$v_r = \int_{T_{ER}}^{t_r} R_E\, dt_r = R_E(t_r - T_{ER}) \tag{44}$$

Total accumulated runoff volume for runoff occurring from time $t_r = 0$ to some given time in Zone III can be determined by adding Equations 43 and 44, with the upper limit on Equation 43 set at $T_{ER}$. The runoff rate and volume equations for Zone II of the seven selected plots are shown in TABLE 2.

Equations determined by analysis of data from the seven selected plots and the equations developed from theory are of the same form. The values of S and R, determined by data analysis, are both greater than zero. This agrees with the values set forth by theory. Both theory and field investigation indicate that runoff from furrow irrigation can be characterized by empirical equations with runoff time as the independent variable.

Values of accumulated runoff volume realized at various times during the irrigation period were calculated for each plot using Equation 43 or 33 (depending on the value of $t_r$), and using the mean rate calculation method. Resulting volume curves of the three representative plots to time $t_r$ equals 1000 minutes are shown in Figs. 19, 20, and 21. Comparison of the values obtained by both methods showed close agreement for runoff occurring during Zone II. Values obtained for Zone III showed less agreement. The degree of

TABLE 2

RUNOFF EQUATIONS DETERMINED FOR THE SEVEN SELECTED PLOTS

| Plot | Runoff rate equation | Correlation coefficient | Runoff volume equation |
|---|---|---|---|
| E-11 | $r = 0.88\ t_r^{0.19}$ | 0.990 | $v_r = 0.74\ t_r^{1.19}$ |
| E-34 | $r = 0.94\ t_r^{0.22}$ | 0.984 | $v_r = 0.77\ t_r^{1.22}$ |
| M-11 | $r = 1.48\ t_r^{0.17}$ | 0.993 | $v_r = 1.26\ t_r^{1.17}$ |
| M-15 | $r = 0.17\ t_r^{0.49}$ | 0.979 | $v_r = 0.12\ t_r^{1.49}$ |
| M-18 | $r = 0.23\ t_r^{0.49}$ | 0.991 | $v_r = 0.16\ t_r^{1.49}$ |
| M-22 | $r = 0.22\ t_r^{0.51}$ | 0.976 | $v_r = 0.15\ t_r^{1.51}$ |
| M-24 | $r = 0.13\ t_r^{0.63}$ | 0.996 | $v_r = 0.08\ t_r^{1.63}$ |
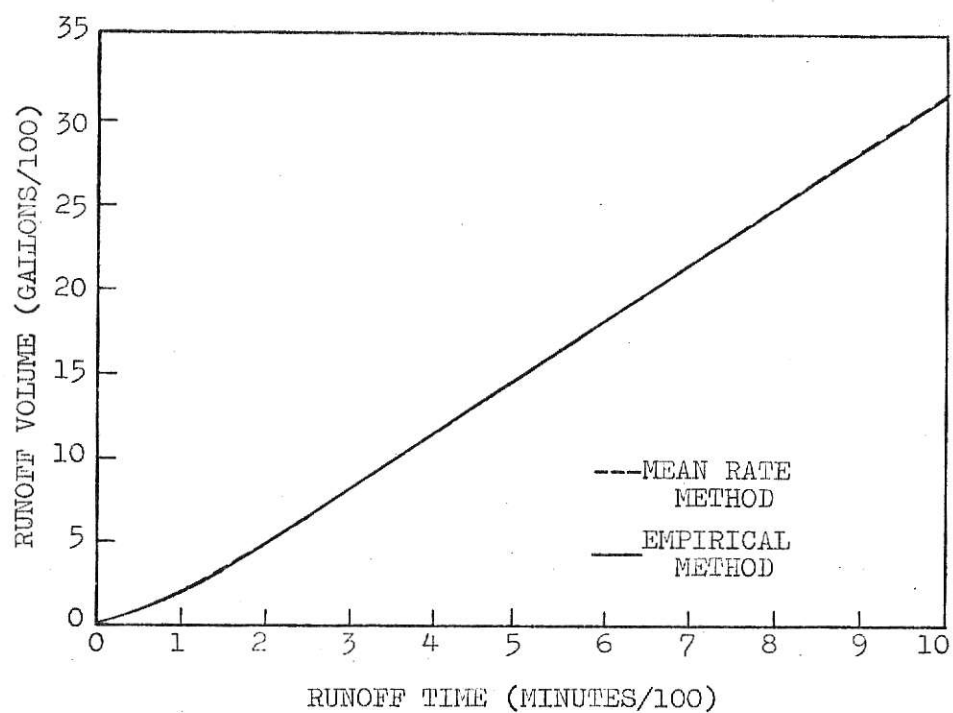
Figure 19. Volume of Runoff from Plot E-34
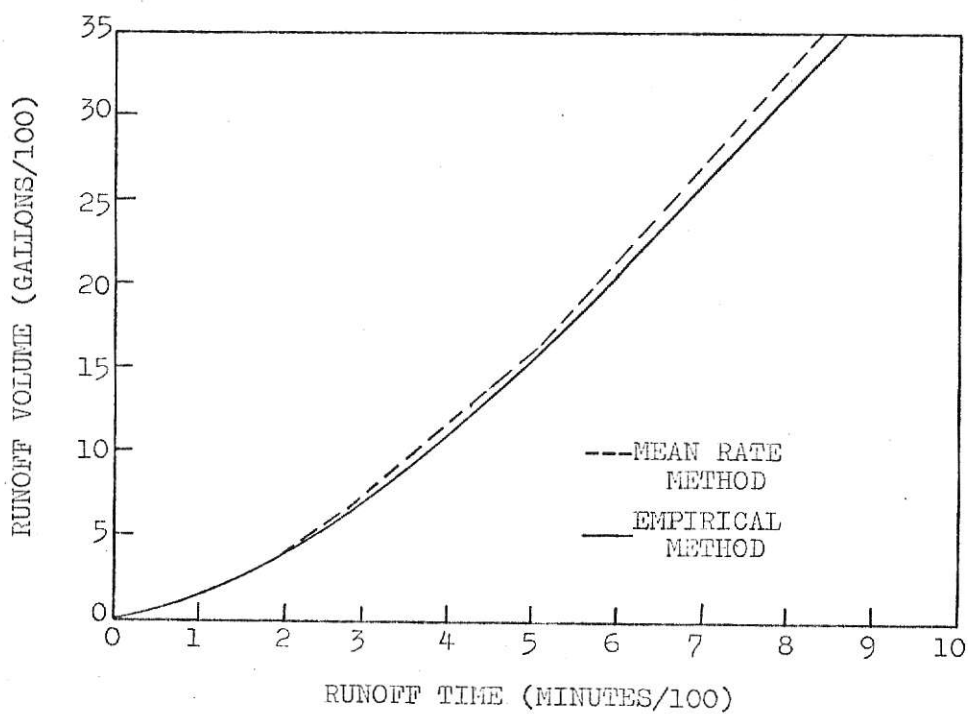


Figure 20. Volume of Runoff from Plot M-18
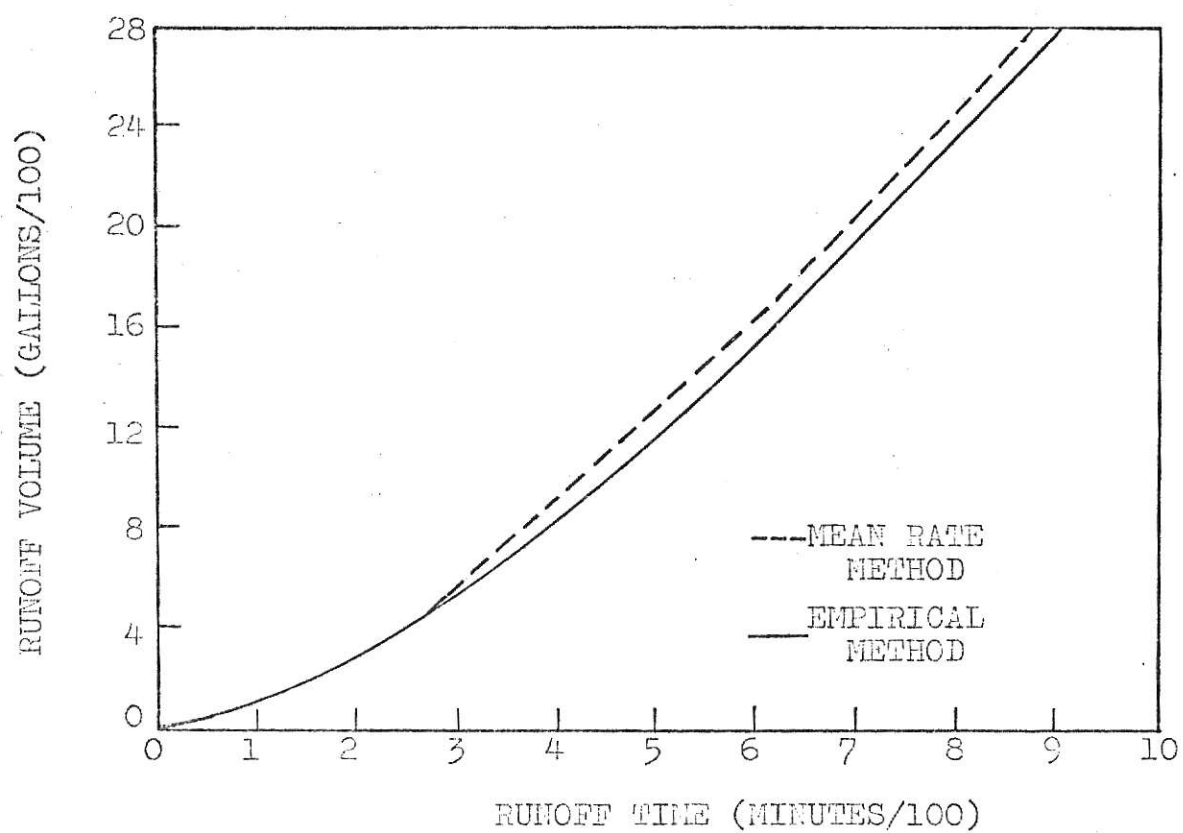
Figure 21. Volume of Runoff from Plot M-15

variation in calculated values varied from plot to plot. The degree of variation can be attributed to the method for determining the value of $R_E$ for each plot. $R_E$ was determined by taking the average of the measured runoff rates for times after a suspected constant runoff rate had been established. The term "constant runoff rate" would normally imply that all the measured runoff rates are equal. However, for field investigations, "constant runoff rate" will involve values that vary somewhat from the constant value line but still indicate a constant value trend. Corresponding runoff volumes calculated by the mean rate method were, by virtue of the method, weighted values. Time intervals are taken into account in calculating runoff volumes by the mean rate method, while they are not for the empirical equation method. A numerical comparison of the total accumulated runoff volume at the end of Zone II and at the end of Zone III for the seven plots calculated by both methods is shown in TABLE 3.

A study was conducted on the effect of the accuracy of the observed value of the runoff starting time on the runoff rate equations and resulting runoff volumes. Considering the observed starting times for the seven selected plots to be accurate and thus the resulting runoff equations to be accurate, runoff starting times were varied by one minute at a time to obtain starting times that were increasingly earlier, or later, than the original starting times. New runoff rate equations were calculated using the new starting times.

Basic results of the study indicated that the accuracy of the starting time is important in obtaining an accurate version of the runoff equation for Zone II. As the starting times became increasingly earlier, the value of R in the equation $r = R t_r^S$, decreased at a decreasing rate. The value of S

TABLE 3

COMPARISON OF RUNOFF VOLUMES CALCULATED BY THE EMPIRICAL
EQUATION METHOD AND BY THE MEAN RATE METHOD

| Plot | Runoff volume at time $T_{ER}$ (gallons) | | | Runoff volume at time $T_{CR}$ (gallons) | | |
|---|---|---|---|---|---|---|
| | Empirical equation method | Mean rate method | Difference | Empirical equation method | Mean rate method | Difference |
| E-11 | 1448 | 1447 | 1 | 3830 | 3794 | 36 |
| E-34 | 653 | 637 | 16 | 4327 | 4352 | 25 |
| M-11 | 1867 | 1886 | 19 | 7044 | 6319 | 725 |
| M-15 | 2164 | 2285 | 121 | 5819 | 5879 | 60 |
| M-18 | 2084 | 2060 | 24 | 7022 | 6798 | 224 |
| M-22 | 1527 | 1501 | 26 | 6950 | 6700 | 250 |
| M-24 | 1349 | 1332 | 17 | 7850 | 8642 | 792 |

increased as the starting times became earlier. The opposite effect was evident for starting times that were later than the original starting time. This indicated that the runoff rate curve became flatter as starting times went from early to late starting times.

Correlation coefficients generally remained high as the starting times were varied. The value of $T_{ER}$, the equilibrium time, was affected by variation of the starting time. The value of $T_{ER}$ increased at an increasing rate as the runoff starting time became later. The amount of the increase in $T_{ER}$ varied from plot to plot. The increase did signify, however, the importance of the value of the true runoff starting time in the determination of the value of $T_{ER}$.

For starting times earlier than the original starting time, the value of $T_{ER}$ increased less drastically as the runoff starting times became increasingly earlier. This would indicate that, on the basis of obtaining more correct values of $T_{ER}$, it would be advisable to judge runoff starting time early rather than late if it is necessary to estimate runoff starting time.

Runoff volumes were also calculated for varied starting times. The total accumulated volume of runoff from Zone II increased as the starting time increasingly became later, and likewise decreased as it increasingly became earlier. Similar to results given concerning $T_{ER}$, in order to obtain a more accurate value for $V_R$ for Zone II, if it is necessary to estimate runoff starting time, it would be better to judge early rather than late. Results indicated that in order to obtain the value of $V_R$ within 5 percent of the true value of $V_R$, starting time should be within 5 minutes of the true starting time. In order to obtain the value of $V_R$ within 10 percent of the true value

of $V_R$, estimated starting time should not be greater than 10 minutes later than the true starting time, but can be estimated 20 to 30 minutes earlier than the true starting time. These generalities are based only on the data obtained from the seven selected plots.

Total accumulated runoff volume from both Zone II and Zone III displayed a different characteristic than did the runoff volume from Zone II alone. Results indicated that a considerably larger error in starting time could be used and still obtain a reasonable result for $V_R$. Generally, a 30 minute error in estimating the runoff starting time resulted in less than 5 percent error in the value of $V_R$. This situation is due to the neutralizing effect of the value of $T_{ER}$, used in both parts of Equation 45, which is used to calculate the volume of runoff from both Zones II and III.

A computer program was written for use on the KSU IBM 360/50 Computer to analyze the inflow and runoff data obtained from the six series of the experiment field. A copy of the computer program is included in Appendix A. The computer program was made up of three basic parts. The first part computed the volume of runoff realized from each plot. The next part of the program computed inflow data for each plot. The final portion computed certain desired irrigation characteristics for each plot such as average depth of irrigation water applied and irrigation efficiency.

Specific runoff information was computed from runoff rate and time data gathered during the course of the irrigations. Runoff rate data included orifice plate head readings and volumetric runoff measurements. The equations needed for calculation of runoff rates using these types of data have been discussed earlier.

Since the time events occurred were based on the time of day, and

elapsed times were required for calculations, it was necessary to convert time of day to elapsed time in minutes based on a common starting time. Midnight of the morning of the day the irrigation was begun was used as the starting point. Irrigation starting and ending times and runoff starting times were computed from this starting point. Elapsed runoff times were calculated using runoff starting time as a basis.

If the runoff starting time had not been measured or recorded for a particular plot, as was the case for many of the plots, it was necessary to estimate this time. Since the irrigations lasted long enough for runoff rates to become constant, estimation of starting times should not have produced large errors in the calculated values of the volume of runoff realized for a plot. This judgment is based on the evidence provided by the study on the required accuracy of the runoff starting time presented earlier.

Runoff volume for each plot was calculated using the form of the empirical equations developed earlier. In order to determine the runoff equation for a given plot, it was necessary to have at least two, preferably three or more, runoff rate measurements from Zone II and at least one measurement from Zone III. A minimum of two readings from Zone II was necessary due to the necessity of two points being required to find the equation of a line that is known not to be horizontal or vertical. Using the equation determined by data analysis for runoff in Zone II and the value of the constant runoff rate for Zone III, it was then possible to solve for the value of $T_{ER}$. The volume of runoff from the entire irrigation for each plot was then calculated using Equation 33.

The computer program next computed the volume of inflow for each plot. Inflow rates were calculated using determined gate coefficients and standpipe

readings.

With both the total inflow and the total outflow known for each plot, it was then possible to calculate the infiltration volume realized from an irrigation. It was not necessary to evaluate the volume of surface storage as this portion of the analysis considered the entire irrigation process. It has been determined earlier that for analysis of characteristics involving the total irrigation process, surface storage adds either to the infiltration volume or becomes runoff and need not be considered as a separate term.

The basic intake rate of the soil was determined by subtracting the obtained value of $R_E$ from the average inflow rate of Zone III. This is possible due to the fact that surface storage is constant in Zone III, and any difference between inflow and runoff must be water that has been infiltrated into the soil.

With the aid of the computer, it was possible to find not only the total volume of infiltration and the basic intake rate of the soil, but also the average depth of irrigation water applied and the efficiency of the irrigation. This was possible using the continuity equation and a mathematical means for expressing runoff.

Besides evaluating specific characteristics of the irrigations, analysis of the data also provided an opportunity to check the ability to express runoff in the form of empirical equations developed from theory and analysis of the data from the seven selected plots. An empirical equation was developed to characterize the runoff from Zone II for each plot that sufficient data was available to do so. Four clear water irrigations and from zero to four irrigations using feedlot runoff effluent were carried out during the summer and fall of 1970. In total, 268 sets of inflow and runoff data were obtained.

Two hundred and twenty-three of the 268 sets contained sufficient data for computer analysis and development of a runoff equation. Sufficient data for analysis required at least two runoff readings in Zone II and at least one reading from Zone III. Of the 223 sets of data suitable for analysis, 219 expressed runoff equations of the form determined earlier. The other four expressed negative slopes, which is impossible unless the infiltration rate increased with time or the plots added water from, or lost water to, other furrows during the course of the irrigation. The second explanation is most probable as this situation was observed to have occurred on some plots. A summary of the 223 plots for which runoff rate equations were able to be determined is shown in TABLE 4.

A review of TABLE 4 shows that out of 161 sets of data that used more than two runoff readings to determine the runoff rate equation, and the resulting equation did not indicate a negative runoff rate slope, 120 plots had a correlation coefficient of 0.95 or better, and 152 plots had a correlation coefficient of 0.80 or better.

TABLE 4

SUMMARY OF CORRELATION COEFFICIENTS FOR RUNOFF EQUATIONS FOR ZONE II

| | Series | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | Effluent | Total |
|---|---|---|---|---|---|---|---|---|
| Total data sets[a] | 33 | 30 | 29 | 40 | 34 | 36 | 21 | 223 |
| No. acceptable equations[b] | 33 | 29 | 28 | 40 | 34 | 34 | 21 | 219 |
| No. sets with $R_C = 1.00$[c] | 7 | 6 | 13 | 15 | 8 | 9 | 0 | 58 |
| Total remaining sets | 26 | 23 | 15 | 25 | 26 | 25 | 21 | 161 |
| No. sets with $R_C \geq 0.95$[d] | 21 | 17 | 14 | 21 | 17 | 17 | 13 | 120 |
| No. sets with $R_C \geq 0.90$[d] | 24 | 22 | 15 | 23 | 21 | 21 | 17 | 143 |
| No. sets with $R_C \geq 0.80$[d] | 24 | 23 | 15 | 23 | 24 | 24 | 19 | 152 |
| Lowest $R_C$ for series | 0.64 | 0.81 | 0.94 | 0.76 | 0.70 | 0.71 | 0.32 | 0.32 |

[a] Includes only the data sets with two runoff readings in Zone II and one in Zone III.

[b] Includes only those runoff equations with positive slopes.

[c] $R_C$ = correlation coefficient.

[d] Excludes those sets with $R_C = 1.00$.

## SUMMARY AND CONCLUSIONS

In furrow irrigation, runoff often represents a sizeable portion of the water initially applied. Unless this water is reused, it is wasted. Various methods of reducing or reusing runoff water have been devised. Most of these methods require a knowledge of the amount of runoff produced by an irrigation. It was the purpose of this study to determine a simple relationship that could be used to determine the amount of runoff produced by an irrigation.

Detailed runoff data were taken from seven selected plots. These data were obtained by measuring the length of time required to fill a one gallon container with runoff water flowing through an orifice plate located at the lower end of each plot. The time at which each measurement was taken was observed and recorded.

From analysis of the runoff data and by theoretical analysis of the irrigation process, it was found that an equation of the form:

$$r = R \, t_r^S \tag{29}$$

where r = the runoff rate, in gallons per minute

R = the y intercept at $t_r$ equals one minute of the line formed by plotting runoff rates and their corresponding time on log-log paper

$t_r$ = runoff time, in minutes

S = slope of the runoff curve plotted on log-log paper

can be used to describe the relationship between runoff rate and runoff time during the rising portion of the flow hydrograph.

Runoff rate reaches a maximum value at the time the basic intake rate of the soil is reached. From this time until the inflow is terminated, runoff rate is constant. This portion of the flow hydrograph can be expressed by an equation of the form:

$$r = R_E \tag{34}$$

where $R_E$ = the maximum, constant runoff rate developed in the flow hydro-
        graph.

Since the two equations determine instantaneous runoff rates, upon integration, accumulated runoff volumes can also be obtained.

These equations then represent a simple method of determining the amount of runoff realized from a given situation. No longer is it required to measure many runoff rates during the course of an irrigation in order to determine the total volume of runoff. Unlike the SCS mean rate calculation method, many points are not required to develop the runoff curve. At a minimum, only two points in the rising portion of the runoff curve and one point on the constant portion are required.

Theory, however, sets certain limits on the use of the runoff equations. Inflow must be constant or nearly constant during the entire irrigation period. Changes in the inflow rate will be reflected in the runoff rate. As the infiltration rate varies with time and location until the basic intake rate has been established, it is impossible to determine the effect of varied inflow rate on the runoff curve.

Theory also dictated that no water other than that put in the furrow at the head end be allowed to enter the furrow. Water that has been placed at the head end of the furrow cannot be allowed to escape from the furrow except by runoff and infiltration. This requirement is necessary to avoid the

effects of water crossing from furrow to furrow in the field.

Experience with the use of the runoff equation has shown the advisability of certain guidelines. In order to determine the runoff equation, it is advisable to observe and record the time runoff starts. If only two runoff readings are to be taken to determine the runoff equation for the rising portion of the overland flow hydrograph, it is advisable to take the two readings several hours apart, avoiding both the lower end and the upper end of the curve. Although only two points are required to determine the equation for the rising portion of the overland flow hydrograph, more than two points would reduce the effects of measurement errors and temporary fluctuations in the runoff rate that may occur. This consideration also applies to the constant portion of the overland flow hydrograph.

SUGGESTIONS FOR FURTHER STUDY

This study determined empirical equations that can be used to calculate runoff rates and runoff volume for furrow irrigation. Equations were determined based on runoff from one to five furrows channeled into an orifice plate. In order to make these equations more widely usable, a study should be conducted to determine if runoff from entire fields can be determined with equations of the same form.

The effects of evapotranspiration were neglected in this study. From observation of runoff rates, it was apparent that evapotranspiration did have some effect on runoff rate. If it is desired to determine a more accurate relationship to characterize runoff from furrow irrigation, the effects of evapotranspiration should be included.

The amount of runoff realized from furrow irrigation is dependent on many factors, including inflow and infiltration. The exact relationships and effects of all these factors was beyond the scope of this study. In order to make the runoff equation more widely usable, a study of the effects of these factors on the runoff equation would be useful.

## NOMENCLATURE

$a_1$      orifice area above the lower head in partially submerged orifice flow, in square feet

$a_2$      orifice area below the lower head in partially submerged orifice flow, in square feet

$A$      empirical coefficient in the advance equation

$A_o$      orifice area, in square feet

$B$      empirical coefficient in the advance equation

$c_r$      coefficient that varies with time in the equation: $\Delta v_r = c_r WLI_c \Delta t$

$c_g$      gate coefficient

$c_o$      orifice coefficient

$c_w$      weir coefficient

$C$      factor that depends on the shape of the water surface and on the shape of the furrow

$C_1$      $1-B(N+1)/B+1$

$C_2$      $WK/12(N+1)$

$C_3$      $C_1 C_2$

$C_4$      $WKL/12(N+1)$

$C_5$      $WKLT_L B/12(B+1)$

$C_6$      constant in the equation $v_r = C_6 t_r^M$

$d_i$      average depth of water added to the soil when expressed as a function of time, in feet

$D_I$      average depth of water added to the soil by an irrigation, in feet

$D_0$      normal depth, in feet

$D_S$      average depth of water stored on the soil surface, in feet

$E$      the puddle factor

f(d)  some factor of the depth of water flowing in the furrow channel

G  force of gravity, 32.2 feet per second squared

$h_d$  distance from the upper water level to the top edge of the orifice in partially submerged orifice flow, in feet

$h_g$  head in the standpipe, in feet

$h_l$  lower head on the orifice in partially submerged or submerged orifice flow, in feet

$h_o$  head on an orifice, in feet

$h_u$  upper head on the orifice in partially submerged and submerged orifice flow, in feet

$h_w$  head on a weir, in feet

i  infiltration rate, in inches per hour

I  irrigation water

$I_c$  final infiltration rate, in inches per hour

K  empirical coefficient in the infiltration equation

L  total furrow length, in feet

M  exponent of $t_r$ in the equation $v_r = C_6 t_r^M$

N  empirical coefficient in the infiltration equation

P  precipitation

q  inflow rate, in gallons per minute

$q_1$  flow rate from the part of the orifice above the lower head in partially submerged orifice flow, in gallons per minute

$q_2$  flow rate from the part of the orifice below the lower head in partially submerged orifice flow, in gallons per minute

Q  constant inflow rate, in gallons per minute

r  runoff rate, in gallons per minute

R  empirical coefficient in the runoff equation for Zone II

$R_E$  constant, maximum runoff rate attained in Zone III

S  empirical coefficient in the runoff equation for Zone II

$S_D$      direct runoff

$t$      irrigation time, in minutes

$t_a$      advance time, in minutes

$t_o$      opportunity time for infiltration, in minutes

$t_r$      runoff time, in minutes

$T_C$      irrigation time at which inflow is terminated, the end of Zone III, in minutes

$T_E$      irrigation time at which the runoff rate reaches a steady state condition, the equilibrium time, the end of Zone II, in minutes

$T_L$      irrigation time at which the water front reaches the end of the furrow, the end of Zone II, in minutes

$T_R$      irrigation time at which recession flow terminates, the end of Zone IV, in minutes

$T_{CR}$      inflow termination time when expressed in terms of runoff time, in minutes

$T_{ER}$      equilibrium time when expressed in terms of runoff time, in minutes

$U$      deep percolation losses

$v_e$      volume of inflow when expressed as a function of time, in gallons

$v_i$      volume of infiltration when expressed as a function of time, in gallons

$v_s$      volume of surface storage when expressed as a function of time, in gallons

$v_r$      volume of runoff when expressed as a function of time, in gallons

$V_E$      total volume of inflow, in gallons

$V_{ET}$      total volume of water lost to evapotranspiration during the irrigation process, in gallons

$V_I$      total volume of water infiltrated into the soil, in gallons

$V_P$      total water from precipitation during the irrigation process, in gallons

$V_S$      total volume of water stored in the furrow, in gallons

$V_R$      total volume of runoff water, in gallons

W      row spacing, in feet

x      distance water has advanced at time $t_a$, in feet

$\Delta D$      change in surface storage

$\Delta M$      change in soil moisture storage

$\Delta t$      increment of time, in minutes

$\Delta v_i$      increment of infiltration volume, in gallons

$\int E\ dt$      evapotranspiration

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APPENDIX A

# ILLEGIBLE DOCUMENT

THE FOLLOWING DOCUMENT(S) IS OF POOR LEGIBILITY IN THE ORIGINAL

THIS IS THE BEST COPY AVAILABLE

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      $JCB              FEO,RUN=FREE,TIME=5,PAGES=2 ,LINES=60,KP=29
1            DIMENSION CH(70),W(70),AH(70),SJAH(7 ),A(7 ),AREA(70),H(300),
            1CDH(300),CAH(300),AA(300),ARE2(300),COE(300),S(300),SI(40),SIH(40)
            2,SIM(40),NS(40),SR(40),SRH(40),SRM(40),FST(40),NT(300),TA(300),TSH
            3(300),TSM(300),TI(300),TT(300),ASH(70),C(70),X(70),Y(70),DH(70),PN
            4(10),T(70),HC(300)
2            DIMENSION ORT(40),WIDTH(40),ROWS(40),DEPTH(40),GIN(40),
            1PERI(40),LR(40),FH(10),Q(250),HEAD(54),TIMEH(54),
            2NR(300),EIT(40),EITH(40),EITM(40),RL(300),TL(300),FL(10)
3            DIMENSION O2(54),DPH(40),TIH(300),TIM(300),RIMP(300),RINT(300),
            2FR(40),RXN(40),CC(40),EWT(40),J6(40),J7(40),CA(250),LT(40),
            3IC(300),LU(40),O3(300),AVRR(40),DHP(40),
            3TIMEM(54),NC(54),J4(40),J3(40),TIMF(54),TE(54),
            4ID(40),IK(40),KL(10),KK(40),IFE(40)
4        100 FORMAT(10A4)
5        101 FORMAT(7F10.3)
6        102 FORMAT(18I4)
7        103 FORMAT(10I4)
8        104 FORMAT(4F10.2,I4,2F10.2,2I4)
9        105 FORMAT(2F10.2,I4,F10.3,I4,F10.2)
10       106 FORMAT(10F7.1)
11       107 FORMAT(18F4.1)
12       108 FORMAT(3F10.2,I4,3F10.2,I4)
13       111 FORMAT(12F6.2)
14       112 FORMAT(F8.3,I2,F9.3,I2,F8.3,I2,F8.3,I2,F8.3,I2,F8.3,I2,F8.3,I2)
15       202 FORMAT(3X,'PLOT NO.=',A4,/)
16       211 FORMAT(5X,F10.3,5X,F10.4,5X,F10.7,5X,F10.4)
17       221 FORMAT(9X,'CH(I)',11X,'AH(I)',11X,'W(I)',8X,'AREA(I)',11X,'C(I)')
18       223 FORMAT(9X,'C(ORIFACE)=',F12.4,'AH**',F12.4,20X,'COCOE=',F12.4,//)
19       224 FORMAT(1X,'FINISH')
20       225 FORMAT(11X,'CDH',12X,'CAH',10X,'AREA',13X,'COE',8X,'HEAD',9X,'TIME
            2',11X,'TT (ERT)',10X,'S')
21       226 FORMAT(5X,F10.3,5X,F10.4,5X,F10.7,5X,F10.4,5X,F7.3,1X,I2,5X,I2,':'
            2,I2,1X,I2,5X,F10.1,5X,F10.4)
22       227 FORMAT(9X,'FST=',F9.1,1X,'MINUTES(EIT)',/)
23       229 FORMAT(9X,'INSUFFICIENT DATA FOR RUNOFF ANALYSIS',/)
24       228 FORMAT(9X,'R=',F12.4,1X,'T**',F12.4,20X,'CC=',F12.4,//)
25       230 FORMAT(///,1X,'IRRIGATION NO.',I4)
26       231 FORMAT(10X,'AVRR',10X,'ORT',12X,'DEPTH',8X,'DPH(IN/HR)',7X,'PERI')
27       232 FORMAT(5X,F10.3,5X,F10.3,5X,F10.3,5X,F10.3,5X,F10.2)
28       233 FORMAT(9X,'TOTAL IRRIGATION IMPUT=',F10.3,1X,'GALLONS',5X,'MAX RUN
            2OFF RATE=',F10.3,1X,'GAL/MIN',5X,'FINAL INTAKE RATE=',F10.3,1X,'IN
            3/HR')
29       234 FORMAT(9X,'C(WEIR)=',F12.4,1X,'AH**',F12.4,20X,'COCOE=',F12.4,//)
30       235 FORMAT(9X,'ECT=',F12.4,10X,'PLOT WIDTH=',F7.2,/)
31       236 FORMAT(9X,'QR=',F12.4,10X,'QAV=',F12.4,/)
32       237 FORMAT(9X,'START IRRIGATION=',F6.1,1X,'MINUTES',10X,'START RUNOFF
            1=',F6.1,1X,'MINUTES',10X,'END IRRIGATION=',F6.1,1X,'MINUTES(EIT)')
33       250 FORMAT('1',60X,'***SUMMARY***',/)
34       251 FORMAT(44X,'MANURE PLOTS-CLEAR WATER APPLICATION',//)
35       252 FORMAT(10X,'IRRIGATION',10X,'RUNOFF RATE EQUATION',10X,'CORRELATIO
            2N COEFFICIENT',/)
36       253 FORMAT(12X,I4,10X,'R=',F10.3,1X,'TIME**',F10.3,20X,F10.4)
37       254 FORMAT(10X,'IRRIGATION',10X,'WATER APPLIED',5X,'TOTAL RUNOFF',5X,
            2'WATER APPLIED',5X,'INFILTRATION RATE',5X,'IRRIGATION')
38       255 FORMAT(33X,'(GALLONS)',9X,'(GALLONS)',8X,'(INCHES)',12X,
            2'(IN/HR)',11X,'EFFICIENCY',/)
39       256 FORMAT(12X,I4,15X,F10.2,9X,F10.2,5X,F10.2,10X,F10.3,10X,F10.2)
40       257 FORMAT(12X,I4,20X,'***',39X,'***')
41       258 FORMAT(12X,I4,15X,F10.2,13X,'***',15X,'***',20X,'***',15X,'***')
```

```
42      259 FORMAT(1 X,'PLOT NC',1 X,'IRRIGATION',1 X,'WATER APPLIED',5X,
            2'TOTAL RUNOFF',5X,'WATER APPLIED',5X,'INFILTRATION RATE',
            25X,'IRRIGATION')
43      26  FORMAT(49X,'(GALLONS)',9X,'(GALLONS)',8X,'(INCHES)',13X,'(IN/HR)',
            21 X,'EFFICIENCY',/)
44      261 FORMAT(12X,A4,15X,I4,1 X,F1 .2,1 X,F1 .2,1 X,F1 .3,1 X,F1 .2,1 X,F
            27.2,/)
45      262 FCRMAT(12X,A4,15X,I4,1 X,F1 .2,14X,'***',12X,'***',15X,'***',18X,'
            2***')
46      263 FORMAT(2 X,'CP',16X,'TIME',11X,'HEAD',12X,'IMPUT RATE')
47      264 FORMAT(15X,F9.4,1 X,F9.2,1 X,F6.2,1 X,F1 .4)
48      265 FORMAT(12X,'TIME',1 X,'SUM IMPUT')
49      266 FORMAT(11X,F6.1,2X,I2,4X,F1 .2)
5       267 FORMAT(1 X,'IMPUT FCR RO ',I2,1X,'=',F1 .2,1X,'GALLONS',5X,'SUM RU
            2WS IMPLT=',F1 .2,1X,'GALLONS',/)
51      269 FORMAT(12X,I2,':',I2,2X,I2,4X,F7.2,1 X,F1 .3,1 X,F1 .3,1 X,F1 .3)
52      268 FCRMAT(15X,'TIME',7X,'EIT',1 X,'IMPUT RATE(GPM)',1 X,'RUNOFF RATE(
            2GPM)',3X,'INTAKE RATE(GPM/1 C FT)',/)
53          REAL NP
54          REAL NC
55          REAL J1
56          INTEGER TBH
57          INTEGER TBM
58          LB=229
59          K1=8
60          K2=231
61          LA=4
62          N=7
63          J9=45
64          LOC=1
65          READ(5,1  )(PN(IZ),IZ=1,LOC)
66          READ(5,1 1)(CH(I),I=1,N)
67          READ(5,1 1)(W(I),I=1,N)
68          READ(5,1 2)(KK(II),II=1,LA)
69          READ(5,1 2)(IK(II),II=1,LA)
70          READ(5,1 2)(ID(II),II=1,LA)
71          READ(5,1 3)(KL(IZ),IZ=1,LOC)
72          READ(5,1 4)(SIH(KA),SIM(KA),SRH(KA),SRM(KA),NS(KA),EITH(KA),EITM(K
            2A),ER(KA),LG(KA),KA=1,LA)
73          READ(5,1 5)(TSH(IB),TSM(IB),AT(IB),H(IB),NR(IB),HO(IB),IB=1,LB)
74          READ(5,1 2)(IFF(II),II=1,LA)
75          READ(5,1 6)(FL(IZ),IZ=1,LOC)
76          READ(5,1 7)(ROWS(II),II=1,LA)
77          READ(5,1 2)(LT(II),II=1,LA)
78          READ(5,1 2)(J6(J5),J5=1,LA)
79          READ(5,1 2)(J7(J5),J5=1,LA)
80          READ(5,111)(HH(JZ),JZ=1,K1)
81          READ(5,1 2)(Q(MN),IQ(MN),MN=1,K2)
82          READ(5,1 2)(J3(J5),J5=1,LA)
83          READ(5,1 2)(J4(J5),J5=1,LA)
84          READ(5,1 8)(HEAD(JB),TIMEH(JB),TIMEM(JB),NC(JB),JB=1,J9)
85          B=5.875
86          G=( .1198* . 02228)/(64.4** .5)
87          D=1. /12.
88          R=D/2.
89          BC= .62+
90          CC= .62
91          M=4
92          K=7
93          J=1
```

```
94              L=3
95              IZ=1
96              II=2
97              KA=2
98              MN=1
99              J5=1
100             GO TO 301
101     311 J=J+7
102             K=K+7
103             M=M+7
104             L=L+7
105             IZ=IZ+1
106             II=II+1
107             KA=KA+1
108             IF(K-N)301,301,999
109     301 WRITE(6,202)PN(IZ)
110             WRITE(6,221)
111             DO 341 I=J,K
112             DH(I)=R+CH(I)
113             IF(CH(I).GT.0)GO TO 321
114             AH(I)=CH(I)
115             IF(AH(I)-R)313,314,315
116     313 A(I)=2.*(ARCOS((R-AH(I))/R))
117             AREA(I)=(A(I)-SIN(A(I)))*((R**2.0)/2.0)
118             GO TO 331
119     314 AREA(I)=((D**2.0)*3.1416/4.0)/2.0
120             GO TO 331
121     315 A(I)=2.*ARCOS((AH(I)-R)/R)
122             AREA(I)= (D**2.0*3.1416/4.0)-(A(I)-SIN(A(I)))*((R**2.0)/2..)
123             GO TO 331
124     321 AREA(I)=(D**2.0)*3.1416/4.0
125              AH(I)=CH(I)
126     331 SQAH(I)=(AH(I))**0.5
127             ASH(I)=AREA(I)*SQAH(I)
128             C(I)=(W(I)-B)*G/ASH(I)
129     341 CONTINUE
130             SUMX2=0.0
131             SUMY2=0.0
132             SUMY=0.0
133             SUMX=0.0
134             SUMXY=0.0
135     361 DO 351 I=M,K
136             WRITE(6,211)CH(I),AH(I),W(I),AREA(I),C(I)
137             X(I)=ALOG(AH(I))
138             Y(I)=ALOG(C(I))
139             SUM=X(I)*Y(I)
140             SUMXY=SUMXY+SUM
141             SUMX=SUMX+X(I)
142             SUMY=SUMY+Y(I)
143             SUMX2=SUMX2+(ABS(X(I)))**2.0
144             SUMY2=SUMY2+(ABS(Y(I)))**2.0
145     351 CONTINUE
146             PRINT,M
147             BB=(SUMX*SUMX)/4.00
148             DB=(SUMY*SUMX)/4.00
149             XM=(SUMXY-DB)/(SUMX2-BB)
150             FA=(SUMY/4.00)-(XM*SUMX/4.00)
151             FA=EXP(FA)
152             CCCOE=(SUMXY-((SUMX*SUMY)/4.00))/SQRT(((SUMX2-((SUMX*SUMX)/4.00))
        2*(SUMY2-((SUMY*SUMY)/4.00)))
```

```
153          WRITE(6,223)FA,XM,COCOE
154          SUMX2=1.0
155          SUMY2=1.0
156          SUMY=0.0
157          SUMX=0.0
158          SUMXY=0.0
159          DO 372 I=J,L
160          WRITE(6,211)CH(I),AH(I),W(I),AREA(I),C(I)
161          X(I)=ALOG(AH(I))
162          Y(I)=ALOG(C(I))
163          SUM=X(I)*Y(I)
164          SUMXY=SUMXY+SUM
165          SUMX=SUMX+X(I)
166          SUMY=SUMY+Y(I)
167          SUMX2=SUMX2+(ABS(X(I)))**2.0
168          SUMY2=SUMY2+(ABS(Y(I)))**2.0
169      372 CONTINUE
170          PRINT,L
171          BB=(SUMX*SUMX)/3.00
172          DB=(SUMY*SUMX)/3.00
173          XN=(SUMXY-DB)/(SUMX2-BB)
174          FB=(SUMY/3.00)-(XN*SUMX/3.00)
175          FB=EXP(FB)
176          COCOE=(SUMXY-((SUMX*SUMY)/3.00))/SQRT((SUMX2-((SUMX*SUMX)/3.00))
             2*(SUMY2-((SUMY*SUMY)/3.00)))
177          WRITE(6,234)FB,XN,CUCODE
178          II=II-1
179          KA=KA-1
180          GO TO 499
181      500 II=II+1
182          KA=KA+1
183          IF(KA.GT.KL(IZ))GO TO 311
184      499 IC=ID(II)
185          IG=IK(II)
186          WIDTH(II)=ROWS(II)*2.5
187          WRITE(6,230)KK(II)
188          IF(LC(KA)-2)390,391,392
189      390 SI(KA)=SIH(KA)*60..+SIM(KA)
190          GO TO 395
191      391 SI(KA)=(SIH(KA)+12.0)*60.0+SIM(KA)
192          GO TO 395
193      392 SI(KA)=(SIH(KA)+24.0)*60.0+SIM(KA)
194      395 IF(NS(KA)-12)769,774,770
195      769 SR(KA)=SRH(KA)*60.0+SRM(KA)
196          GO TO 772
197      774 SR(KA)=(SRH(KA)+12.0)*60.0+SRM(KA)
198          GO TO 772
199      770 IF(NS(KA).GT.21)GO TO 771
200          SR(KA)=(SRH(KA)+24.0)*60.0+SRM(KA)
201          GO TO 772
202      771 SR(KA)=(SRH(KA)+36.0)*60.0+SRM(KA)
203      772 FST(KA)=SR(KA)-SI(KA)
204          IF(LR(KA).GT.1)GO TO 773
205          EIT(KA)=((EITH(KA)+24.0)*60.0+EITM(KA))-SI(KA)
206          GO TO 779
207      773 EIT(KA)=((EITH(KA)+36.0)*60.0+EITM(KA))-SI(KA)
208      779 WRITE(6,237)SI(KA),SR(KA),EIT(KA)
209          WRITE(6,227)FST(KA)
210          WRITE(6,225)
211          DO 404 IO=IG,IC
```

```
212          PRINT,IB
213          IF(NT(IB)-12)775,776,777
214      775 TA(IB)=TSH(IB)*60.0+TSM(IB)
215          GC TO 790
216      776 TA(IB)=(TSH(IB)+12.0)*60.0+TSM(IB)
217          GC TO 790
218      777 IF(NT(IB).GT.21)GC TC 778
219          TA(IB)=(TSH(IB)+24.0)*60.0+TSM(IB)
220          GC TC 790
221      778 TA(IB)=(TSH(IB)+36.0)*60.0+TSM(IB)
222      790 TI(IB)=TA(IB)-SI(KA)
223          TT(IB)=TI(IB)-FST(KA)
224          IF(TT(IB).GT.0.0)GO TO 70
225          TT(IB)=1.0
226       70 TIH(IB)=TSH(IB)
227          TIM(IB)=TSM(IB)
228          TBM=TIM(IB)
229          TBH=TIH(IB)
230          IF(NR(IB)-2)800,801,802
231      800 CDH(IB)=CO-H(IB)
232          IF(CDH(IB).GT.D)GC TC 380
233          CAH(IB)=CDH(IB)
234          IF(CAH(IB)-R)381,382,383
235      381 AA(IB)=2.0*(ARCOS((R-CAH(IB))/R))
236          ARE2(IB)=(AA(IB)-SIN(AA(IB)))*((R**2.0)/2.0)
237          GO TC 402
238      382 ARE2(IB)=((D**2.0)*(3.1416/4.0))/2.0
239          GO TC 402
240      383 AA(IB)=2.0*(ARCOS((CAH(IB)-R)/R))
241          ARE2(IB)=(D**2.0*(3.1416/4.0))-(AA(IB)-SIN(AA(IB)))*((R**2.0)/2.0)
242      402 COE(IB)=FB*CAH(IB)**XN
243          GO TO 403
244      380 ARE2(IB)=(D**2.0)*(3.1414/4.0)
245          CAH(IB)=CO-H(IB)
246          COE(IB)=FA*(CAH(IB)**XM)
247      403 S(IB)=(COE(IB)*ARE2(IB)*SQRT(2.0*32.2*CAH(IB)))/(0.002228)
248          GO TC 405
249      801 S(IB)=60.0/H(IB)
250          GO TO 405
251      802 IF(AR(IB)-4)799,803,804
252      799 S(IB)=1.0/H(IB)
253          GO TO 405
254      803 S(IB)=60.0/(H(IB)/2.54)
255          GC TC 405
256      804 IF(NR(IB)-6)805,806,807
257      805 S(IB)=1.0/(H(IB)/2.54)
258          GC TO 405
259      806 CAH(IB)=CO-H(IB)
260          COE(IB)=FA*(CAH(IB)**XM)
261          ARE2(IB)=(D**2.0)*(3.1416/4.0)
262          S(IB)=(COE(IB)*ARE2(IB)*SQRT(64.4*(HO(IB)-H(IB))))/(0.002228))
263          GO TC 405
264      807 CAH(IB)=CO-H(IB)
265          COE(IB)=FA*(CAH(IB)**XM)
266          CAHO=BO-HO(IB)
267          IF(CAHO-R)808,809,810
268      808 AA(IB)=2.0*(ARCOS((R-CAHO)/R))
269          ARE2(IB)=((D*D)*3.1416/4.0)-(AA(IB)-SIN(AA(IB)))*((R*R)/2.0)
270          GO TC 811
271      809 ARE2(IB)=(D*D)*(3.1416/8.0)
```

```
272          GO TC 811
273      810 AA(IB)=2.C*(ARCOS((CAHG-R)/R))
274          ARE2(IB)=(AA(IB)-SIN(AA(IB)))*((R*R)/2.C)
275      811 SC1=(CCE(IB)*ARE2(IB)*SQRT(64.4*(((HO(IB)-H(IB))+(CO+R-H(IB)))/2.0
             2)))
276          TAREA=C*D*3.1416/4.0
277          SC2=(CCE(IB)*(TAREA-ARE2(IB))*SQRT(64.4*(HO(IB)-H(IB))))
278          S(IB)=(SC1+SC2)/0...02226
279      405 WRITE(6,226)CDH(IB),CAH(IB),ARE2(IB),CCE(IB),H(IB),NR(IB),TBH,
             2TBM,NT(IB),TT(IB),S(IB)
280      404 CONTINUE
281          IF(IG.EQ.IC)GO TO 407
282          SUMR2=C.0
283          SUMT=C.0
284          SUMR=C.C
285          SUMRT=C.0
286          SUMT2=C.0
287          IY=IFE(II)
288          NO=IY-IG
289          L9=IY-1
290          DO 450 IB=IG,L9
291          PRINT,IB
292          RL(IB)=ALOG(S(IB))
293          TL(IB)=ALOG(TT(IB))
294          SMU=RL(IB)*TL(IB)
295          SUMRT=SUMRT+SMU
296          SUMR=SUMR+RL(IB)
297          SUMT=SUMT+TL(IB)
298          SUMR2=SUMR2+RL(IB)*RL(IB)
299          SUMT2=SUMT2+TL(IB)*TL(IB)
300      450 CONTINUE
301          BA=(SUMT*SUMT)/NO
302          DA=(SUMT*SUMR)/NO
303          RXM(II)=(SUMRT-DA)/(SUMT2-BA)
304          FR(II)=(SUMR/NO)-(RXM(II)*SUMT)/NO
305          FR(II)=EXP(FR(II))
306          CC(II)=(SUMRT-((SUMR*SUMT)/NO))/SQRT((SUMT2-((SUMT*SUMT)/NO))*(SU
             2MR2-((SUMR*SUMR)/NO)))
307          WRITE(6,228)FR(II),RXM(II),CC(II)
308          JR=IY
309          SUMC=0.0
310          DO 451 IB=JR,IC
311          SUMC=SUMC+S(IB)
312      451 CONTINUE
313          NP=IC-JR+1
314          AVRP(II)=SUMC/NP
315          ECT(II)=EXP((ALOG(AVRR(II)/FR(II)))/RXM(II))
316          WRITE(6,235)ECT(II),WIDTH(II)
317          IF(ECT(II).GT.TT(JR))GO TO 406
318          CAV=AVRR(II)*(EIT(KA)-(EQT(II)+FST(KA)))
319          CR=(FR(II)/(RXM(II)+1))*ECT(II)**(RXM(II)+1)
320          WRITE(6,236)CR,CAV
321          CRT(II)=CR+CAV
322          GO TC 555
323      407 EQT(II)=1.0
324          IY=IFE(II)
325          JR=IY
326          NP=1
327      406 WRITE(6,229)
328      555 GIN(II)=0.0
```

```
329           IRO=1
330           IF(MN.EC.1)GO TO 599
331           J5=J5+1
332      599  J8=J6(J5)
333           J11=J7(J5)
334           J1C=J11-J8+1
335           PRINT,J5,J8,J11,J1C
336           J1=J3(J5)
337           J2=J4(J5)
338           DC 975 JB=J1,J2
339           C3(JB)=C.C
340      975  CONTINUE
341      603  SUMC=C.C
342           DO 601 JZ=J8,J11
343           IF(JZ.EC.J8)GC TC 602
344           MN=MN+1
345      602  IF(IC(MN).GT.1)GO TO 600
346           CA(MN)=(6C.C/C(MN))
347           GO TC 611
348      600  CA(MN)=1.C/C(MN)
349      611  CP1=(CA(MN)/SCRT(64.4*(4.33-HH(JZ))))
350           SUMC=SUMC+CP1
351      601  CONTINUE
352           CP=SUMC/J1C
353           WRITE(6,263)
354           DO 604 JB=J1,J2
355           IF(NC(JB)-12)605,606,607
356      605  TIME(JB)=TIMEH(JB)*60.C+TIMEM(JB)
357           GO TO 608
358      606  TIME(JB)=(TIMEH(JB)+12.C)*6C.C+TIMEM(JB)
359           GC TC 608
360      607  IF(NC(JB).GT.21)GO TO 609
361           TIME(JB)=(TIMEH(JB)+24.C)*6C.C+TIMEM(JB)
362           GO TC 608
363      609  TIME(JB)=(TIMEH(JB)+36.C)*6C.C+TIMEM(JB)
364      608  TE(JB)=TIME(JB)-SI(KA)
365           C2(JB)=CP*SCRT(64.4*(4.33-HEAD(JB)))
366           C3(JB)=C3(JB)+C2(JB)
367           WRITE(6,264)CP,TE(JB),HEAD(JB),C2(JB)
368      604  CONTINUE
369           JD=J1+1
370           JE=J2-1
371           WRITE(6,265)
372           CUANT=C2(J1)*TE(J1)
373           WRITE(6,266)TE(J1),NC(J1),CUANT
374           DO 610 JB=JD,J2
375           JF=JB-1
376           CUANT=CUANT+((C2(JB)+C2(JF))/2.C)*(TE(JB)-TE(JF))
377           WRITE(6,266)TE(JB),NC(JB),CUANT
378      610  CONTINUE
379           GINI=CUANT+(C2(J2)*(EIT(KA)-TE(J2)))
380           WRITE(6,266)EIT(KA),LR(KA),GINI
381           GIN(II)=GINI+GIN(II)
382           WRITE(6,267)IRO,GINI,GIN(II)
383           IRO=IRO+1
384           MN=MN+1
385           LZ=LT(II)-1
386           IF(MN.LE.LZ)GC TC 603
387           DO 50 JB=J1,J2
388      50   CONTINUE
```

```
389        900 WRITE(6,268)
390            JB=J1
391            DO 910 IB=IG,IC
392        902 IF(TI(IB).GT.TE(JB))GO TO 901
393            IF(JB.EQ.J1)GO TO 903
394            IF(JB.EQ.J2)GO TO 903
395            IR2=JB-1
396            IF(Q3(JB).GT.Q3(IR2))GO TO 899
397            RIMP(IB)=(Q3(IR2)-Q3(JB))*((TE(JB)-TI(IB))/(TE(JB)-TE(IR2)))+Q3(JB
               2)
398            GO TO 904
399        899 RIMP(IB)=(Q3(JB)-Q3(IR2))*((TI(IB)-TE(IR2))/(TE(JB)-TE(IR2)))+Q3(I
               2R2)
400            GO TO 904
401        903 RIMP(IB)=Q3(JB)
402            GO TO 904
403        901 IF(JB.EQ.J2)GO TO 903
404            JB=JB+1
405            GO TO 902
406        904 RINT(IB)=(RIMP(IB)-S(IB))/(FL(IZ)/100.0)
407            TBH=TIH(IB)
408            TBM=TIM(IB)
409            WRITE(6,269)TBH,TBM,NT(IB),TI(IB),RIMP(IB),S(IB),RINT(IB)
410        910 CONTINUE
411            DHP(II)=0.0
412            DO 926 IB=IY,IC
413            DHP(II)=DHP(II)+RIMP(IB)
414        926 CONTINUE
415            DHP(II)=DHP(II)/NP
416            IF(IC.EQ.IC)GO TO 453
417            IF(EQT(II).GT.TT(JR))GO TO 452
418            DEPTH(II)=(((GIN(II)-QRT(II))/7.481)/((FL(IZ)/1.000)*WIDTH(II)))*
               212.0
419            DPH(II)=(DHP(II)-AVRR(II))/(FL(IZ)*WIDTH(II)/100.0)
420            PERI(II)=((GIN(II)-QRT(II))/(GIN(II)/100.0))
421            WRITE(6,231)
422            WRITE(6,232)AVRR(II),QRT(II),DEPTH(II),DPH(II),PERI(II)
423            GO TO 500
424        453 AVRR(II)=S(IC)
425        452 DPH(II)=(DHP(II)-AVRR(II))/(FL(IZ)*WIDTH(II)/100.0)
426            WRITE(6,233)GIN(II),AVRR(II),DPH(II)
427            GO TO 500
428        599 M1=1
429            GO TO 8
430          9 M1=M1+1
431          8 IF(M1.GT.2)GO TO 998
432            WRITE(6,250)
433            WRITE(6,251)
434            II=1
435            KA=1
436            DO 10 IZ=1,LCC
437            WRITE(6,202)PN(IZ)
438            WRITE(6,252)
439         11 IC=IO(II)
440            IG=IK(II)
441            IF(IG.EQ.IC)GO TO 16
442            WRITE(6,253)KK(II),FR(KA),RXM(KA),CC(KA)
443            GO TO 12
444         16 WRITE(6,257)KK(II)
445         12 II=II+1
```

```
446          KA=KA+1
447          IF(KA.LE.KL(IZ))GO TO 11
448       10 CONTINUE
449          II=1
450          KA=1
451          DO 13 IZ=1,LCC
452          WRITE(6,252)PN(IZ)
453          WRITE(6,254)
454          WRITE(6,255)
455       18 JR=IFE(II)
456          IC=IC(II)
457          IG=IK(II)
458          IF(IG.EC.IC.OR.EQT(II).GT.TT(JR))GO TO 17
459          WRITE(6,256)KK(II),GIN(II),QRT(II),DEPTH(II),DPH(II),PERI(II)
460          WRITE(6,268)
461          DO 31 IB=IG,IC
462          TBM=TIM(IB)
463          TBH=TIH(IB)
464          WRITE(6,269)TBH,TBM,NT(IB),TI(IB),RIMP(IB),S(IB),RINT(IB)
465       31 CONTINUE
466          GO TO 15
467       17 WRITE(6,258)KK(II),GIN(II)
468       15 II=II+1
469          KA=KA+1
470          IF(KA.LE.KL(IZ))GO TO 18
471       13 CONTINUE
472          I4=1
473          IZ=1
474          II=1
475          GO TO 21
476       20 II=KL(IZ-1)+I4
477          IF(II.GT.LA)GO TO 22
478          IF(II.GT.KL(IZ))GO TO 24
479       21 WRITE(6,259)
480          WRITE(6,260)
481          JR=IFE(II)
482          IC=IC(II)
483          IG=IK(II)
484          IF(IC.EC.IC.OR.EQT(II).GT.TT(JR))GO TO 23
485          WRITE(6,261)PN(IZ),KK(II),GIN(II),QRT(II),DEPTH(II),DPH(II),
             1PERI(II)
486          GO TO 24
487       23 WRITE(6,262)PN(IZ),KK(II),GIN(II)
488       24 IZ=IZ+1
489          GO TO 20
490       22 IZ=1
491          I4=I4+1
492          II=I4
493          IF(II.GT.4)GO TO 9
494          GO TO 21
495      998 WRITE(6,224)
496     1000 STOP
497          END
```

EQUATIONS FOR RUNOFF FROM FURROW IRRIGATION

by

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While irrigation water can be applied by various methods, furrow irrigation is popular in many areas. Runoff from furrow irrigation often represents a sizeable portion of the total water initially applied. Various methods have been devised to reduce or to reuse runoff water so that it will not be wasted. Most of these methods require a knowledge of the amount of runoff produced by an irrigation. It was the purpose of this study to obtain a simple relationship that could be used to determine runoff from furrow irrigation.

Detailed runoff data were taken from seven selected plots. These data were obtained by measuring runoff rates and the time at which each runoff measurement was taken. Initial runoff time was also measured. From analysis of data, it was found that the relationship between runoff rate and time for the rising portion of the outflow hydrograph can be described by an equation of the form:

$$r = Rt_r^S$$

where r equals the runoff rate in gallons per minute, R is the y intercept of the line formed by plotting runoff rates and their corresponding time on log-log paper, $t_r$ is the runoff time in minutes, and S is the slope of the runoff curve on log-log paper.

Runoff rate reaches a maximum value as the basic intake rate of the soil is reached along the entire length of the furrow. From this time until inflow is terminated, runoff rate is constant. This portion of the outflow hydrograph can be expressed by an equation of the form:

$$r = R_E$$

where $R_E$ represents the constant, maximum runoff rate attained.

Since these two equations determine instantaneous runoff rates, integration will yield equations by which runoff volume can be obtained. These equations were also determined by theoretical evaluation of the irrigation process. Additional data from other plots were also analyzed to determine the ability to express runoff in the form of these two equations. Of 223 sets of data analyzed, 219 sets developed equations of the same form.

A study was performed to determine the required accuracy of the initial runoff time reading. Results indicated that the initial runoff time reading should be within 5 minutes of the true time for determination of the equation for the rising portion of the outflow hydrograph. For the equation determining runoff from both the rising portion and the constant portion, the reading should be within 30 minutes of the true initial runoff time.

These equations then represent a simple method of determining the amount of runoff realized from an irrigation. No longer is it required to measure many runoff rates during the course of an irrigation in order to determine the runoff. At a minimum, only two points on the rising portion of the runoff curve and one point in the constant portion are required.