EFFECT OF FURROW FORMING TOOLS ON WATER FLOW CHARACTERISTICS

by

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INTRODUCTION

Furrows are used for applying irrigation water to the majority of row crops that are irrigated by surface methods. As instruments of application, irrigation furrows are used to achieve two objectives. The first objective is to achieve an acceptable uniformity of soil moisture distribution over the area irrigated. The second objective is the achievement of a high water application efficiency.

In most furrow irrigation systems the furrows are graded. Graded means that the furrow slopes from one end to the other. Level or ungraded furrows are used in very few surface irrigation systems. In the graded furrows the energy for distributing the water over the area irrigated is derived from gravity. The gravitational forces are due to the slope of the water surface and the slope of the furrow. In the case of level furrows, the slope of the water surface is the only force producing factor present.

Water is entered into the upper end of an irrigation furrow and, due to the forces present, advances down the length of the furrow. As the water advances, water is lost to the soil being irrigated along the wetted length of the furrow. The water thus lost to the soil becomes soil moisture. It has been shown by scientific investigations that the amount or volume of water lost from the furrow, at any point along its wetted length, is a function of the infiltration characteristics of the soil being irrigated and the length of time the point in question has been wetted. Due to the fact that time is required for the water to advance down the length of the furrow, it is apparent that perfect equality of water loss along a length of furrow is not possible. Therefore the rate of advance of water down an irrigation furrow is an important factor in achieving an acceptable uniformity of soil moisture distribution. Criddle, David, Pair, and Schockley (10) have determined that a nearly uniform distribution of soil moisture is achieved when the water reached the lower end of the furrow in one-fourth of the total irrigation time. Irrigation time is the time required to infiltrate the desired amount of water to the soil along the furrow. Irrigation time will vary with different soils and is a function of the infiltration characteristics of the soil being irrigated.

Experienced irrigators know that the rate of advance can be controlled by the stream size in the furrow. Stream size refers to the rate of flow of the water in an irrigation furrow. By increasing the stream size the rate of advance can be increased. Criddle, Davis, Pair, and Schockley (10) have determined the maximum allowable furrow stream. The maximum allowable furrow stream is the maximum rate of flow permissible in an irrigation furrow without eroding soil from the flow channel. This rate of flow can be determined by the empirical equation, Q equals 10/S; where Q is the rate of flow, in gallons per minute, and S is the slope of the furrow in percent of slope. The number of furrows that can be irrigated at one time from a given head or quantity of irrigation water is determined by the stream size.

In general irrigation practice, assuming the length of the furrow is within acceptable limits of length, the maximum allowable furrow stream results in high runoff losses from the lower end of the furrow. This results if the rate of flow is not reduced after the water reaches the end of the furrow, in a low application efficiency. These losses are due to more water being entered into the furrow than can be lost by infiltration along the length of furrow. To minimize these losses, and thereby increase the efficiency of application, the rate of flow must be reduced or "cut-back" to an amount that more nearly equals the loss of water by infiltration along the length of the furrow. Application of "cut-back" methods to furrow irrigation requires labor for reducing the rate of flow in the furrows. Labor is also required to divert the water thus saved to other furrows where it can be efficiently used.

In general irrigation practice, to conserve labor, irrigators compromise in accomplishing the two objectives of surface irrigation. Using the maximum allowable stream size, some irrigators achieve excellent water distribution but, by not expending the labor necessary to reduce the stream size when necessary, much water is wasted due to the large volume of runoff from the lower end of the furrows. The large volume of runoff results in a low application efficiency. Other irrigators achieve excellent visual application efficiency by using a small stream size and allowing no runoff from the furrow. Due to the slow rate of advance, the small stream size results in over irrigation of the soil at the upper end of the furrow and under irrigation of the lower end. Over irrigation at the upper end of the furrow results in deep-perculation losses. Deep-perculation losses are the result of water perculating below the root zone of the crop being irrigated. While the loss of water due to deep perculation is not visual, these losses reduce the application efficiency of an irrigation.

From experience in irrigation, it is apparent that the rate of advance, achieved with a given stream size, is not constant from season to season or from irrigation to irrigation. The difference is due to varying hydraulic conditions in the furrow. Hydraulic condition refers to the roughness and the soil condition in the furrow channel. Freshly formed irrigation furrows, formed in different seasons, rarely have the same hydraulic conditions. The hydraulic condition also changes during the irrigation process due to the action of the water flowing the furrow.

Irrigation furrows are formed with various tools. These tools are adaptations of tools designed for other tillage purposes. Included are middlebreaker or lister shovels, rotary moldboards from planting equipment, ordinary cultivator shovels, and many others. The condition of the furrows formed with these tools varies between tools. The hydraulic condition of furrows formed with any one of these tools varies from season to season. This is due to the different soil conditions encountered in different seasons. The rate of advance of a given quantity of water flowing in any one of these furrows will vary due to the variability of the hydraulic condition of the freshly formed irrigation furrow.

To improve the condition of freshly formed irrigation furrows, some irrigators make a practice of dragging some object in the freshly formed irrigation furrow during the furrowing operation (5).

The object may be a piece of metal pipe or a wooden fence post. The action of the dragging object smoothes the flow channel. TenEyck (15) evaluated a similar method of furrow treatment and found that the rate of advance was significantly improved, when the stream size was reduced, in the first one-fourth of the length of the furrow. However, this treatment did not materially influence the rate of advance over the entire length of furrow when the stream size was reduced.

This principle is also used with the "furrow slicker" treatment developed by Larsen and Moden (3). The slicker attachment is designed for use with corrugation equipment. This method requires that the soil moisture be within a given range for optimum action of the slicker.

The various methods of furrow treatment discussed aid somewhat in conditioning the furrow for an improved rate of advance of water in an irrigation furrow. It appears that studies to further develop furrowing equipment are warranted. Further development of furrowing equipment may result in irrigation furrows with a significantly improved rate of advance with a smaller stream size. If this development can be achieved, less water due to a reduction in stream size, will be needed for good water distribution. Therefore, for a given head of irrigation water available to an irrigator, more furrows can be irrigated at one time. Spreading the water over more area, and at the same time achieving good moisture distribution, will increase the water application efficiency of surface irrigation.

PURPOSE OF STUDY

The purpose of this study was to develop a design for and field test an experimental irrigation furrowing tool. In the field test the experimental tool was compared with a popular irrigation furrowing tool.

The main objective of the experimental design was to achieve more efficient use of irrigation water. In furrow irrigation this can be realized by improving the rate of advance, and thereby the soil moisture distribution pattern of the irrigation for a given quantity of water entering the irrigation furrow. The achievement of better rates of advance with a smaller quantity of water entering the furrow will make water available for the irrigation of other furrows. This will improve the water use efficiency of a given head of water available for irrigation.

In the field tests, determination of the influence of the furrowing tool on the rate of advance for small quantities of water was stressed. The influence of the furrowing tool on factors influencing the rate of advance was also evaluated.

REVIEW OF LITERATURE

The study of the flow of water in surface irrigation systems has been the subject of many investigators. These studies include both theoretical and experimental approaches conducted in the laboratory and in the field. Few investigators have studied and evaluated the influence of the device or tool used to form the irrigation furrow.

Hall (1) derived an equation for determining the rate of advance of water in border irrigation systems. The equation considered the hydraulic roughness of the surface, the shape of the water surface profile, and a variable infiltration rate. Hall's equation was based upon the law of the conservation of mass and is therefore considered mathematically correct.

Modifying Hall's equation, Davis (2) derived an equation for estimating the rate of advance of water flowing in an irrigation furrow.

When water flows into an irrigation furrow, part of the volume of water entering the furrow filtrates into the soil. The balance of the volume entering the furrow is stored upon the surface of the soil along the wetted length of the furrow. The volumes can be equated as follows:

$$V_e = V_i + V_s$$

where V_e, is the volume of water entering the furrow, V_i is the volume of water infiltrated into the soil, and V_s is the volume of water in storage in the furrow. Davis presents the following equation for computing the volume of water in surface storage at any point as the water advanced down the furrow.

$$V_s = (c \cdot f(d) + e) X$$

where c is a factor that depends upon the shape of the water surface and the shape of the furrow, f(d) is some function of the depth of water flowing, e, described as the puddle factor and represents the depth of water that would remain in the depressions along the length of furrow in question if the furrow were first filled with water and then drained, and X, which represents the length of furrow the water has covered in its advance.

Assuming the shape of the water surface to be a cubical parabola, Davis gives the following values for c. For a rectangular shaped furrow, c equals 0.75; for a triangular shaped furrow, c equals 0.375; and for a semicircular shaped furrow, c equals 0.321. These values indicate the influence of furrow shape upon the volume of water, V_s, that is stored in the furrow.

The depth of water flowing is a function of the shape of the furrow and the hydraulic roughness of the channel. Davis states that this can be calculated by using Manning's equation and assuming a value for Manning's "n". This calculation includes many variables, i.e. rate of flow, channel shape, and the error in assuming a value of Manning's "n". A study of the influence of rate of flow and channel shape on Manning's "n" was conducted by Thornton (11). The results of this study show that the value of Manning's "n" is inversely related to the rate of flow. It is also related to channel shape, but this relationship is not defined by this study.

The rate of flow of water in an irrigation furrow decreases along the length of the furrow as water is lost by infiltration along the length of the furrow. A decreasing rate of flow indicates that Manning's "n" will vary throughout the length of the furrow. Variation in the value of Manning's "n" makes the calculation of the depth of water flowing as recommended by Davis to be an impractical approach to determining the depth of water flowing.

The equation derived for computing the volume of water infiltrated into the soil, V_i, was based upon the empirical infiltration equation, $I = Kt^n$. The derived equation is not presented here due to its complexity. Davis assumes that the data for evaluating this relationship, for the soil in question, will be obtained from cylinder or furrow infiltrometer devices. This relationship was modified in the advance equation by a factor F. With this modification the relationship was more representative of the infiltration characteristics of a length of irrigation furrow.

Davis subjected the equation, as derived, to field tests and found it to give good results. Results of the field tests proves the basic assumptions used in deriving the equation are sound. The equation is limited in its application because the unknown factors, i.e. c, K, F, e, and f(d) must be evaluated from field test data. This is true because so little is known about predicting these factors prior to the actual advance of water in an irrigation furrow.

The equation, even though it is limited in its practical application, does indicate the factors that influence the rate of advance of water in an irrigation furrow. These factors are the volume of water in surface storage, V_s, and the volume of water infiltrated into the soil, V_i, for a given volume of water entering the furrow. The volumes, V_s and V_i, can be shown to be interdependent.

From a discussion of the process of infiltration by Yong and Warkentin (13) it would appear that the rate of infiltration of water from the furrow into the soil depends upon the porosity of the surface in contact with the flowing water. Freshly formed irrigation furrows may contain a volume of "soil rubble." Soil rubble is defined for the purpose of this discussion as any loose soil particles regardless of particle size. The volume of soil rubble in the furrows contains large sized or macro pores between the soil particles. These macro pores are in contact with the flowing water. Under these conditions infiltration rates are high and remain high until the macro pores of the volume of soil rubble are filled. The infiltration rate will change when the soil rubble is wetted and the water from this wetted layer of soil begins to infiltrate into the undisturbed soil below it. Because this soil was undisturbed during the furrowing operation it will have a different infiltration rate, due to pore size, than that of the soil rubble. From this discussion it appears that an irrigation furrow may, due to the surface conditions present in the furrow, have a compound infiltration rate. This relationship can materially influence the rate of advance.

It appears that any influence the condition of the irrigation furrow has on the empirical infiltration relationship, will influence the value of the factor F in Davis's equation. The factor F, used as a modifier of the empirical relationship determined from sources other than the furrow, also varies with furrow conditions. The factor F then may vary with furrowing method and also from irrigation to irrigation as the condition of the furrow is changed by the irrigation process. Furrowing tools or shovels with the ability to limit the change in the condition of irrigation furrows would limit this variation in factor F. Limiting the change in condition of irrigation furrows would result in the rate of advance as predicted being influenced by the infiltration characteristics of the soil in question and not the condition of the soil in the irrigation furrow.

Bassett and Tinney (6) conducted studies of flow variables in irrigation furrows under laboratory conditions. These studies were conducted using a tilting flume with no infiltration allowed from the furrow being studied. The influence of several variables upon the depth of water flowing, and therefore the volume of water stored, in the furrow was investigated.

The variables investigated included five stream sizes, 0.1, 0.2, 0.3, 0.4, and 0.5 cfs, five channel slopes, 0.0, 0.1, 0.25, 0.5, and 1.0 percent, and three degrees of channel roughness. The three degrees of channel roughness were simulated by using the smooth concrete channel, 3/8" x 3/4" expanded metal, and 3/8" - 3/4" crushed rock.

Results of these studies prove that the depth of flow in an irrigation furrow is directly related to stream size and inversely related to the percent of channel slope. The channel shape used in these investigations is not given but it would appear that these results would be valid for any channel shape.

*The results of the tests of hydraulic roughness show that the depth of flow in the smooth concrete channel is the lowest. The expanded metal produced a greater depth of flow than the smooth concrete channel and the crushed rock roughness simulation produced the highest flow depth. While not stated, it appears that the flow depths observed with these three degrees of hydraulic roughness are directly related to the height of the roughness.

The hydraulic roughness simulations investigated in this study appear to simulate some of the roughness conditions found in irrigation furrows under field conditions. The smooth concrete may be considered representative of a smooth earthen channel. The expanded metal and crushed rock simulations may be considered representative of varying degrees of hydraulic roughness caused by soil rubble that is found in irrigation furrows after the furrowing operation. While these simulations may give some valid indication of the influence of the hydraulic roughness caused by soil rubble upon the depth of flow, it does not consider the stability of the roughness under hydraulic conditions. Crushed rock and expanded metal would be very stable under the hydraulic conditions present during the flow in irrigation furrows. Soil rubble does not have this stability under the same conditions. If the results obtained using the roughness simulations are related to soil rubble, it would appear to be a valid relationship only in the initial stages of wetting of the soil rubble. This would indicate that the influence of the hydraulic roughness due to soil rubble is a transitory influence. Therefore, the depth of flow, and at the same time the volume of water in storage, in an irrigation furrow containing soil rubble is transitory.

Flow resistance in simulated irrigation furrows was studied by Kruse, Huntley, and Robinson (4) under laboratory conditions. These studies were conducted on irrigation furrows constructed in soil-like material in a tilting flume. As with the studies of

Bassett and Tinney, no infiltration from the furrow was allowed. The use of the tilting flume allowed the investigators to study flow resistance on several slopes. Flow rates ranged from 0.01 to 1.1 cfs. Rectangular and parabolic shaped channels with varying degrees of roughness were used in the collection of data. The roughness used was obtained by various methods of channel forming. After forming the roughness was stabilized with a cement like substance. This allowed the roughness to be measured and also to be subjected to various flow conditions.

Results from these studies indicate that the resistance coefficient for rough, laminar flow can be predicted by the following prediction equation:

$$f = \frac{6.0 \times 10^4 S^{0.5} \left(\frac{\sigma}{\lambda p}\right)}{Re}$$

where f is the resistance coefficient from the Darcy-Weisbach formula, S is the slope of the channel, Re is the Reynolds number, and σ and λp are measures of the roughness height and the longitudinal spacing of the crests of the heights respectively. More specifically the roughness height measurement represents one standard deviation about the mean elevation of the stream bed.

The resistance coefficient for turbulent, hydraulically rough flows can be predicted for both wide rectangular and parabolic channels by the following prediction equations:

$$\frac{C}{g} = 6.06 \log \frac{R}{\chi}$$

and $$\chi = 12.9\,\sigma^{1.66}$$

where C, if Chezy's resistance coefficient, g, is the acceleration due to gravity, and R is the hydraulic radius of the flow.

Further conclusions drawn from these studies indicate that the variation in flow resistance caused by a range of parabolic cross sections is negligible compared to the effects of boundary roughness.

The resistance prediction equations determined by Kruse, Huntley, and Robinson, were subjected to field test by Heermann, Wenstrom, and Evans (12). The results of the field tests verify the validity of the prediction equations when subjected to field conditions.

From these studies, it appears that the value of the parameter σ, is important in determining the resistance to flow in an irrigation furrow. In the case of turbulent flow a large value of σ, results in a small value of Chezy's "C". For rough laminar flow a large value of σ results in a large value of Darcy-Weisbach's friction factor, f. The influence of σ can, in the case of rough laminar flow, be modified by the average longitudinal spacing of the roughness crests. A large average spacing results in a smaller f, and a small average spacing in the crests results in a larger f if the height of the crests σ remains constant.

The resistance coefficients, calculated by these prediction equations, have a direct relationship upon the factor f(d) as defined by Davis (2) in the derivation of the rate of advance equation. With this knowledge it can be shown that the volume of water in surface storage is directly related to the flow resistance of the irrigation furrow.

It would appear that the parameters, σ and λp used in the prediction equations for calculating the resistance coefficients, can be influenced by the tool used to form the furrow. If the tool forms a channel containing soil rubble that consists of large soil particles, σ would have a large value and λp would depend upon the number of large soil particles per unit length of the furrow. The value of λp would also be influenced by the random placement of the soil particles making up the soil rubble and also the amount of the soil particles. A furrowing tool or shovel that eliminates or minimizes the volume of soil rubble in the furrow channel will reduce the flow resistance of the channel. Reducing the flow resistance will reduce the volume of water in surface storage along the length of the furrow. Reduction of the volume of water in storage per unit length of the furrow allows the volume of water entering the furrow to wet a longer furrow length.

The argument that soil rubble influences the volume of water stored in the furrow and the volume of water stored in the soil is supported by a study of furrowing shovels conducted by Thornton (11). In this study two shapes or irrigation furrows were compared in a field study. One shape was a flat-bottom furrow. The other furrow was described as a "conventional shaped" furrow. The description, "conventional shaped," does not clearly define the furrow shape. Rate of advance data was collected during the field trials conducted in this study.

Thornton plotted rate of advance curves, distance vs time, from the data collected, and found this to be a straight line on log-log paper. The equation of this curve is:

$$L = a\ t^{b}$$

where L is the distance the water has advanced in the time t; a, the distance of the advance at t equals unity; t, the time in minutes required for the advance to the point in question; and b, an exponent of the logrithmic function. The constants a and b are determined by plotting experimental data.

Thornton, in his interpretation of the results of this study, states that furrow shape will affect the rate of advance of water in an irrigation furrow. It required 4 hours for the same rate of flow to advance 800 feet in the "conventional" furrow while only 3 hours were required in the flat-bottom furrow. Thornton then states that the reason for the difference in the rate of advance in the two types of irrigation furrows was due to one of the shovels removing most of the dry soil, the soil rubble, from the flow channel. He further states that the dry, loose soil remaining in the "conventional" furrow resulted in a higher initial rate of infiltration of water to the soil.

On the basis of these statements, it appears that one would be justified in concluding that both the shape of the channel and the presence or absence of the soil rubble in the channel influenced the rate of advance of the water in the furrows. The conclusion is further justified by the assumptions used by Davis (2) in deriving his advance equation.

The relationship of the length of advance vs time in

Thornton's study plotted as a straight line on log-log paper. Christiansen analyzed field data collected by Criddle that indicated the same relationship of length of advance vs time. From the results of studies of these investigators, one can assume that length of advance vs time will plot as a straight line on log-log paper.

EVALUATING EQUATIONS

From the review of literature it appears that the furrowing tool or shovel may influence the volume of water stored in the furrow and also the volume of water infiltrated to the soil. Christiansen, Bishop, Keifer, and Fok (8) have developed mathematical solutions suitable for performing an analysis of this influence.

Israelsen and Hansen (14) presents two equations that can be used to represent the infiltration characteristics of soil. These equations are empirical and have been determined from infiltration data collected during experimental studies.

The equations are:

$$I = Kt_i^n \qquad (1)$$

and

$$I = C + Kt_i^n \qquad (2)$$

where I is the rate of infiltration or intake rate at any t_i; K is the rate of infiltration at t_i equals 1; n is an exponent that is always negative with values between 0 and -1. The factor C in equation (2) is the rate of infiltration when t_i equals infinity. Equation (1) is the same as used by Davis (2) in deriving his rate of advance equation. This infiltration equation has been used by Criddle, Davis, Pair, and Shockley (10) in their evaluation of experimental data. Equation (2) provides a better fit of experimental data collected from soils requiring long infiltration times to infiltrate the desired volume of water to the soil.

The accumulated depth of water, D, that enters the soil in any contact time, t_i, can be determined by intergrating equations (1) and (2) with respect to time between the limits of t equals 0 and t equals t_i. Thus for equation (1) one obtains:

$$D = \frac{Kt_i^{n+1}}{(n+1)} \qquad (3)$$

and for equation (2)

$$D = Ct_i + \frac{Kt_i^{(n+1)}}{(n+1)} \qquad (4)$$

The following terms and assumptions are used by Christiansen, Bishop, Kiefer, and Fok in the development of their solutions.

L = length of furrow wetted in a given time t_1. For purposes of this analysis, the average storage is assumed constant. This assumption has been used by other investigators.

Q = rate of flow entering the furrow, assumed constant

W = spacing of the furrows

q = Q/W rate of flow per unit width

D_a = the average depth of water that has entered the soil in time t_1

D_s = the equivalent average depth of water stored on the surface

One can then write for any time t_1

$$\therefore Qt_1 = D_sWL - D_aWL$$ or dividing by W

$$qt_1 = D_sL - D_aL$$

where

Qt_1 = the volume of water that has entered the furrow in time t_1

D_sWL = the volume of water remaining on the surface at time t_1

D_aWL = the volume of water that has entered the soil

The average depth of water that enters the soil, as it flows down a furrow in time t_1, can be approximated by integrating equations (3) and (4) between the limits of t equals 0 and t equals t_1, and dividing by t_1. Performing this integration and division on equation (3) one obtains:

$$D_a = \frac{Kt_1^{n+1}}{(n+1)(n+2)} \qquad (5)$$

and for equation (4)

$$D_a = \frac{Ct_1}{2} + \frac{Kt_1^{n+1}}{(n+1)(n+2)} \qquad (6)$$

Equations (5) and (6) are approximations applicable until the water reaches the end of the furrow.

Keifer (7) observes that the average depth D_a, determined by equations (5) and (6) is an exact solution if the rate of advance is constant. Using the rate of advance equation, L equals at^b, Keifer modified equations (5) and (6) so that exact solutions were possible when the actual rate of advance was used. In the case of (1) the resulting equation is:

$$D_{at} = FD_a = \frac{FKt_1^{n+1}}{(n+1)(n+2)} \qquad (7)$$

and in the case of equation (2)

$$D_{at} = FD_a = \frac{CT_1}{(b+1)} + \frac{FKt_1^{n+1}}{(n+1)(n+2)} \qquad (8)$$

The factor F in these solutions is the beta function for which exact solutions are available. This value can, however, be approximated by the simple equation:

$$F = \frac{n-bn+2}{1+b}$$

Using the relationship expressed by equation (7), experimental data may be analyzed by plotting the function:

$$D_{at} = \frac{FKt_1^{n+1}}{(n+1)(n+2)} \qquad (9)$$

$$= \frac{qt_1}{L} - D_s$$

against the time t_1, on log-log paper. If the basic equation (1) is valid, a straight line should result. The intercept of this straight line for t_1 equals 1 is the value of F K/(n+1)(n+2), and the slope of the line is the value of (n+1).

If a straight line does not result, but rather a curve which is concave upward, it might be possible to use equation (8) and secure a better fit. In this case:

$$\frac{F\ K\ t_1^{n+1}}{(n+1)(n+2)} = \frac{qt_1}{L} - D_s - \frac{C\ t_1}{2} \qquad (10)$$

The best value of C can be determined by trial and error.

While trial and error methods must be used in plotting the expression for $F\ K\ t_1^{n+1}/(n+1)(n+2)$ from either equation (9) or (10), these solutions allow one to analyze the influence of furrowing tools on the volume of water stored on the surface, D_s, and the rate of infiltration of water into the soil. To do this one only needs to know the quantity of water flowing into the furrow, Q, and by experimentation determining the rate of advance equation $L = at^b$ for the furrow in question.

DESIGN ON THE FURROWING TOOL

The forming of an irrigation furrow, accomplished in one field operation, can be considered the result of two distinct mechanical operations. The first operation is the excavation of the flow channel from the soil surface. The second operation is the deposition of the excavated material or spoil upon the berms of the flow channel. Most of the conventional tools used to form irrigation furrows excavate the furrow channel and by a throwing action attempt to deposit the spoil on the berms of the channel. The throwing action results in much of the loose material, the soil rubble, dropping back into the channel.

In the development of the experimental tool it was decided that the excavated material would be pushed to the berms. It is obvious that the greater the side slope, i.e., more horizontal units of measurement per unit of furrow depth, of the furrow channel, the less the difficulty that will be encountered when depositing the spoil on the berms. Less difficulty is encountered because loose soil is more easily deposited upon a flat slope than on a steep slope. Utilizing this approach, the physical size of the furrowing tool and the spacing of the crop rows become important factors in determining the size of the irrigation furrow. Also the depth the tool is operated influences the condition of the finished furrow. If the tool is operated too deep, more material will be excavated than the tool has the ability to place on the berms. Should the tool have the physical size to place the material, the width of the crop row may limit the berm width thereby limiting the size of the area where the spoil can be deposited. The inability of the furrowing tool to deposit the spoil on the berms will result in a furrow containing soil rubble.

From the results of Kruse, Huntley, and Robinson (4), it would appear that a parabolic channel, regardless of its size, would influence the flow resistance due to channel shape the least of any furrow shape. However a furrow of complete parabolic shape will be hard to form. A tool could be designed to excavate a parabolic channel but, depending upon channel size and depth, the deposition of the spoil could be difficult. This is true because the side slope of a true parabolic shaped channel approaches the infinite.

Considering these facts, and the discussion of the term c, by Davis (2) in the derivation of the rate of advance equation, a furrow shape composed of a combination of parabolic and trapezoidal shapes was selected as the more practical shape.

The shape of the furrow cross section was developed as follows: Assuming a desired channel side slope, and width of the parabolic section w, the first derivative of the parabolic equation $y = ax^2$, was equated to the value of the desired side slope at $x = w/2$, and solved for a. Using this value of a in the original parabolic equation, a depth of channel was calculated using a value of $x = w/2$. At this depth and channel width the trapezoidal shaped section and the parabolic section, making up the cross sectional shape of the furrow, are tangent. Tangency at this point results in the boundary of the flow channel being continuous even though the shape of the furrow is a composite of two different geometric shapes. This procedure determines the shape of the cross section of the experimental irrigation furrows.

Using the cross sectional shape determined by the procedures explained, it was then projected onto a plane surface that was inclined at an angle of 15° from the horizontal. The plane thus shaped, becomes the basic part of the experimental furrowing tool. Moldboards to prevent the soil, excavated from the furrow channel, from flowing over the plane and being redeposited in the channel, were attached on the upper surface of the inclined plane. These moldboards forced the excavated soil to flow toward the berms of the excavated channel as the tool is drawn through the soil. Steel plates, conforming to the side slope of the channel, were welded to the under side of the plane. These plates assist in the deposition of the spoil on the channel berms. The plates also aid in preventing loose soil from the furrowing operation, soil rubble, from being deposited in the furrow. The resulting furrow has a smooth boundary and is essentially free of soil rubble.

Two experimental tools were constructed using these procedures. The shovels are shown in Plate I. The two tools formed irrigation furrows differing only in the side slope of the furrow channel. One tool constructs furrows with a channel side slope of 2.0:1 and the other 1.5:1. A common width of the parabolic section was used in the construction of both tools, namely w = 3.5 inches. These tools were designed for a row width of 40 inches.

PUDDLE FACTOR STUDY

In the rate of advance equation, derived by Davis (2), the factor e is described as the puddle factor. The puddle factor, multiplied by furrow length in question, represents the volume of water that is stored in the depressions along that length of furrow. Such water can best be described as "dead water" because it does not contribute, except in an indirect way, to the volume of water necessary for flow in an irrigation furrow. Davis states that the puddle factor is due to surface roughness and the land grading accuracy of the area being irrigated. In the field trials he conducted, he estimated the size of this volume to be within a range of .001 and .003 cubic feet per foot of furrow length.

The value of e is used in the equation as a correction factor. When used in this manner, errors in estimating the value of e may not materially influence the fit of the equation to field data. However the need to fill this volume will influence the actual rate of advance in the field. Removing or minimizing this volume in an irrigation furrow should improve the rate of advance

EXPLANATION OF PLATE I

Experimental Furrowing Tools

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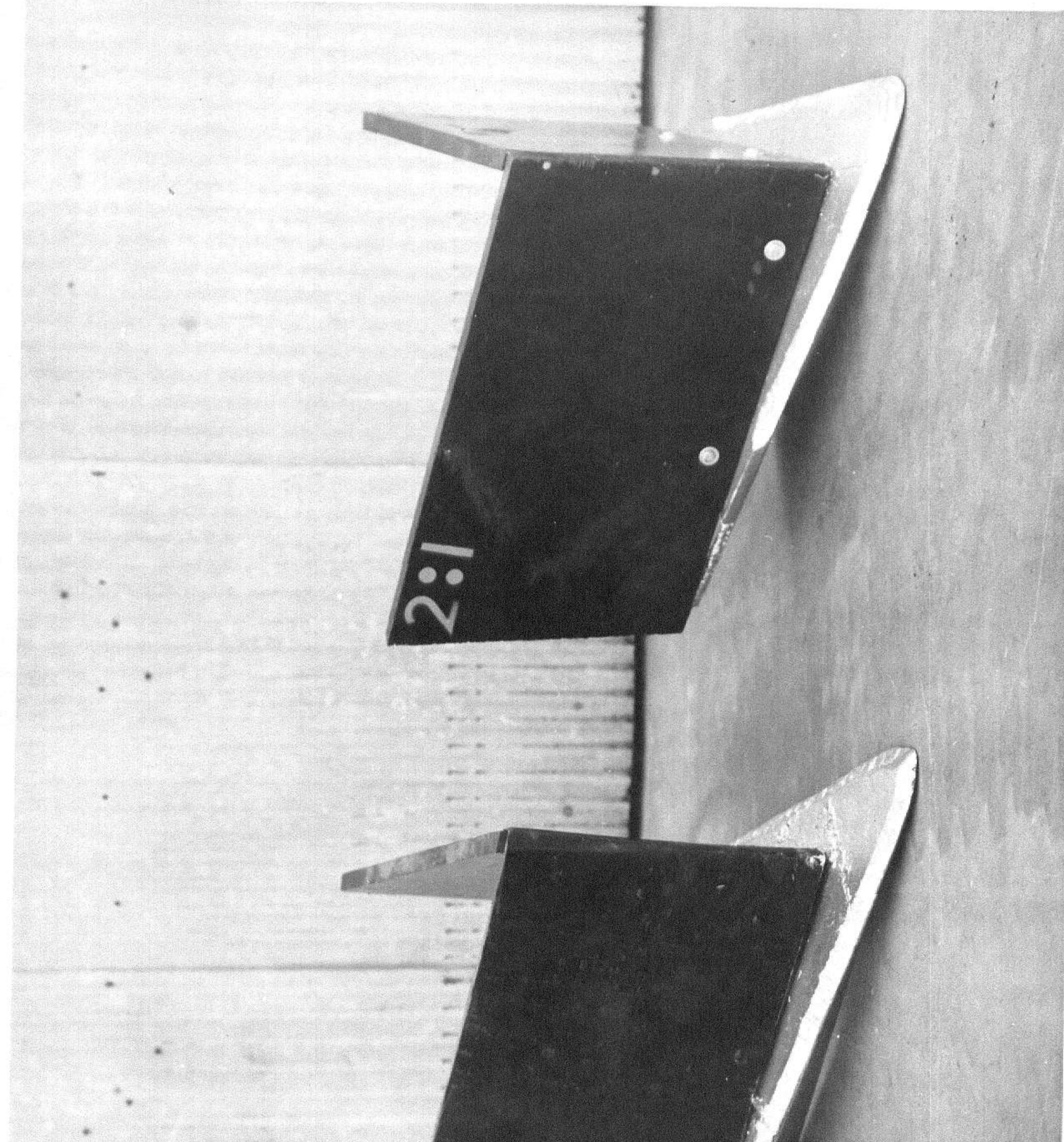
PLATE I



obtained with a given quantity of water entering the furrow. It would become more important as the quantity of water entering the furrow decreases.

Most furrowing tools are mounted on a tool bar and become an integral part of the traction unit or tractor used for the furrowing operation. The pitch and roll of the traction unit, due to roughness of the soil surface, and the resulting influence on the furrowing tool, may be a factor in creating depressions along the furrow. The pitch and roll action may also increase the value of the puddle factor. Pitch of the traction unit is defined, for the purpose of this discussion, as rotation of the traction unit about its rear axle. Roll is defined as the rotation of the traction unit about the point of contact with the soil surface of either rear wheel. Rotation of the traction unit about its rear axle will influence the working depth of the furrowing tool mounted on the tool bar. The influence due to roll will depend upon which rear wheel is the center of rotation, the position of the furrowing tool on the tool bar and its distance from the center of rotation.

The tool bar is, on most farm tractors, controlled by the hydraulic system of the tractor. The hydraulic system can be adjusted so that it will control the working depth of the tool mounted on the tool bar. The system can also be adjusted so that the draft requirements of the tool remain constant. Variable draft requirements of the tool will actuate the hydraulic system thereby changing the working depth of the tool. Most hydraulic systems can be adjusted to respond to a combination of the above conditions. The control actions of the hydraulic system on the tool bar may also contribute to the value of the puddle factor.

PROCEDURE AND EQUIPMENT

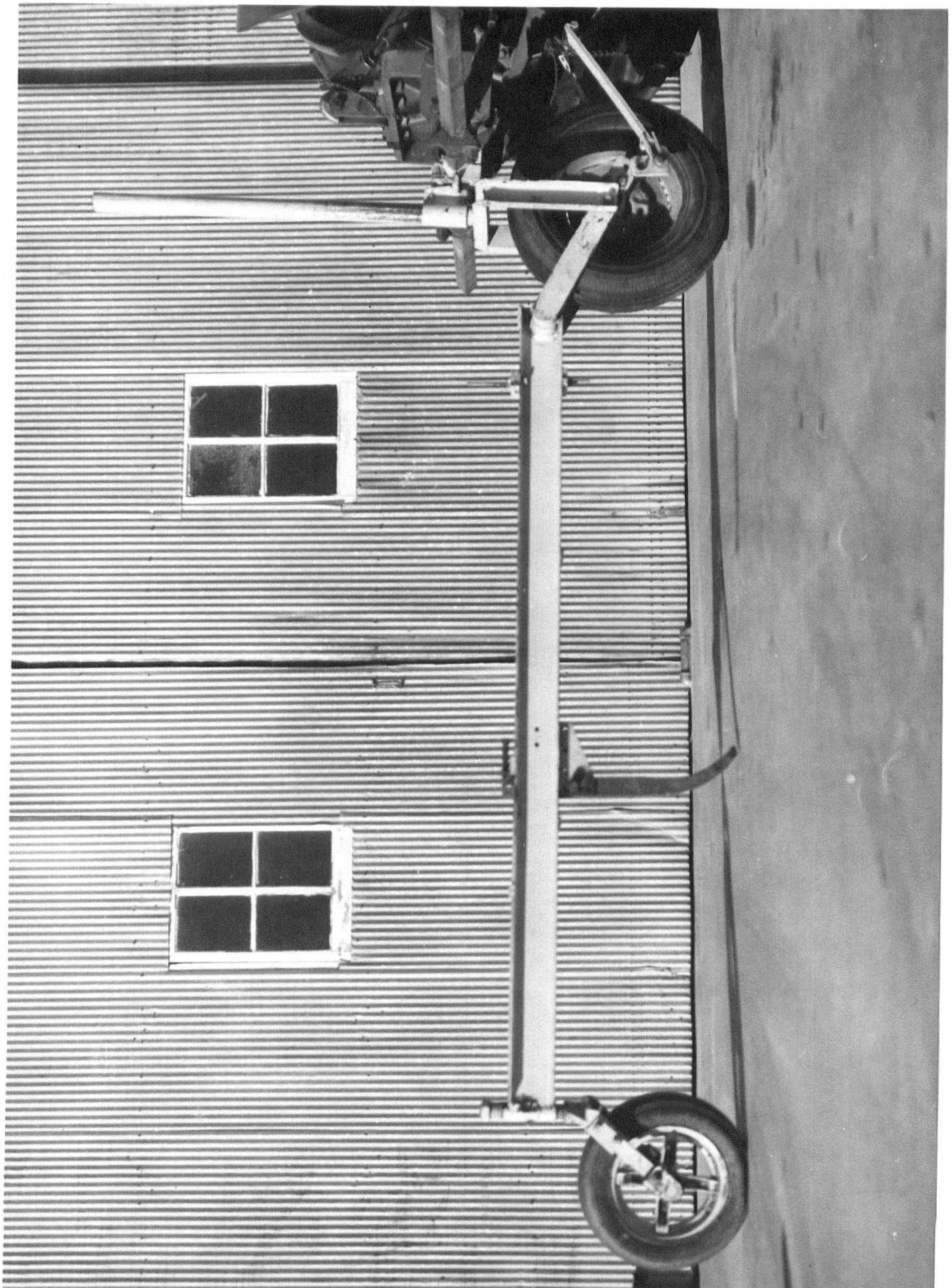
A field study was conducted to determine if the tool bar mounting of furrowing tools influences the puddle factor and thereby the rate of advance of water in an irrigation furrow. The study compared tool bar mounted furrowing tools and furrowing tools mounted on an experimental mounting device. For this study the tool bar mounted furrowing tool was mounted on the center line of the traction unit. Mounted in this position the influence of roll will be reduced one half. Roll in either direction will influence the tool equally. Furrowing tools mounted on the experimental mounting device were free of any influence of the traction unit or its hydraulic system. A photograph of the experimental mounting device is shown, with the furrowing tool removed, in Plate II. From the photograph it is readily apparent that only the contact of the front and rear wheels with the soil along the center line of the furrow being formed will influence the action of the furrowing tool. When the furrowing tool is mounted on the experimental mounting device, the point of the shovel operated at a point approximately half the distance between the supporting wheels. Mounted in this manner the influence of surface roughness of the soil being furrowed on the working depth of the tool will be minimized due to the lever arm action of the experimental device. The working depth of the tool, when mounted on the experimental mounting device, was controlled

EXPLANATION OF PLATE II

Experimental Furrowing Tool

Mounting Device

PLATE II



by rotating the front wheel about its pivot point.

The puddle factor study consisted of 4 treatments. The treatments were as follows:

T1 - 1.5 : 1 Experimental tool mounted on tool bar

T2 - 1.5 : 1 Experimental tool mounted on experimental device

T3 - 2.0 : 1 Experimental tool mounted on tool bar

T4 - 2.0 : 1 Experimental tool mounted on experimental device

Each treatment was used to furrow 5 irrigation furrows spaced on 80-inch centers. Each furrow was 340 feet in length. These treatments were randomized and replicated three times.

An equal rate of flow, 2.6 gpm, of water was entered into each furrow. The rate of flow was obtained by establishing a predetermined head of water on 3/4" siphon tubes.

The time required for the water to advance 340 feet was recorded for the center 3 furrows of each plot. The data collected from this study is recorded in Appendix A.

RESULTS

An analysis of variance was used to analyze the results of this study. The mean value of data collected from the three furrows in each plot was calculated and used as the value for the plot in this analysis. The results of this analysis are shown in Table 1. The F test was used to determine significance among the variables.

Table 1.

Source	D/F	ss	ms	F
Tool Shape (S)	1	0.00	0.00	0.0
Tool Mounting (M)	1	4,486.33	4,485.33	4.39*
S X M	1	75.00	75.00	----
Error	6	6,130.67	1,021.78	

*Denotes significance at the .10 level.

The results of the analysis indicates that the two different experimental tools, used in this study, did not significantly influence the rate of advance of water in the furrow. Therefore, the two channels, although different in dimensions, are equal in their rate of advance performance. Tool mounting was significant at the 10 percent level. Due to the placement of the furrowing tool on the tool bar, the influence on the furrowing tool due to the roll of the traction unit may have been minimized. The conclusion is drawn that mounting of furrowing tools influences the rate of advance of water in an irrigation furrow.

COMPARISON OF FURROWING TOOLS

A field study comparing the performance of an experimental furrowing tool with a popular furrowing tool was conducted on crete soils at the Irrigation Experiment Field, Scandia, Kansas. The field study was conducted during the period of July 16 through July 19, 1968.

The popular furrowing tool selected for this study was a rotary moldboard type furrowing tool. The rotary type tool was selected due to its popularity of use in the area where the study was conducted. A photograph of the rotary furrowing tool is shown in Plate III.

The crop irrigated in the study was corn planted in 30-inch rows. The experimental tools used in the puddle factor investigation were designed for use in 40-inch rows. The change in row width made it necessary to design an experimental tool for use in 30-inch rows.

The basic design of the experimental furrow cross section, as described in the section of this thesis on design of the furrowing tool, was not changed. The construction of the tool was changed in some respects but this did not influence the resultant action of the finished tool. In designing the tool for 30-inch rows, the width of the parabolic section was reduced from 3.5 inches to 3.0 inches. The side slope of the furrow channel was changed to 1.0 : 1. A photograph of the experimental furrowing tool used in the comparison study is shown in Plate IV. Plate V is a photograph of the experimental furrowing tool in operation.

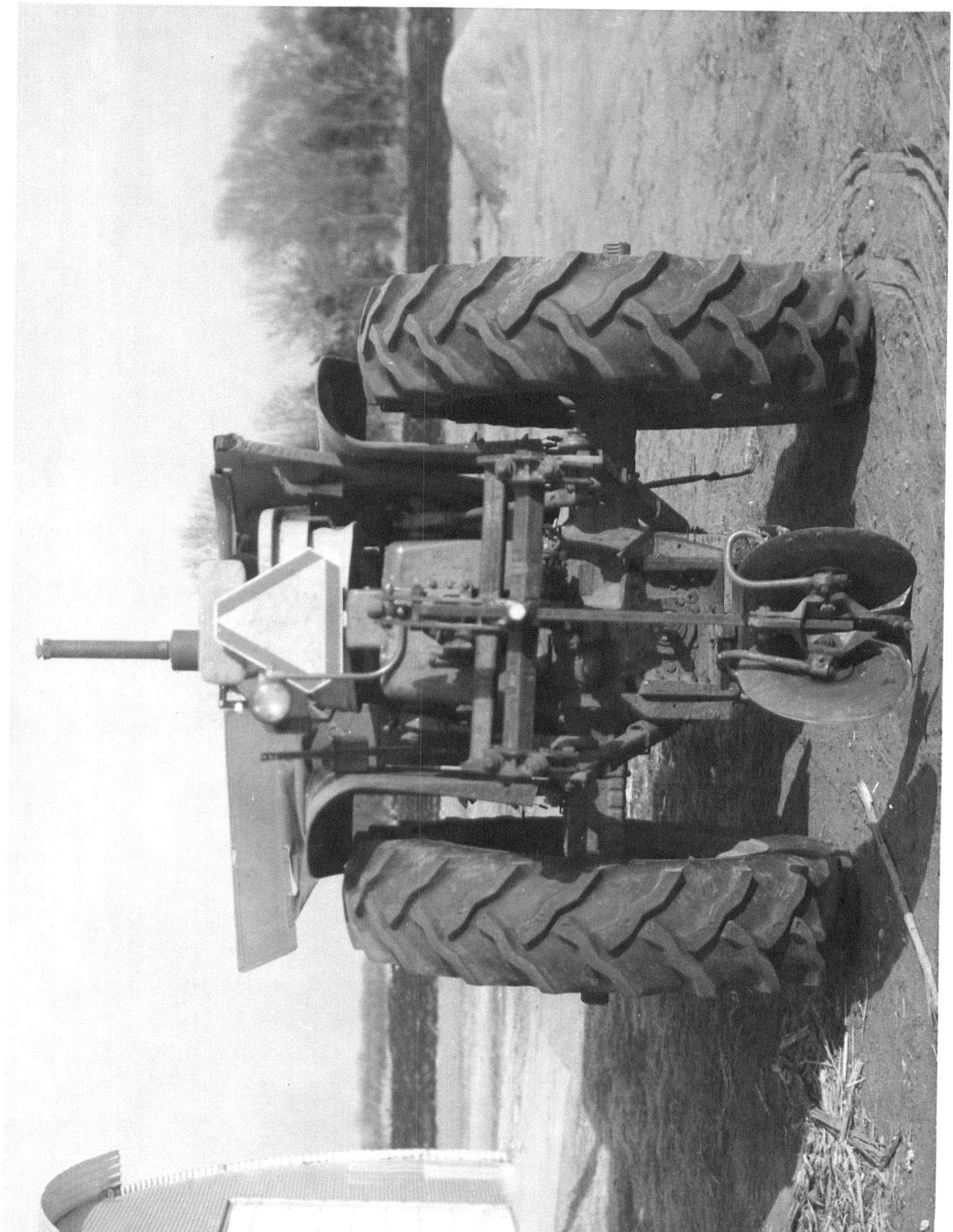
EXPERIMENTAL PROCEDURE

A land area measuring 300 feet by 350 feet was selected. The area was selected for its uniformity of soil. Use of this area reduces the variable of soil in this study. The area was prepared by land planing the surface prior to the corn planting operation.

EXPLANATION OF PLATE III

Rotary Type Furrowing Tool

PLATE III



EXPLANATION OF PLATE IV

Experimental Furrowing Tool

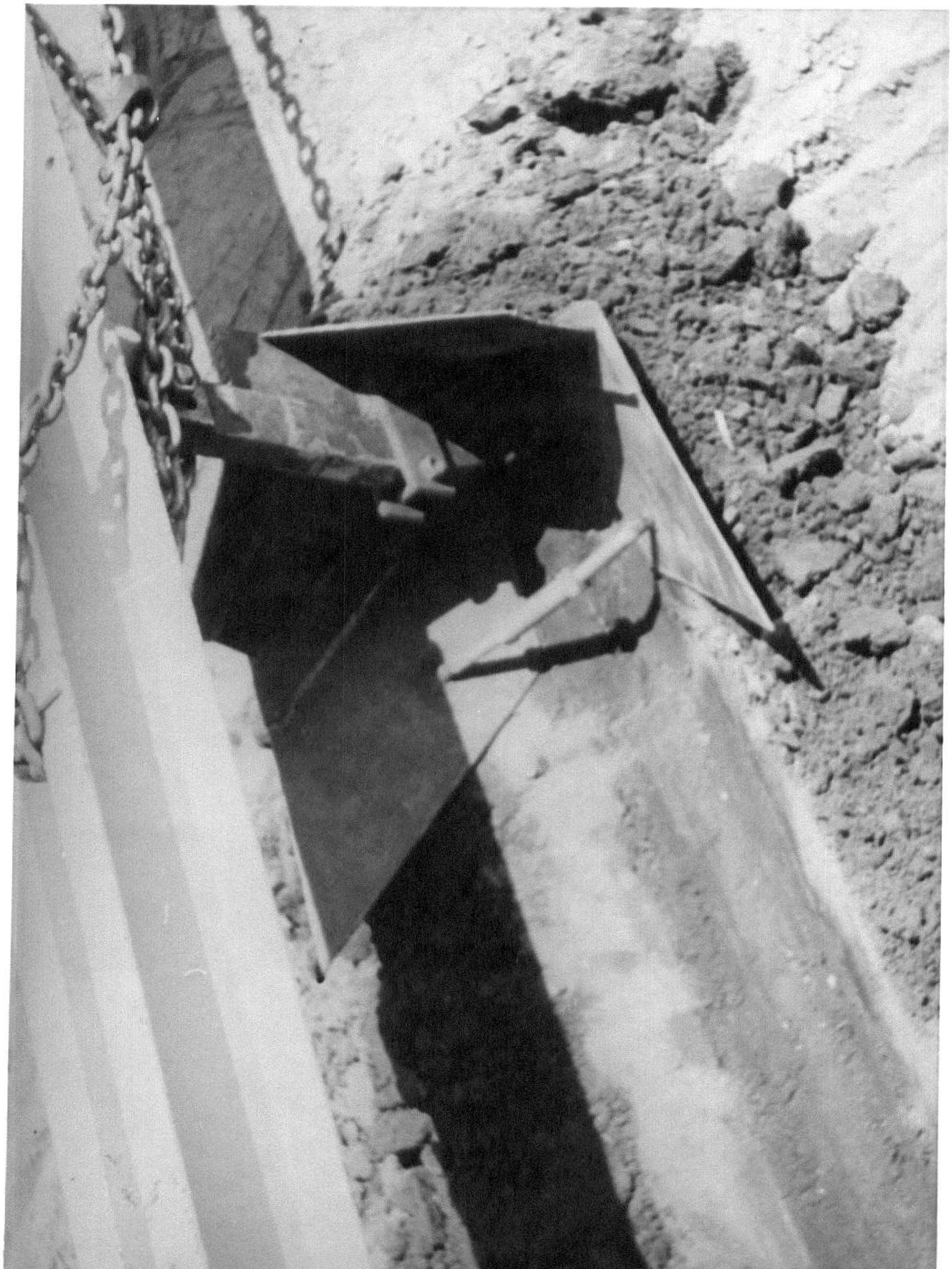
Used in the Comparison Study

PLATE IV

EXPLANATION OF PLATE V

Experimental Furrowing Tool
in Operation

PLATE V



Six random variables were considered. The treatments were, 2 furrowing tools, experimental and rotary, and 3 rates of flow, .94, 3.1, and 6.1 gallons per minute. Each plot consisted of one furrow 100 feet in length, formed by one of the tools, having a predetermined flow rate. The plots were spaced on 60-inch centers. Each replication consisted of 6 randomized plots. The plots were designated by the following code:

Code	Furrowing Tool	Flow Rate
X1	Experimental	.94 gpm.
X3	Experimental	3.10
X5	Experimental	6.10
L1	Rotary moldboard	.94
L3	Rotary moldboard	3.10
L5	Rotary moldboard	6.10

Four replications were used in the study.

The rates of flow were obtained by subjecting a siphon tube of selected diameter to a predetermined head of water. The water from the siphon tube was dropped onto a plastic apron and was conveyed thereon to the 0 station of the 100-foot furrow. Stations at 10-foot intervals were marked along the length of the furrow. These stations were used to determine the length of advance vs time curve necessary for use with the evaluating equations developed by Christiansen, Bishop, Keifer, and Fok (8). The water leaving the furrow, the runoff, was conveyed from the 100-foot station of the furrow to the place of measurement on another plastic apron. The runoff water was measured volumetrically. Three identical studies were conducted in the selected area on slopes of .2, .4, and .6 percent. The slopes were possible in the selected area by selecting the direction of the crop rows.

within the area. Slope was not considered a random variable in the study.

The plots were furrowed July 9, 1968. Plaster of paris casts were made of furrow shapes formed with each furrowing tool. The casts record the condition of the freshly formed irrigation furrows. The casting sites were chosen by random drawing. Plate VI is a photograph of the four casts made. Casts No. 1 and 2 are from the furrow formed with the experimental tool. Casts No. 3 and 4 are from the furrow formed with the rotary furrowing tool. From the casts the amount and size of the soil rubble present in the furrows can be observed. The flow channel of the furrows formed with the experimental tool is well defined. The shape of the casts from the furrows formed with the rotary type tool indicates that the flow channel still must be defined by the water that will flow in the furrow. The amount and size of the soil rubble in the furrows indicates the resistance to flow of the flow channels. The size of the pores in the soil rubble in the furrows formed with the rotary type tools indicates a high rate of infiltration of water from the furrow to the soil.

Soil samples, to be used for soil moisture determinations, were taken from each furrow immediately prior to entering water in the furrow.

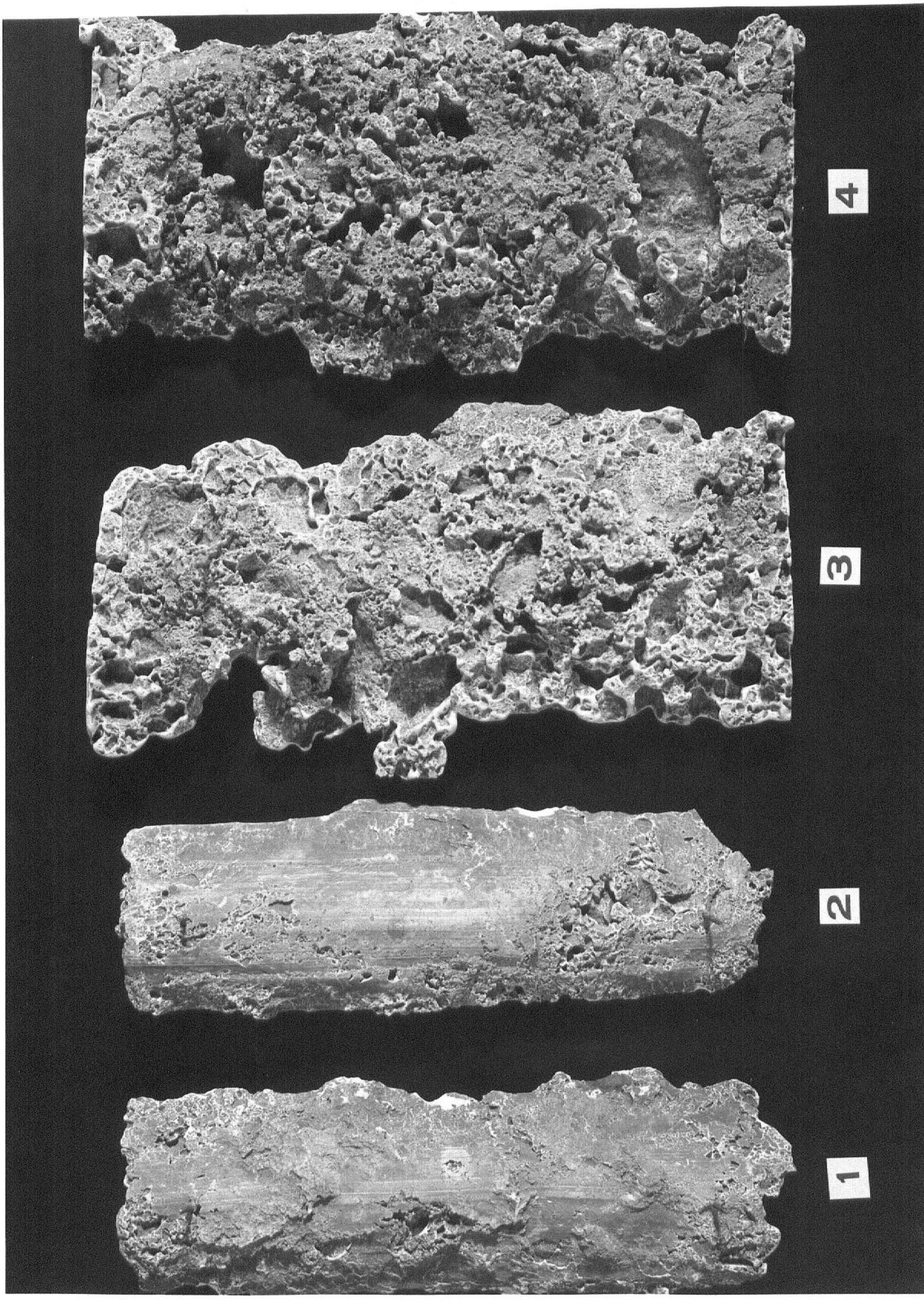
The time was recorded as the water passed the 0 station of the furrow. The elapsed time was noted and recorded as the water reached each of the 10-foot stations along the furrow and was continued until the water reached station 100. Measurement of the rate of runoff was made periodically throughout the period

EXPLANATION OF PLATE VI

Plaster of Paris Casts of

Freshly Formed Irrigation Furrows

PLATE VI



of irrigation. The elapsed irrigation time when the runoff measurements were made was also recorded. All data collected during the irrigation of the three studies is recorded in Appendix B.

ANALYSIS OF DATA

The moisture content of the soil in the various plots, of like treatment, varied. The time required for the water to advance the length of the plot, 100 feet, also varied. The relationship of these variables was investigated and no apparent correlation between the variables was discovered.

The total time of advance for all plots on a given slope were subjected to an analysis of variance. On all slopes, the difference in total time of advance due to furrowing tool, rate of flow, and the interaction of flow rate and furrowing method were highly significant. The results of the analysis of variance for the studies conducted on .2, .4, and .6 percent slopes are presented in Tables 2, 3, and 4.

Table 2.--Results of analysis of variance, total time of advance, .2% slope.

Source	D/F	ss	ms	F
Furrowing tool (T)	1	23,445.63	23,445.63	156.9***
Flow rate (F)	2	46,616.12	23,308.06	156.0***
T X F	2	14,735.80	7,367.90	49.3***
Error	15	2,241.74	149.45	

*** Denotes significance at all levels.

Table 3.--Results of analysis of variance, total time of advance, .4% slope.

Source	D/F	ss	ms	F
Furrowing tool (T)	1	24,089.47	24,089.47	175.9***
Flow rate (F)	2	63,675.98	31,837.99	232.5***
T X F	2	16,924.39	8,462.19	61.8***
Error	15	2,054.15	136.94	

*** Denotes significance at all levels.

Table 4.--Results of analysis of variance, total time of advance, .6% slope.

Source	D/F	ss	ms	F
Furrowing tool (T)	1	40,525.42	40,525.42	743.3***
Flow rate (F)	2	47,308.34	23,654.17	433.9***
T X F	2	21,306.98	10,653.49	195.4***
Error	15	817.84	54.52	

*** Denotes significance at all levels.

The advance data, collected from individual furrows, was tested for a linear relationship between the two variables, distance and time. A linear relationship was determined when the variables were plotted on log-log paper.

The rate of advance date, from four furrows of like treatment on a given slope were pooled and subjected to regression analysis. In this analysis, L, or distance is considered the independent variable. The dependent variable is T, or time. The variables were considered in this manner due to the layout of the study. Therefore time T, was regressed on distance L. The resulting regression equation is, T equals AL^B. The equation, T equals AL^B, was considered to be the average representative of a given treatment. The determined regression constants A and B are recorded in Table 5.

The determination of the equation, T equals AL^B, was necessary for use in the evaluating equations. However, it is in the wrong form. Keifer's (7) modification of Christiansen, Bishop, and Fok's equations requires this relationship to be expressed as L equals at^b. Solving the equation T equals AL^B for L, one can prove mathematically that the value of b is the reciprocal of B. Therefore, the reciprocal of B was used for b when using the evaluating equations.

Table 5.--Constants A and B for use in the equation, $T = AL^B$

Treatment	Slope					
	.2		.4		.6	
	A	B	A	B	A	B
X1	.028	1.646	.021	1.769	.019	1.594
X3	.009	1.780	.007	1.752	.017	1.406
X5	.008	1.573	.008	1.540	.010	1.281
L1	.248	1.455	.338	1.389	.456	1.306
L3	.101	1.408	.120	1.330	.201	1.261
L5	.085	1.284	.096	1.243	.154	1.158

The trial and error solutions required by the evaluating equations were performed and the empirical infiltration equations for the average representative of the six treatments were determined. Both empirical infiltration equations presented by Israelsen and Hanson (14) were needed to fit the data of the various treatments. The evaluating equations also evaluated the depth of surface storage D. The constants evaluated by the trial and error solutions for the empirical equations and D_s for the six treatments are recorded in Appendix B.

The depth of storage, D_s, was converted into a volume, V_s by multiplying D_s by the width of the crop row and the length of the plot. Since the rate of advance is inversely related to the volume of storage, V_s, the influence of furrowing method on V_s is important. The influence of furrowing method on V_s on all slopes is presented graphically in Plate VII.

The rate of advance is also inversely related to infiltration rate. Therefore the influence of furrowing method upon the infiltration rate is also important. The value of K alone, from the empirical infiltration equations, does not represent the infiltration characteristics of all the furrows studied due to the fact that one empirical equation was not evaluated for all furrows. Therefore the infiltration rate at t_i, irrigation time, equals 1 minute, was calculated and used to show the influence of furrowing tool on infiltration rate on all slopes. The influence of furrowing method on infiltration rate on all slopes is presented graphically in Plate VIII.

From Plate VII and Plate VIII it is apparent that the furrows formed with the rotary furrowing tool have a larger volume of water in storage and also have a higher infiltration rate than the furrows formed with the experimental furrowing tool. The presence of soil rubble in the rotary furrow causes a greater resistance to flow. Increased flow resistance increases

EXPLANATION OF PLATE VII

Fig. 1 Volume of water in surface storage in furrows on .2 percent slope.

Fig. 2 Volume of water in surface storage in furrows on .4 percent slope.

Fig. 3 Volume of water in surface storage in furrows on .6 percent slope.

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PLATE VII

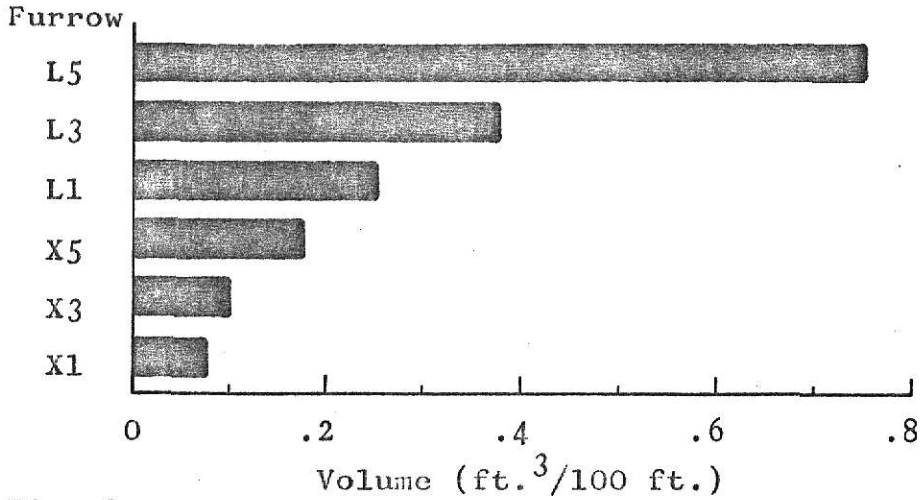


Fig. 1

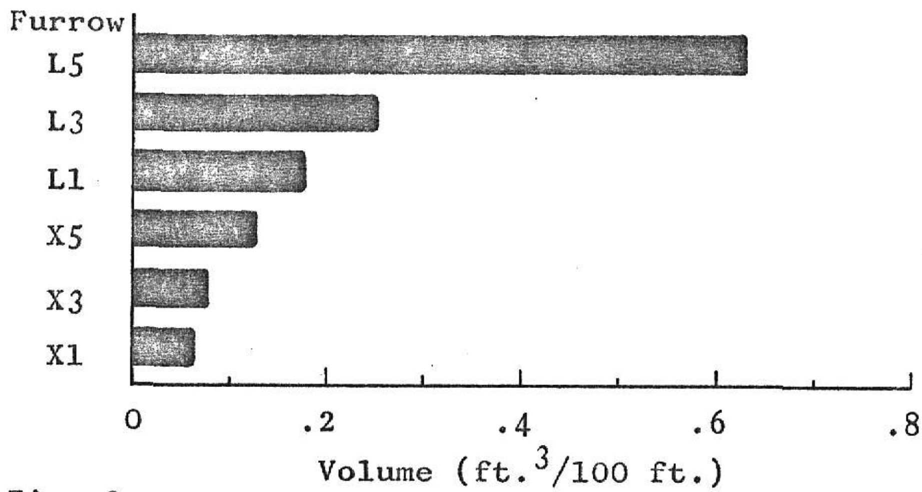


Fig. 2

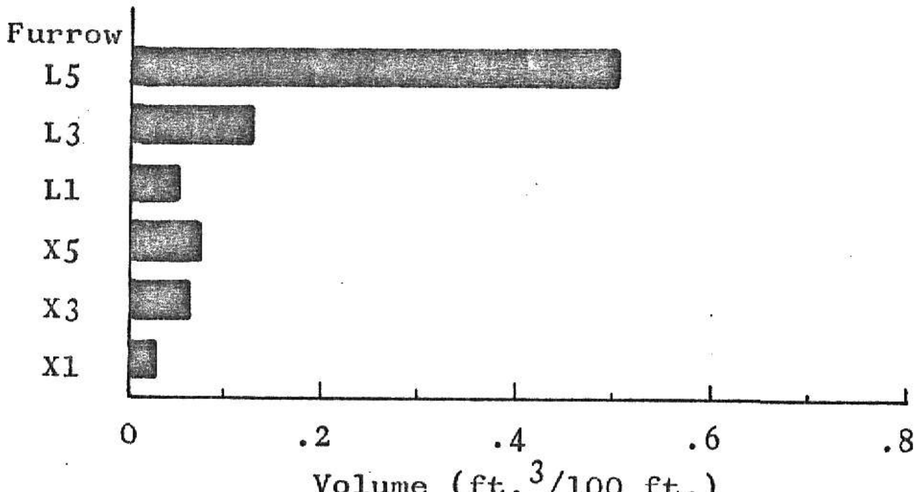


Fig. 3

EXPLANATION OF PLATE VIII

Fig. 1 Intake rate of irrigation furrows @ t_i equals 1 minute on .2 percent slope.

Fig. 2 Intake rate of irrigation furrows @ t_i equals 1 minute on .4 percent slope.

Fig. 3 Intake rate of irrigation furrows @ t_i equals 1 minute on .6 percent slope.

PLATE VIII

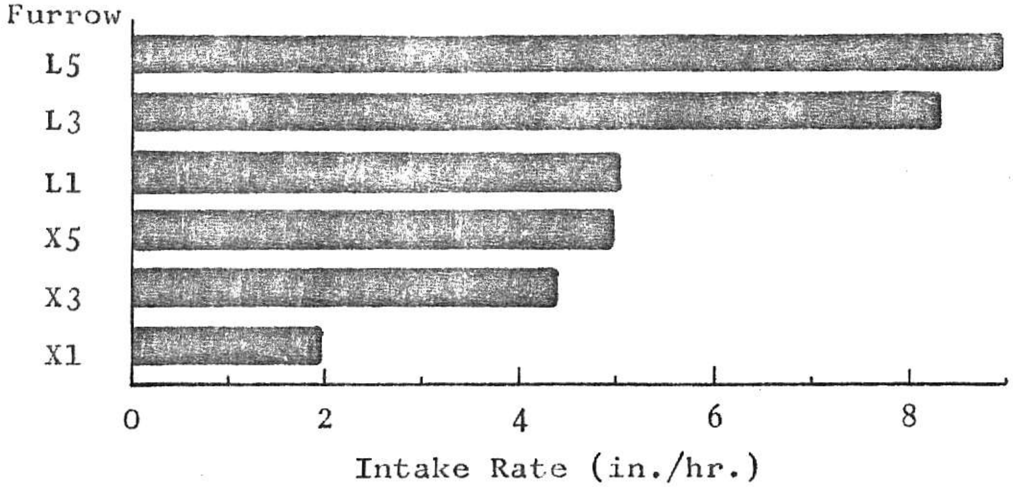


Fig. 1

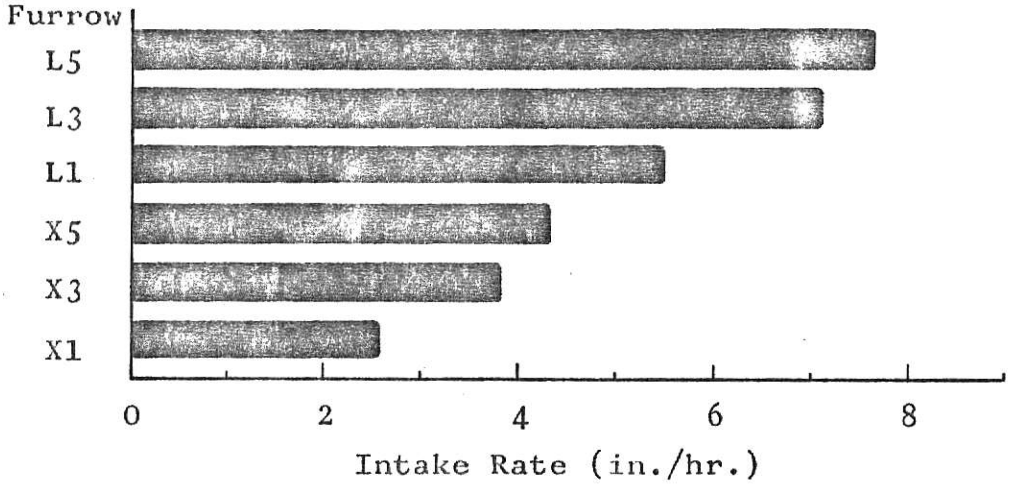


Fig. 2

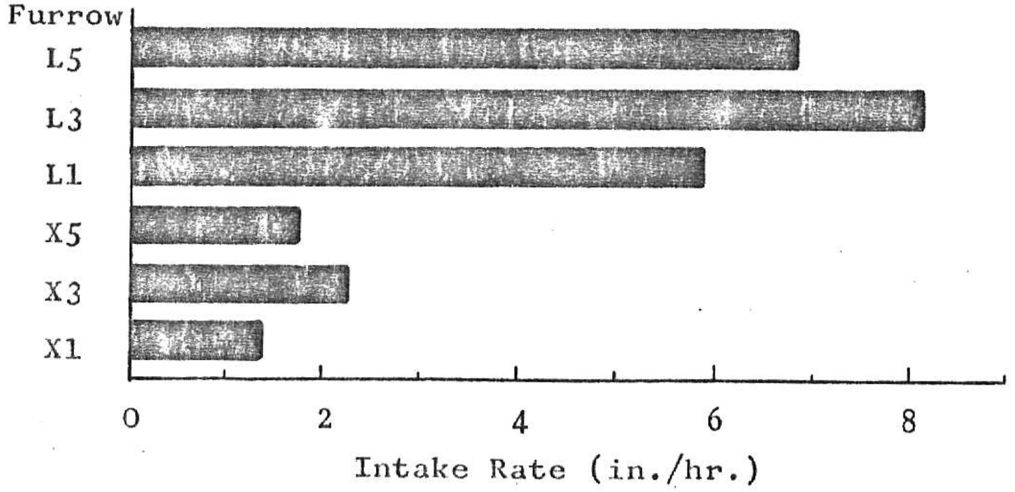


Fig. 3

the volume of storage V_s. The soil rubble also causes the furrow to have a higher rate of infiltration. These two factors combine to cause a slower rate of advance for a given quantity of water in the rotary furrow on a given slope.

Using the runoff data collected, average observed intake rates for the 100-foot furrows were determined. To do this the outflow rate was subtracted from the inflow rate and the remainder was divided by the width of the crop row in feet, 2.5 feet. The elapsed irrigation time, recorded when the runoff measurement was made during the collection of the data, was used to define the relationship of the average observed intake rate with irrigation time.

The intake rate vs time data from 4 furrows of like treatment on a given slope were pooled. The pooled data was subjected to regression analysis, regressing intake rate on time. The resulting regression equation is assumed to represent the average observed intake rate of a treatment at any valid time. Valid time in this case means any elapsed irrigation time within the elapsed irrigation times used to compute the regression equation. The regression equations are recorded in Appendix B. The plotted regressions representing average observed intake rate vs time are presented in Plates IX and X.

The empirical infiltration equations determined by the evaluating equations were used to calculate the average intake rate for the average representative of a treatment. The calculation was made as follows: Assuming an elapsed irrigation time, for this purpose 600 minutes was used, a rate of infiltration

EXPLANATION OF PLATE IX

Fig. 1 Average observed intake rate, in./hr., vs elapsed irrigation time, t_i, on .4 percent slope.

Fig. 2 Average observed intake rate, in./hr., vs elapsed irrigation time, t_i, on .6 percent slope.

PLATE IX

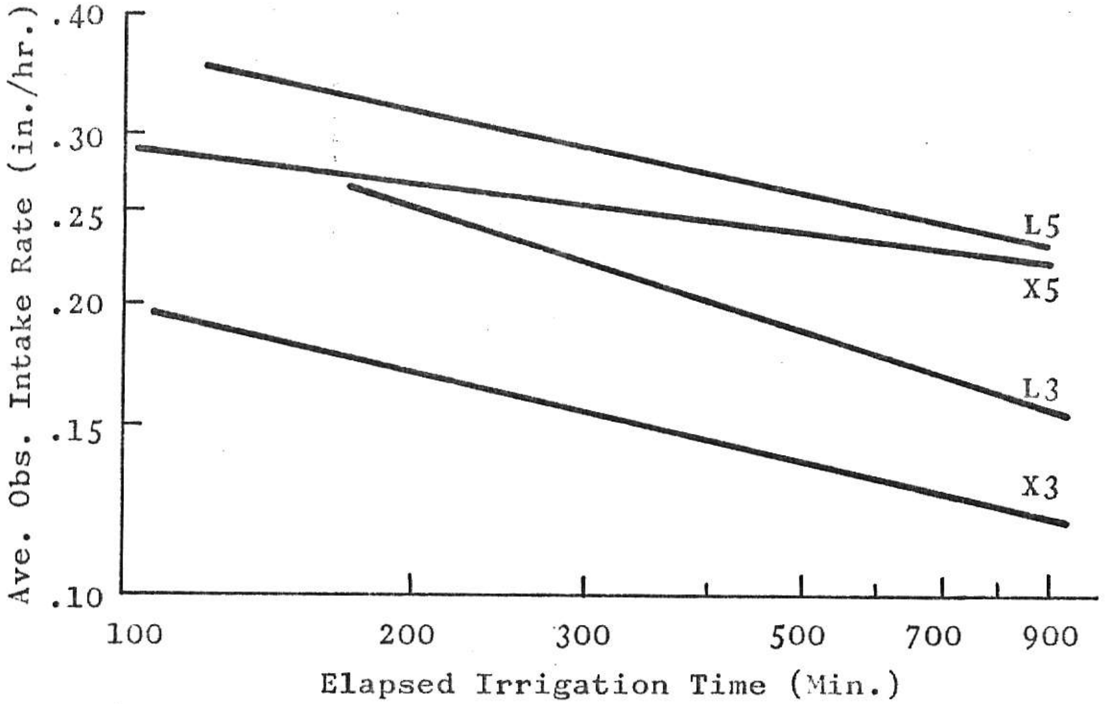


Fig. 1

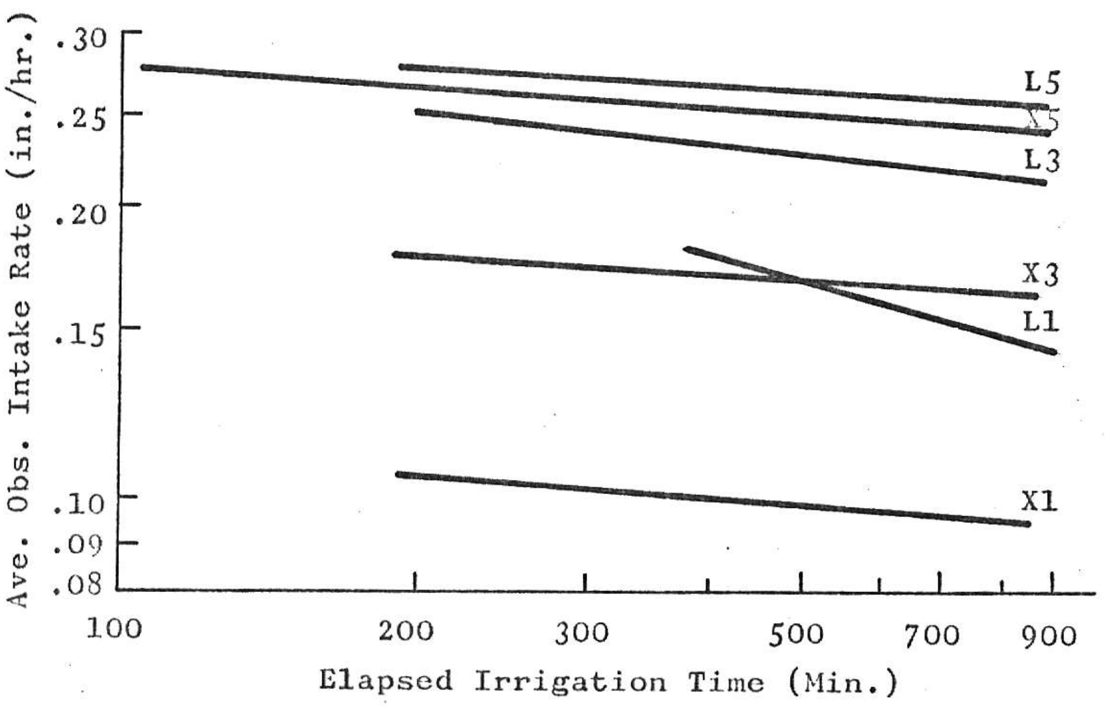
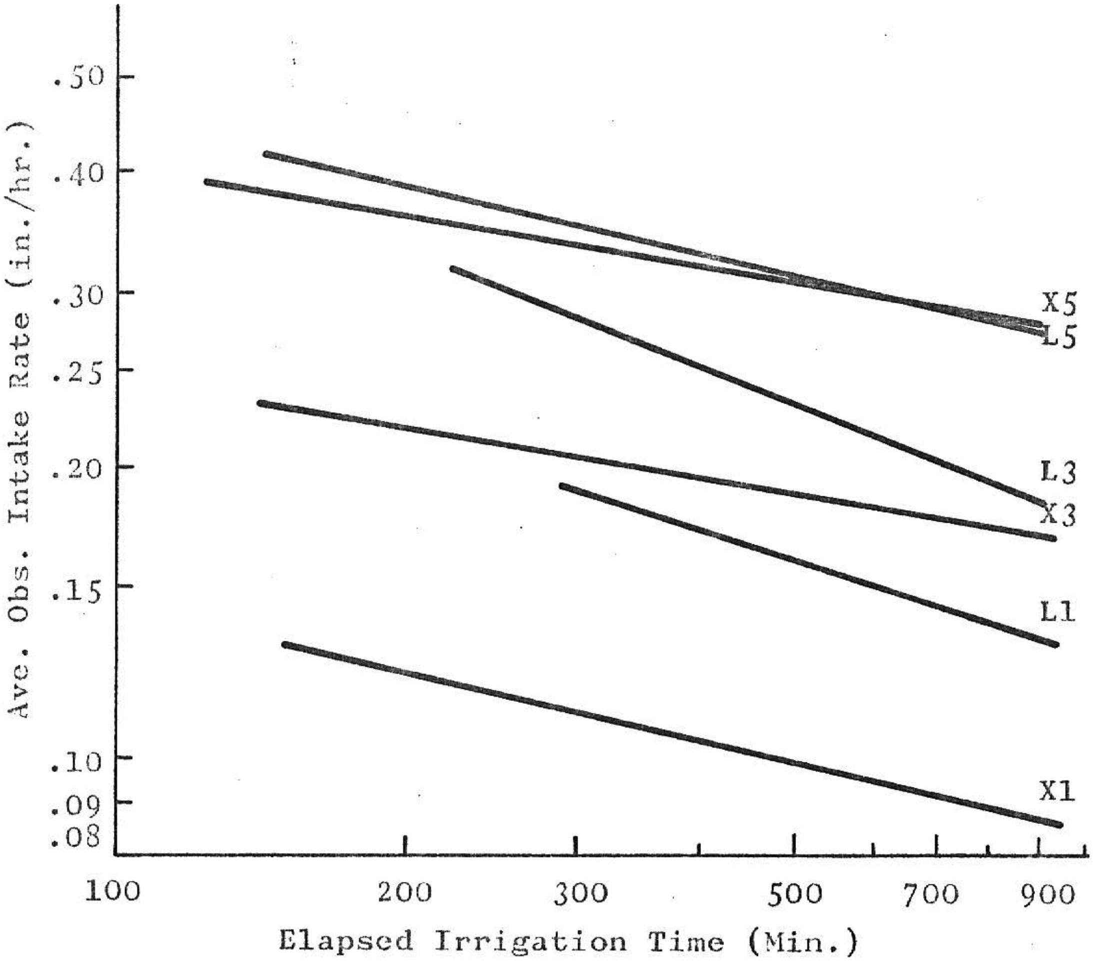


Fig. 2

EXPLANATION OF PLATE X

Average observed intake rate, in./hr., vs elapsed irrigation time, t_i, on .2 percent slope.

PLATE X


.50
.40
.30
.25
.20
.15
.10
.09
.08
Ave. Obs. Intake Rate (in./hr.)
X5
L5
L3
X3
L1
X1
100
200
300
500
700
900
Elapsed Irrigation Time (Min.)

was determined at the 100-foot station. The infiltration time used at the 100-foot station was 600 minutes minus the time of advance as determined by the advance equation T equals AL^B. Summing the two infiltration rates determined in this manner and dividing by 2 the result was assumed to be an average calculated intake rate of the treatment at 600 minutes. These calculated values, for all furrows, and value of intake rate at 600 minutes determined from the regressions are reported in Table 6.

Table 6.--Average observed and calculated intake rate @ 600 minutes.

Furrow	Slope .6 Ave. Obs.	Slope .6 Calc.	Slope .4 Ave. Obs.	Slope .4 Calc.	Slope .2 Ave. Obs.	Slope .2 Calc.
X1	.092	.025	----	.063	.095	.043
X3	.165	.110	.132	.140	.181	.158
X5	.245	.013	.231	.072	.295	.095
L1	.158	.057	----	.064	.150	.071
L3	.220	.055	.176	.061	.214	.098
L5	.257	.185	.250	.201	.295	.066

From Plates IX and X it can be seen that the average observed intake rate varies between the six treatments of the study. On any given slope the L5 and X5 treatments have essentially the same intake rate. The intake rates of the L3 and X3 treatments are different. The intake rate of the L3 treatment is, on all slopes, higher initially than the intake rate of the X3 treatment. The same relationship is apparent for the L1 and X1 treatments. However in the case of the L1 and X1 treatments the initial and final intake rates vary more than in the case of the L3 and X3 treatments. The regression equations that represent the average observed intake rate for the L3 and X3 treatments are convergent. Convergence was also noted in the regression equations for the L1 and X1 treatments.

The data indicates that the rate of flow in the L5 treatment was sufficient to define a flow channel in the length of irrigation time studied. Since the average observed intake rates of the L5 and X5 treatments are essentially the same, it can be assumed that the infiltration characteristics of the flow channel, defined by flowing water, of the L5 treatment is the same as the flow channel formed by the experimental tool in the case of the X5 treatment.

The convergence of the regression equations in the case of the L3 and X3 and also the L1 and X1 treatments, indicates that after sufficient irrigation time has elapsed, the infiltration characteristics of the two furrowing treatments will approach a common value. The elapsed irrigation time required for this to happen may be more than the time required for any one irrigation.

From the plotted regressions it is readily apparent that the filtration of water from the furrow to the soil is related directly to the rate of flow in the furrow. The relationship is the same for the rotary furrowing tool and the experimental furrowing tool. This finding is not in agreement with findings of Criddle, Davis, Pair and Shockley (10).

The infiltration characteristics of an irrigation furrow appears to be influenced by slope, however the relationship is not well defined from the data collected in this study.

Comparing the average observed intake rates with the calculated intake rates, after 600 minutes of irrigation, Table 6, it is apparent that the empirical infiltration equations, determined from advance data, do not accurately predict the infiltration characteristics of the furrow after an elapsed period of irrigation. The calculated and observed values for the X3 treatment on all slopes have the least variance. The reason for the minimal variance is not apparent. The empirical infiltration equations, determined from advance data, represent the infiltration characteristics of an irrigation furrow during the time of advance, however they do not accurately represent the infiltration characteristics of the soil irrigated.

SUMMARY AND CONCLUSIONS

The influence of furrowing tools and furrowing tool mounting on the rate of advance of water in an irrigation furrow was studied. Due to a change in crop row widths, it is not possible to compare the performance of the experimental furrowing tools used in the puddle factor study with the experimental tool used in the furrowing tool comparison study.

From the analysis of the puddle factor study data, it is concluded that tool bar mounted furrowing tools significantly retard the rate of advance of water in an irrigation furrow. The experimental mounting device, used in the puddle factor study, successfully tested a mounting principle, however the device is not considered to be a design to be used in future furrowing equipment.

It appears that several conclusions can be drawn from the furrowing tool comparison study. Furrowing tools do significantly influence the volume of water in surface storage required for flow of water in an irrigation furrow. Furrowing tools also significantly influence the infiltration characteristics of an irrigation furrow. By influencing the surface storage volume and the infiltration characteristics, furrowing tools significantly influence the rate of advance of a given quantity of water in an irrigation furrow.

The infiltration characteristics are also influenced by the rate of flow of water in the furrow. Results of the comparison study indicate a direct relationship. Criddle, Davis, Pair and Shockley (10) state that rate of flow does not influence the filtration of water from an irrigation furrow. Assuming the relationship determined from the comparison study data, the rate of advance of water in an irrigation furrow becomes more important in achieving acceptable soil moisture distribution than when one accepts the assumption of Criddle, Davis, Pair and Shockley.

SUGGESTIONS FOR FURTHER STUDY

The furrowing tool comparison study, reported in this thesis, was conducted during the first irrigation of the crop season. The rate of advance of water was superior in the furrows formed with experimental furrowing equipment when compared to the rate of advance of water in furrows formed with a rotary tool. Further study of the influence of furrowing tools during the second and third irrigations was prevented due to the weather conditions of the 1968 season.

The rate of advance of water in furrows of like treatment varied. The reason for this variability could not be ascertained from the data collected. The author would suggest, in future studies of this type, that soil temperature be monitored to determine the influence of a varying soil temperature upon the rate of advance of water in an irrigation furrow.

The benefit of the experimental equipment is obvious during the first irrigation. Experience in field irrigation would indicate that the experimental tools would have superior performance during the first irrigation of all years.

Further study is required to determine the variability of performance of the experimental tools throughout a total irrigation season. The variability of furrowing tool performance from irrigation season to irrigation season is also important. By using furrowing equipment that results in irrigation furrows that vary the least in performance, throughout an irrigation season and from irrigation season to irrigation season, an irrigator will achieve better control of irrigation water. Control of irrigation water should enable an irrigator to apply irrigation water more effectively and efficiently than is presently possible.

ACKNOWLEDGMENTS

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APPENDIX A

Experimental Data

PUDDLE FACTOR STUDY

TOTAL TIME OF ADVANCE

TREATMENT	FURROW	REP. I	II	III
T1	2	248	169	190
	3	176	184	188
	4	216	212	188
T2	2	187	264	261
	3	135	239	159
	4	160	199	---
T3	2	333	336	198
	3	243	211	175
	4	166	169	336
T4	2	176	226	254
	3	235	190	274
	4	193	240	334

APPENDIX B

Experimental Data

% Slope	Furrow	Code	Cumulative Times (Minutes) Station 10	20	30	40	50	60	70	80	90	100	% Soil Moisture
.2	1	X3	.44	2.45	7.00	14.31	19.40	23.65	28.85	33.60	34.60	40.30	14.6
	2	L5	2.25	5.08	7.30	11.00	15.42	19.60	24.70	28.85	32.00	35.90	---
	3	L3	2.25	22.30	28.40	46.30	46.50	46.85	53.65	60.75	70.35	76.90	14.9
	4	X5	.28	.65	1.20	2.00	2.60	4.70	5.95	6.90	8.15	9.65	12.2
	5	X1	1.20	5.12	8.90	9.98	11.60	23.65	25.55	40.30	52.00	73.10	10.5
	6	L1	4.80	11.95	31.15	41.20	62.50	105.00	---	---	---	170.00	13.8
	7	X1	1.35	5.30	8.65	9.30	18.35	28.35	34.80	44.75	61.70	68.55	14.3
	8	X5	.30	1.22	1.92	3.56	4.54	5.95	8.52	9.51	10.46	12.07	13.0
	9	L5	1.50	4.18	7.14	10.33	13.70	17.25	29.75	31.80	36.35	42.35	---
	10	L3	3.70	9.40	13.95	18.70	24.80	31.65	41.30	54.50	71.80	77.30	15.2
	11	L1	6.70	19.50	35.60	62.04	87.82	106.70	120.90	138.30	162.00	202.20	12.8
	12	X3	.45	3.05	5.40	9.20	10.30	12.75	17.90	20.50	---	30.45	11.6
	13	X1	.82	7.47	16.82	18.32	23.02	28.62	31.02	33.17	46.92	53.07	12.6
	14	X3	.40	.75	1.20	1.95	2.75	5.85	7.10	8.10	12.70	14.75	12.5
	15	L3	2.05	7.00	12.65	16.10	23.85	27.80	34.95	40.20	44.40	51.80	17.3
	16	X5	.23	.50	.85	1.30	4.30	5.00	7.00	7.80	8.90	10.75	11.7
	17	L1	6.15	20.70	34.60	67.00	86.00	94.10	118.15	154.75	174.20	214.45	15.0
	18	L5	1.46	3.73	6.10	8.56	10.65	13.10	16.05	19.09	23.85	28.10	15.4
	19	L5	.95	3.60	5.95	8.95	11.70	16.05	18.95	21.00	24.30	28.30	13.4
	20	L3	2.20	8.35	12.15	17.20	22.85	28.90	34.80	48.10	50.00	60.30	13.6
	21	X1	.75	3.65	5.25	6.50	8.10	11.30	13.40	19.85	36.40	43.65	12.3
	22	L1	7.05	21.50	43.80	58.10	73.79	94.20	114.70	133.45	160.60	181.30	11.8
	23	X5	.40	1.17	1.57	2.07	2.55	4.55	5.05	7.45	9.00	10.28	18.3
	24	X3	.65	1.30	9.90	11.70	15.60	22.45	25.50	31.65	37.80	41.15	11.1

% Slope	Furrow	Code	Cumulative Times (Minutes) Station 10	20	30	40	50	60	70	80	90	100	% Soil Moisture
.4	1	L5	1.48	3.12	5.92	8.95	11.78	15.50	18.15	21.30	24.85	28.44	14.7
	2	L1	9.40	21.90	42.30	55.50	80.50	110.60	130.48	---	220.00	---	---
	3	X3	.36	.78	2.90	4.18	7.00	8.00	10.80	11.75	15.00	18.70	9.3
	4	L3	2.70	5.70	9.10	13.55	18.15	22.25	27.60	35.45	41.40	48.45	10.9
	5	X5	1.02	1.24	2.08	3.46	5.82	7.69	10.00	11.77	13.40	15.67	13.6
	6	X1	.65	5.50	10.70	14.70	18.30	42.89	48.31	58.06	69.65	78.50	---
	7	X1	1.50	4.30	9.20	18.20	21.10	26.16	41.21	57.26	61.16	77.85	13.8
	8	X5	.23	---	---	1.78	2.62	3.24	4.03	6.05	8.37	9.66	15.0
	9	L3	2.40	6.20	11.70	---	23.00	28.75	34.40	40.00	47.90	54.30	17.3
	10	L1	5.80	20.50	33.30	57.00	73.70	110.77	128.11	137.40	220.00	---	13.8
	11	X3	.35	1.68	3.37	4.40	8.90	---	12.30	14.55	16.60	20.00	12.1
	12	L5	2.30	4.41	7.05	9.80	12.95	15.80	19.47	23.35	26.40	30.73	10.8
	13	X1	.90	5.00	10.60	13.80	22.00	24.90	37.00	42.70	51.10	62.80	11.5
	14	X5	.25	.49	1.01	1.80	3.30	3.91	4.81	5.95	7.07	8.35	13.5
	15	L5	1.78	4.95	8.24	11.35	14.39	16.85	20.51	23.69	26.63	30.46	15.3
	16	X3	.47	1.22	2.42	4.66	9.00	10.35	12.77	14.20	16.75	19.78	11.1
	17	L3	2.89	7.60	12.25	18.83	23.30	29.59	36.89	47.27	57.80	63.16	15.9
	18	L1	9.30	20.90	40.00	60.00	65.00	96.00	110.00	135.00	---	---	15.0
	19	L1	8.78	20.50	40.00	58.00	72.00	82.00	130.00	150.00	165.00	---	10.3
	20	X1	.85	2.36	11.83	12.80	19.25	24.92	37.00	42.00	46.00	54.00	12.1
	21	X3	.11	1.65	3.50	7.39	9.20	11.80	16.95	20.17	26.49	28.03	12.9
	22	X5	.24	.89	1.54	2.59	3.19	4.10	5.13	6.42	7.46	8.98	---
	23	L3	2.46	6.28	11.22	16.64	21.60	27.93	33.00	39.14	46.24	53.77	10.4
	24	L5	1.40	3.30	6.70	9.50	12.00	14.90	18.20	21.50	25.10	28.20	---

% Slope	Furrow	Code	Cumulative Times (Minutes) Station 10	20	30	40	50	60	70	80	90	100	% Soil Moisture
.6	1	X3	.55	1.00	1.50	2.05	3.30	4.20	5.10	6.60	8.40	9.60	17.8
	2	X5	.20	.55	.97	1.30	1.85	2.30	2.80	3.20	3.65	5.00	13.6
	3	L1	11.37	21.60	36.55	51.30	72.40	89.90	114.50	148.00	186.30	212.40	13.9
	4	L5	2.70	5.35	8.70	12.00	15.50	19.30	23.20	27.40	30.90	35.00	14.2
	5	L3	4.05	8.10	16.05	19.85	24.90	35.90	42.40	51.80	59.85	66.00	14.6
	6	X1	1.65	2.15	4.00	5.70	7.10	9.60	12.10	17.50	22.15	29.50	9.3
	7	X1	1.70	2.15	4.30	7.40	11.52	14.85	25.33	33.60	35.10	51.40	12.0
	8	L5	2.30	4.70	7.20	9.55	11.75	15.05	20.05	24.00	27.57	32.05	13.4
	9	L1	8.32	19.60	35.08	53.60	63.50	93.20	116.10	139.80	158.80	199.00	14.4
	10	X3	.40	1.05	2.15	3.00	4.40	---	5.95	---	7.50	8.45	15.5
	11	X5	.20	.60	.90	1.20	1.60	2.17	2.95	3.65	4.25	4.95	16.4
	12	L3	2.95	7.25	11.80	16.70	22.35	31.20	37.85	48.55	55.85	66.50	14.1
	13	X3	---	1.05	1.65	4.50	5.80	9.60	11.65	13.60	14.65	16.00	---
	14	L5	2.60	4.35	6.30	9.30	12.30	15.00	18.25	22.75	26.20	30.95	16.4
	15	L1	13.12	24.38	39.00	58.25	75.30	97.40	112.80	133.50	156.70	185.60	17.0
	16	X1	.90	1.75	2.55	6.82	8.32	9.80	17.00	19.05	21.25	34.82	13.3
	17	X5	.20	.45	.80	1.17	1.47	1.85	2.20	2.65	3.05	3.65	14.6
	18	L3	3.20	8.80	14.00	20.30	25.40	31.40	37.90	49.50	57.60	63.90	8.2
	19	L5	1.80	3.90	6.05	9.20	12.05	15.35	18.70	21.75	24.95	30.30	14.9
	20	X3	---	1.40	2.05	4.30	6.45	8.40	---	11.50	13.35	15.70	12.2
	21	L3	4.80	9.75	16.35	23.15	31.35	39.30	49.35	57.60	64.00	70.55	---
	22	L1	9.24	23.50	38.90	53.43	72.00	95.95	121.30	151.50	178.40	218.60	15.2
	23	X1	.70	1.40	4.10	5.90	9.10	12.60	15.84	18.40	30.80	39.87	14.0
	24	X5	---	---	3.85	4.23	4.55	4.90	6.80	7.60	8.17	8.65	15.2

Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.	Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.
X1	5	131	.94	.58	.14	X3	12	241	3.10	2.60	.20
		284		.76	.07			348		2.64	.18
		364		.66	.11			472		2.58	.21
		630		.71	.09			580		2.63	.19
		756		.71	.09			819		2.80	.12
								950		2.79	.12
X1	7	125	.94	.54	.12	X3	14	237	3.10	2.65	.18
		272		.75	.08			351		2.64	.18
		360		.64	.12			468		2.60	.20
		618		.75	.08			583		2.62	.19
		748		.70	.08			816		2.82	.11
								945		2.80	.12
X1	13	185	.94	.68	.10	X3	24	219	3.10	2.26	.34
		294		.62	.13			377		2.51	.24
		414		.64	.12			447		2.33	.31
		526		.62	.12			602		2.26	.34
		763		.73	.08			795		2.42	.27
		892		.72	.09			929		2.34	.30
X1	21	167	.94	.60	.14	X5	4	119	6.10	5.41	.28
		312		.61	.13			204		5.38	.29
		400		.62	.13			360		5.12	.39
		540		.62	.13			437		5.55	.22
		744		.70	.10			705		5.51	.24
		878		.74	.08			831		5.55	.22
X3	1	88	3.10	2.78	.13						
		159		2.68	.17						
		329		2.67	.17						
		393		2.71	.16						
		674		2.74	.14						
		799		2.76	.14						

Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.	Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.
X5	8	127	6.10	5.06	.42	L1	17	312	.94	.37	.22
		217		5.19	.36			416		.44	.20
		361		5.06	.42			544		.43	.19
		452		5.00	.44			763		.54	.14
		705		5.45	.26			895		.55	.16
		835		5.51	.24						
X5	16	121	6.10	5.08	.41	L1	22	424	.94	.51	.17
		245		4.96	.46			405		.38	.22
		352		4.92	.47			552		.52	.17
		478		5.00	.44			753		.66	.11
		701		5.45	.26			887		.66	.11
		830		5.45	.26						
X5	23	114	6.10	5.04	.42	L3	3	263	3.10	2.38	.29
		268		5.17	.37			343		2.46	.26
		344		5.17	.37			503		2.52	.23
		494		5.12	.39			577		2.56	.22
		692		5.55	.22			847		2.65	.18
		825		5.55	.22			973		2.63	.19
L1	6	275	.94	.51	.17	L3	10	254	3.10	2.48	.25
		361		.53	.16			352		2.48	.25
		621		.65	.12			489		2.52	.23
		750		.65	.12			587		2.51	.24
								832		2.74	.14
								962		2.71	.16
L1	11	298	.94	.46	.19	L3	15	244	3.10	2.40	.28
		428		.54	.16			363		2.40	.28
		531		.51	.17			475		2.37	.29
		774		.55	.16			822		2.58	.21
		905		.63	.12			952		2.58	.21

Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.	Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.
L3	20	233	3.10	2.47	.25	L5	18	125	6.10	5.22	.35
		375		2.50	.24			256		5.16	.33
		463		2.46	.26			354		5.20	.36
		604		2.42	.27			486		5.14	.38
		811		2.61	.20			701		5.54	.22
		944		2.64	.18			833		5.54	.22
L5	2	77	6.10	5.00	.44	L5	19	155	6.10	5.12	.39
		153		5.23	.35			290		5.29	.32
		318		5.36	.30			385		5.24	.34
		388		5.08	.41			732		5.66	.18
		665		5.26	.34			864		5.60	.20
		791		5.34	.30						
L5	9	128	6.10	5.26	.34						
		220		4.89	.48						
		361		4.92	.47						
		455		4.82	.51						
		706		5.22	.35						
		835		5.24	.34						

Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.	Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.
X3	3	88	3.10	2.32	.31	X5	8	110	6.10	5.26	.34
		260		2.46	.26			283		5.38	.29
		394		2.44	.26			372		5.38	.29
		604		2.65	.18			627		5.60	.20
X3	11	75	3.10	2.55	.22	X5	14	84	6.10	5.37	.29
		251		2.54	.22			220		5.32	.31
		378		2.74	.14			395		5.52	.23
								521		5.50	.24
								740		5.66	.18
X3	16	65	3.10	2.64	.18	X5	22	76	6.10	5.38	.29
		81		2.82	.11			94		5.36	.30
		178		2.76	.14			140		5.32	.31
		355		2.70	.16			273		5.47	.25
		481		2.72	.15			423		5.42	.27
		699		2.95	.06			567		5.43	.27
								794		5.15	.38
X3	21	63	3.10	2.50	.24	L3	4	86	3.10	2.30	.32
		93		2.60	.20			259		2.56	.22
		193		2.68	.17			392		2.54	.22
		345		2.74	.14			602		2.52	.23
		484		2.76	.14						
		713		2.88	.09						
X5	5	110	6.10	5.55	.22	L3	9	79	3.10	2.25	.34
		282		5.70	.16			254		2.50	.24
		417		5.15	.38			382		2.58	.21
		627		5.76	.14			597		2.72	.15

Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.	Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.
L3	17	78	3.10	2.18	.37	L5	12	133	6.10	5.32	.31
		177		2.50	.24			308		5.53	.23
		341		2.58	.21			436		5.52	.23
		479		2.58	.21			653		5.55	.22
		697		2.70	.16						
L3	23	61	3.10	2.17	.37	L5	15	62	6.10	5.27	.33
		88		2.29	.32			114		5.20	.36
		91		2.32	.31			248		5.30	.32
		186		2.65	.18			423		5.26	.34
		331		2.60	.20			549		5.36	.30
		487		2.53	.23			758		5.40	.28
		710		2.75	.14						
L5	1	150	6.10	5.24	.34	L5	24	68	6.10	4.90	.48
		322		5.40	.28			119		5.38	.29
		456		5.45	.26			242		5.36	.30
		670		5.55	.22			766		5.34	.30

Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.	Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.
X1	6	66	.94	.60	.14	X3	10	198	3.10	2.76	.14
		193		.68	.09			336		2.72	.15
		344		.65	.12			474		2.80	.12
		416		.73	.08			557		2.77	.13
		744		.71	.09			870		2.76	.14
		828		.75	.08			968		2.73	.13
X1	7	65	.94	.52	.17	X3	13	208	3.10	2.64	.18
		194		.66	.11			360		2.65	.18
		343		.63	.12			489		2.73	.15
		417		.66	.11			583		2.69	.16
		741		.71	.09			862		2.68	.17
		830		.71	.09			995		2.48	.25
X1	16	64	.94	.84	.04	X3	20	191	3.10	2.70	.16
		227		.68	.10			375		2.60	.20
		345		.78	.06			475		2.66	.18
		450		.65	.12			595		2.64	.18
		738		.70	.10			864		2.64	.18
		864		.70	.10			1009		2.65	.18
X1	23	49	.94	.39	.22	X5	2	138	6.10	5.36	.30
		241		.63	.12			250		5.45	.26
		331		.64	.12			416		5.58	.21
		464		.70	.10			474		5.53	.23
		721		.67	.11			815		5.47	.25
		879		.75	.08			887		5.55	.22
X3	1	211	3.10	2.48	.25	X5	11	117	6.10	5.32	.31
		318		2.55	.22			260		5.71	.16
		488		2.68	.17			395		5.55	.22
		542		2.63	.17			481		5.52	.23
		886		2.64	.18			791		5.36	.30
		954		2.66	.18			894		5.43	.27

Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.	Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.
X5	17	94	6.10	5.32	.31	L1	22	256	.94	.34	.24
		260		5.32	.31			349		.42	.21
		376		5.45	.26			479		.48	.18
		484		5.40	.28			739		.58	.14
		768		5.39	.28			895		.75	.03
		897		5.45	.26						
X5	24	78	6.10	5.50	.24	L3	5	205	3.10	2.52	.23
		275		5.30	.32			328		2.62	.19
		360		5.40	.28			482		2.68	.17
		498		5.54	.22			550		2.58	.21
		752		5.53	.23			879		2.60	.20
		913		5.55	.22			962		2.65	.18
L1	3	222	.94	.32	.25	L3	12	192	3.10	2.44	.26
		385		.50	.18			340		2.46	.26
		445		.50	.18			472		2.45	.26
		783		.54	.16			562		2.44	.26
		859		.58	.14			867		2.46	.26
								973		2.49	.24
L1	9	233	.94	.40	.22	L3	18	198	3.10	2.48	.25
		375		.51	.17			367		2.44	.25
		454		.50	.18			480		2.50	.24
		772		.59	.14			592		2.48	.25
		867		.56	.15			870		2.51	.24
								1004		2.53	.23
L1	15	243	.94	.38	.22	L3	21	187	3.10	2.46	.26
		364		.50	.18			375		2.50	.24
		466		.48	.18			472		2.66	.18
		758		.56	.15			598		2.60	.20
		880		.62	.13			861		2.60	.20
								1112		2.60	.20

Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.	Code	Furrow	Elapsed irrigation time	Inflow gpm	Outflow gpm	Intake in./hr.
L5	4	191	6.10	5.22	.35	L5	14	170	6.10	5.45	.26
		309		5.55	.22			327		5.45	.26
		467		5.71	.16			451		5.71	.16
		532		5.67	.17			550		5.36	.30
		867		5.55	.22			844		5.31	.32
		944		5.58	.21			963		5.30	.32
L5	8	144	6.10	5.38	.29	L5	19	123	6.10	5.17	.37
		276		5.45	.26			299		5.34	.30
		422		5.46	.26			407		5.29	.32
		498		5.63	.19			524		5.32	.31
		819		5.42	.27			799		5.30	.32
		911		5.43	.27			937		5.40	.28

AVERAGE OBSERVED INTAKE RATE REGRESSIONS

	.2	.4	.6
X1	$.432(t_i)^{-.238}$	----	$.134(t_i)^{-.0504}$
X3	$.532(t_i)^{-.169}$	$.560(t_i)^{-.225}$	$.245(t_i)^{-.0621}$
X5	$.932(t_i)^{-.179}$	$.517(t_i)^{-.125}$	$.379(t_i)^{-.0678}$
L1	$1.173(t_i)^{-.321}$	----	$.982(t_i)^{-.283}$
L3	$2.80(t_i)^{-.402}$	$1.405(t_i)^{-.324}$	$.432(t_i)^{-.105}$
L5	$1.362(t_i)^{-.238}$	$.923(t_i)^{-.204}$	$.383(t_i)^{-.0632}$

t_i = elepsed irrigation time

INFILTRATION EQUATION CONSTANTS

$$I = Kt_i^n \quad \text{OR} \quad I = C - Kt_i^n$$

CODE	CONSTANT	PERCENT SLOPE .2	.4	.6	CODE	CONSTANT	PERCENT SLOPE .2	.4	.6
X1	n	-.60	-.56	-.63	L1	n	-.69	-.72	-.75
	K (ft)	.0027	.0031	.0019		K (ft)	.0070	.0076	.0082
	C (ft/min)	0	0	0		C (ft/min)	0	0	0
	D_s (ft)	.0003	.00025	.0001		D_s (ft)	.001	.0007	.0002
X3	n	-.57	-.56	-.72	L3	n	-.70	-.75	-.79
	K (ft)	.0060	.0053	.0030		K (ft)	.0115	.0098	.0011
	C (ft/min)	.00006	.00005	.00012		C (ft/min)	0	0	0
	D_s	.0004	.0003	.00025		D_s	.0015	.001	.0005
X5	n	-.62	-.64	-.77	L5	n	-.77	-.81	-.87
	K (ft)	.0069	.0060	.0024		K (ft)	.0124	.0104	.0093
	C (ft/min)	0	0	0		C (ft/min)	0	.00022	.00022
	D_s	.0007	.0005	.0003		D_s	.003	.0025	.002

EFFECT OF FURROW FORMING TOOLS ON WATER FLOW CHARACTERISTICS

by

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B. S., Kansas State University, 1951

AN ABSTRACT OF A MASTER'S THESIS

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The rate of advance of irrigation water in an irrigation furrow is an important factor in achieving an acceptable distribution of soil moisture during the irrigation process. Acceptable rates of advance are always possible by increasing the rate of flow of water in the furrow. Large volumes of water are wasted however, if the increased rate of flow is not reduced, when the water reaches the lower end of the furrow. Increasing the rate of flow in the individual irrigation furrow reduces the number of furrows that can be irrigated with a given head or quantity of irrigation water. Improving the rate of advance with smaller rates of flow should improve the efficiency of use of irrigation water.

Studies related to the flow of water in irrigation furrows, conducted by several investigators, were reviewed. The results of these studies indicate the influence of various hydraulic conditions of irrigation furrows on the rate of advance of water in irrigation furrows. A design of experimental furrowing tools, based on the results of the hydraulic studies reviewed, is presented.

A field study comparing an experimental furrowing tool with a rotary type furrowing tool was conducted at the Irrigation Experiment Field, Scandia, Kansas. The soils of the area are crete silty clay loam. The study considered furrows, formed with experimental and rotary type furrowing equipment and three rates of flow as random variables. Identical studies were conducted on .2, .4 and.6 percent slopes. Slope was not however considered a random variable. The effect of furrowing tool mounting on the rate of advance of water in an irrigation furrow was also studied.

The influence of furrowing tool upon the surface storage of water required for flow and the initial rate of water filtration from the furrow was evaluated mathematically.

The time required for the water, of any of the given rates of flow studied, to advance 100 feet was less in furrows formed with the experimental furrowing tool. The results of the analysis indicates highly significant differences in the rate of advance due to furrowing tool and the rate of flow. Results of the mounting study indicates that tool bar mounting of irrigation furrowing equipment significantly retards the rate of advance of water in an irrigation furrow.