CHARACTERISTICS OF FLOW IN IRRIGATION FURROWS

Thesis for the Degree of Ph. D.

MICHIGAN STATE UNIVERSITY

John Rowland Davis

1958

This is to certify that the

thesis entitled

CHARACTERISTICS OF FLOW IN IRRIGATION FURROWS

presented by

John Rowland Davis

has been accepted towards fulfillment
of the requirements for

Ph. D. degree in Agrl. Engineering

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Date January 14, 1959

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by

John Rowland Davis

AN ABSTRACT

Submitted to the School for Advanced Graduate Studies of

Michigan State University of Agriculture and

Applied Science in partial fulfillment of

the requirements for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

1958

Approved E H Kidder

The efficient use and distribution of irrigation water is predicated upon a knowledge of the behavior of water flow in irrigation systems. Unfortunately, the interactions of flowing water, soils and crops have been difficult to analyze; resulting in a general inability to express these interactions quantitatively and accurately. Only recently have researchers become aware of the need for more precise designs and descriptive mathematical tools, and have been encouraged to study the basic variables and fundamental principles of the hydraulics of surface irrigation systems. This study was an attempt to describe or define some of the hydraulic aspects of flow in irrigation furrows, to contribute to a better understanding of furrow irrigation and the ultimate achievement of more efficient use of water.

The basic variables involved in this problem were (1) the infiltration phenomenon, and (2) flow regimes in small earth channels. Considerable achievements have been made in the field of infiltration and flow of water through soils, but the effects of the geometry of a furrow irrigation system have been only superficially investigated. Studies to date have indicated that furrow shape and depth of water affect infiltration rates and wetting patterns to a considerable degree.

The characteristics of non-uniform flow in a channel with erosive boundaries have not been studied to any extent, except for some work on furrow erosion. Several workers have attempted to define or predict flow of water in irrigation borders, but these methods have met with varying degrees of success.

The most critical part of a furrow system design is the rate of advance of water down a furrow, for this affects not only the distribution of water but also the erosion hazard, the water requirement of the system, and the operation and management of the system. The main purpose of this study was the development of a mathematical expression for rate of advance and a description of the variability of the individual components of this expression.

The rate of advance equation, based on a conservation of mass, was developed and applied to field measurements at two locations in California during the 1958 irrigation season. These locations represented two distinctly different soil types and cropping systems. Data from other workers were also used to discern whether or not the equation would prove satisfactory with limited measurements.

Comparisons of observed and calculated rate of advance showed that the equation was capable of predicting rate of advance accurately under a variety of conditions. The fact that the equation could be used successfully to describe the flow in a furrow was significant in itself, but the fact that the equation also designated the relative importance of the variables involved was of great importance.

Studies of furrow infiltration in a sand model resulted in the conclusion that furrow geometry and water depth affected the infiltration rate considerably. Although infiltration was correlated with water depth, the relative potency of such parameters as wetted perimeter and top width was much greater than that of water depth. Furrow spacing was not correlated with infiltration rate.

Field measurements with the Hamilton furrow infiltrometer indicated that this instrument might be useful in describing infiltration from a furrow; but that the change in furrow shape, the movement of water and sediments in a flowing furrow, and the seasonal effects may alter any relationships appreciably.

Studies of furrow shape at Davis, California, indicated that furrow shape is likely to be a function of soil texture and structure and the flow rate. Generally, higher flow rates created a flatter bottom in a furrow; which did not change during subsequent irrigations. Furrow shape and hydraulic roughness appeared to be related. This led to the hypothesis that a furrow channel may conform to a certain shape or attain a certain hydraulic radius and area depending on the flow rate. Should this be a valid hypothesis, it would then become possible to predict the shape and size of a furrow as affected by flow rate and seasonal variation in roughness, for any soil condition. This would result in an even more practical and widespread use of the rate of advance equation.

The rate of advance equation developed should prove an extremely valuable tool for the design and evaluation of furrow irrigation systems. It will certainly promote a better understanding of the flow characteristics of furrows and should stimulate further research in the fundamental aspects of surface irrigation hydraulics.

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Approved E H Kidder

G15232
6/20/61

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Doctor of Philosophy

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ACKNOWLEDGEMENTS

The author wishes to acknowledge above all other things, the professional and moral influence of Prof. Ernest H. Kidder, who has so unselfishly given his time and skill to his profession and the development of young staff members. The author also expresses sincere thanks to him for the patient supervision of an interrupted graduate program.

The author is pleased to acknowledge the leadership of Prof. A. W. Farrall, Head of the Agricultural Engineering Department, whose capable administration has resulted in a stimulating and friendly atmosphere for professional development.

The writer also wishes to express thanks to the other members of the original graduate committee: Dr. W. D. Baten, Dr. R. D. Spence, and Dr. L. M. Turk; for their suggestions and guidance during early phases of the graduate program.

A special note of gratitude is due Prof. G. E. Spencer, Head of the Agricultural Engineering Department at Purdue University and Prof. R. M. Hagan, Chairman of the Irrigation Department at the University of California, for their constant encouragement and forbearance during the course of these studies. Special thanks are due also to Drs. Warren A. Hall and Gilbert Levine, who reviewed parts of the manuscript and made many helpful suggestions.

The most heartfelt thanks go to the writer's wife, Lois, and children; whose faith that some day the requirements for the degree might be completed was of constant encouragement.

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INTRODUCTION

The Problem

A sound engineering approach to the design of surface irrigation systems has been seriously inhibited for some time by a lack of understanding of the factors affecting the flow of water over soils. The inability to express some of these factors quantatively and accurately has resulted in inefficient, impractical designs; and only recently have researchers been encouraged to study the basic variables and underlying principles of the hydraulics of surface irrigation systems.

The objective of efficient surface irrigation is to distribute a design depth of water over the soil surface with a minimum of soil erosion, in such a manner that water is stored uniformly within the root zone of the crop. The efficient use of irrigation water; and the effects of irrigation on soil compaction, soil salinity, soil fertility and proper drainage are all affected by this ultimate objective. Efficient water distribution is dependent on the design and operation of the irrigation system, and is thus predicated upon a clear understanding of the hydraulics of irrigation systems.

A committee on the hydraulics of surface irrigation in the American Society of Agricultural Engineers (32) expressed these views quite aptly in defining the position and scope of the committee. Reports of this committee and a recent paper by Hansen (33) further defined the basic variables in hydraulics of surface irrigation and presented a review of literature which have been included in this

dissertation. These variables are listed and discussed as follows:

1. Rate of application

   The rate at which water is applied controls the depth of application and the uniformity with which water is applied. The principal need here is for improved methods of measurement and delivery of water.

2. Roughness characteristics

   The roughness of the channel governs not only the flow characteristics but also the intake function. The major need today is for the evaluation of an effective coefficient of roughness for open channel flow in borders and furrows, and the factors that affect the value of this coefficient.

3. Intake rate

   One of the most complex aspects of the hydraulics of surface irrigation is the variable rate at which water enters the soil. The major need here is for careful analysis of factors involved in water intake, particularly at soil moisture contents more realistic to irrigation. Standardization of techniques for measuring intake rate and careful analysis and interpretation of data will be required.

4. Shape of the flow channel

   The characteristics of any fluid flow are modified by the shape of the flow channel. This effect is complex for furrow irrigation. Careful attention needs to be given to a shape factor in characterizing flow and intake function.

5. Slope of the land surface

The slope of the land has a major influence upon the rate at which water moves over the surface. The desirability of variable slope in a field irrigation system is being given some thought, and considerable effort is being made toward the solution of the problems of erosion in furrows.

6. Fluid characteristics

Fluid properties cannot be ignored, because of the effects of viscosity and density on flow of water through soils and in channels.

7. Rate of advance

The rate that water moves over the surface is of basic importance and is one of the most important characteristics of surface irrigation systems. It is this characteristic, in fact, that is used as the chief criteria for the determination of distribution efficiency. The interpretation of rate of advance data depends upon the entire hydraulics of the system, and will be difficult to complete until the hydraulics of the flow are evaluated.

8. Surface profile shape

The profile of water flowing in an open unlined channel has a definite shape, which is affected by slope, roughness, velocity, depth and infiltration of water into the soil.

Knowledge of the surface shape is necessary to evaluate channel storage.

Hansen (33) cited the further importance of knowledge of the hydraulics of surface irrigation, because of the inherent shortcomings of the field-trial method now being employed by the Soil Conservation Service. This casts no reflection on the SCS, but it is inherent in any field trial that the results are limited only to the field and to the conditions existing at the time of the test. Extrapolation to other fields or to a future condition is difficult and hazardous. Only after sound practical mathematical expressions describing the hydraulic features of flow have been developed and the basic variables involved in the system are evaluated will the results of field trials be more meaningful and be used satisfactorily to predict future behavior or conditions on other lands.

The problem, then, was to define, determine and relate the above factors affecting the hydraulics of surface irrigation systems. The correlation and integration of these basic variables will then provide a sound and significant solution to problems of design and evaluation, and will assist in stimulating a united, coordinated effort for the betterment of irrigated agriculture.

The Objective

The rate of advance of water in irrigation furrows is an important phase of irrigation hydraulics, and represents the integration of all other factors for a solution of the design problem. The objective of this study was to present a mathematical analysis of flow in furrows,

and a numerical solution for rate of advance in furrows. Although other authors have presented various mathematical expressions for rate of advance in borders, it was hardly likely that the same expressions would be valid for furrows. Thus, a mathematical analysis of furrow flow appeared warranted.

One should recognize that any theoretical analysis at the present time possesses several limitations, due to the fact that the full effects of variables such as roughness, surface profile, furrow shape and intake functions are yet unknown and indeterminate to a degree. However, a proposed analytical method should help to point out current deficiencies in existing data and, at the same time, provide a better working tool for the practicing engineer than a field trial method.

A secondary objective of the study was the analysis of the effects of furrow shape and furrow spacing on the intake function. Because of the wide variability in soils, this part of the study should be considered as only preliminary; but the results should be indicative of the effects of these furrow parameters. To fulfill this objective, a model study was justified to provide a greater degree of control of the variables involved.

It was anticipated that the latter study would facilitate the usefulness of the mathematical expression developed for rate of advance. Future studies on channel roughness, surface profile and furrow shape will better define the applicability of the equations and provide an even sounder approach to the solution of the problem.

REVIEW OF LITERATURE

Movement of water through soils

Because of the importance of water movement through soils in the fields of irrigation and hydrology, it has been studied extensively under both field and laboratory conditions. Many equations, both theoretical and empirical, have been developed to define the flow of gases and liquids through porous media; and as a result, some discrepancies in data and in interpretation of data appear in the literature. Some equations are quite complex and difficult to interpret; others are simplified to the point that inaccuracies in their application are likely to occur. Most of the pertinent research in this field was reviewed to enhance a more complete understanding of the infiltration phenomenon.

Israelson (35) and Dallavalle (19) listed a number of flow equations and defined the parameters involved, with emphasis particularly on Darcy's equation. Richards (64) recently defined a number of terms used in the field of soil moisture and made definite recommendations regarding the usage of these terms. Jacob (38) also discussed the question of the function of the permeability coefficient and its associated nomenclature. Also, a number of authors; namely Israelson (34), Richards (62) (63), Russell and Klute (67), and Slater (69); have attempted to explain the concepts of water movement through soils by the use of simple hydrodynamical analyses.

Richards defined Darcy's Law as follows:

$$Q = ks\ (H + e)/e$$

where Q = volume of water passed in unit time

s = area of filter bed

e = thickness of bed

H = height of water on the filter

k = coefficient depending on the soil

Originally, Darcy's equation was developed empirically for the saturated flow of water through filter sands. Since then, however, it has been proved that it is applicable also for unsaturated flow through soils. This evidently prompted Childs' remarks in his discussion of Richards' paper that he prefers Darcy's Law as $V = -k \text{ grad } \phi$, which expresses more explicitly the potential gradient under conditions of unsaturated flow.

Gardner and Hsieh (25) defined three types of velocity of water movement through soils, and stated that the factors affecting flow velocity were: magnitude of the moving force, size of channels, inertia of the moving water and frictional forces. As expressed in their paper, Darcy's Law represents macroscopic velocity, which they define as the volume rate of flow divided by the bulk cross-sectional area. Thus $V \text{ macro} = - K \nabla \phi$, where ϕ is the moisture potential and $\nabla \phi$ is then the potential gradient. In saturated soils, $\phi = \frac{P}{\rho_w} + gZ$ where P is the hydrostatic pressure, Z is the vertical distance above the plane in which ϕ is to be determined, and ρ_w is the density of water. In unsaturated flow, $V \text{ macro} = - Kf \nabla \Phi$, where $\Phi = \Psi + \phi$. The symbol Ψ is the moisture potential due to surface tension and ϕ is the gravitational potential. The factor f is dimensionless and varies from zero to one, depending on the moisture content. They further defined

the value of f as a result of determining dye-track velocities in blotting paper. Gardner invalidated this latter work, however, by stating that dye movements cannot be easily related to rate of flow, and do not properly reflect the true rate of water movement (77).

Hansen (31) presented several expansions of Darcy's equations for movement of water through soil during irrigation, based on the volume of water stored in the soil. For horizontal flow, he derived the expression

$$Q^2 = \frac{K_t n S A^2 h_t}{2t}$$

where Q is the volume rate of flow

n is the soil porosity

S = degree of saturation after wetting--degree of saturation before wetting

A is the area, normal to the distance x, through which the water passes

h_t = head loss in distance x, or = $\frac{P}{w}$

Thus, the rate of movement, $I = \frac{Q}{A}$ was expressed as $I = \sqrt{\frac{K_t n S h_t}{2t}}$; and if K_t, n, S and h_t are constant, the rate of movement is a function of the recripocal of the square root of time. Thus, as time increases, I decreases and will be asymptotic to zero at large values of time.

For upward flow, the potential gradient was expressed as $\frac{h_t - y}{y}$, where y is the vertical coordinate measured in the direction of movement. Then $Q = K_t A \frac{(h_t - y)}{y}$ and as y approaches h_t, I approaches zero. Thus, there will be a definite limit to the extent of upward movement of water.

For downward flow, the potential gradient was expressed as $\frac{h + y}{y}$, and assuming h_t constant, $Q = K_t A \frac{(h_t + 1)}{y}$. Where h_t does not increase with time, $\frac{(h_t + 1)}{y}$ approaches one as time and y increase. Thus, I will approach the value of K_t as time increases. Hence, for soils where the infiltration rate approaches a constant, that constant rate can be interpreted as an effective transmission hydraulic conductivity under the existing conditions. This has been verified by the work of others (7) (51).

These equations as proposed by Hansen perhaps could be affectively employed for the solution of two-dimensional flow into and through soils, and may have a considerable bearing on the understanding of flow of water into soils from furrows or point sources.

Hansen also found that the rate of entry into moist soils was less than in dryer soils; and that the wetting front appeared to be an effective, restrictive layer to downward movement of water, due primarily to the energy loss in the wetting front.

The classic experiments of Bodman and Colman (8) (16) have served to define soil moisture-depth relationships and infiltration-time relationships which have been recognized and adopted by many workers in this field. Their studies were conducted with tubes made of special, short cylinders 5 mm. high, such that the entire column of soil could be sliced into thin samples for soil moisture determinations.

Their results showed that the infiltration-time relation assumed the form $h = Kt^n$, where n is positive but less than unity. The more important result, however, was the classification of soil moisture distribution within the soil column. Four distinct zones of soil moisture were noted:

1. The surface layer of soil approximately one cm. deep reached approximately pore space saturation. In silt loam, apparent supper-saturation was noted, evidently due to swelling of the soil upon wetting.

2. Below the saturated surface layer, soil moisture content de-decreased with depth until it reached a value about half way between moisture equivalent and pore space saturation. Soil moisture contents in this zone were not exceeded upon further penetration of infiltering water. Hansen (31) called this zone the transmission zone, and stated that within this zone, the moisture content was essential constant (approximately 80 percent saturation). Because of the approximate linear relationship between moisture content and hydraulic conductivity over this range of saturation, it is then possible that a simple expression for hydraulic conductivity in terms of moisture content can be obtained to represent effective transmissibility of this transmission zone. Also, because the moisture potential-depth curves of the transmitting zone maintain a constant type of configuration, a constant hydraulic conductivity is implied.

3. Below the transmission zone, moisture content decreased with depth until dry soil was reached. This in turn caused a decrease in hydraulic conductivity. Within this zone, called the wetting zone, downward progress of the wetting front was accompanied with an increasing moisture content of the soil. In a moist soil, the wetting zone was of greater length than in a dry soil; due principally to the greater hydraulic conductivity or a smaller loss of potential per unit length.

4. The wetting zone terminated abruptly at the wetting front. In every case in Bodman and Colman's experiments, water moved into air dry soil as a distinct wet wave, and there was no visual evidence of any diffusion of moisture ahead of the obviously wetted soil. Because of the high potential loss in the wetting front, this appeared to be an effective, restrictive layer to downward movement of water. In moist soils, the potential loss was smaller; hence, the wetting front advanced more rapidly when the soil was wet. Its moisture content was characteristic of the soil and was probably independent of the depth of the wetted soil.

Bodman and Colman also pointed out that decreased in observed infiltration rates with time were due to a decrease in moisture potential

gradient, resulting primarily from an increasing depth of penetration. It thus appears feasible that an equation in the form of the infiltration equation could also be used to describe the advance of the wetting front. It was also evident that moisture potential conditions represent the chief factors influencing changes in infiltration rates and that the other factors usually cited operate as a modifying influence.

Regarding texturally layed columns, less permeable layers limited entry into the soil surface regardless of whether they laid above or below the more permeable one. If the less permeable layer occupies the lower position, a positive hydrostatic pressure will develop in the layer above. This pressure increases with time, but shows no influence on the rate of water entry into the lower layer. Examples of this phenomenon are the case of hillside seeps, where the less permeable soil slopes in the direction of the hillside; and the irrigation of hardpan soils, where ultimate water logging of the soil results if too much water is applied.

More recent work by Miller and Felix (51) fully substantiated Bodman and Colman's results. In fact, they also concluded that the average velocity of flow through the transmitting zone must be very nearly equal to the infiltration rate. They found that the hydraulic gradient in the transmitting zone was relatively uniform, greater than unity and decreased with time to unity as a limit. The gradients of various materials differed at corresponding stages of infiltration. For Yolo loam, for example, the hydraulic gradient, dh/dl, equalled 1.25.

Numerous authors have attempted various mathematical expansions

of Darcy's equation. Gardner and Widtsoe (26), for example, used the form of Darcy's equation $V = K \rho \nabla \Phi$, where

V = mean velocity at a point in the soil

ρ = moisture density at the point

K = a proportionality constant

Φ = the sum of three potentials

The development of their equations, however, applied more to soil moisture conditions in a soil column after drainage than it did to water penetration during irrigation.

One of the assumptions of Gardner and Widtsoe was the fact that the inherent moisture conductivity of the soil was independent of the moisture content. This is true, but only because the moisture content of the transmission zone in a soil is essentially constant. Klute (40) pointed out that the conductivity of an unsaturated medium will depend on the moisture content and will decrease with decreasing moisture content. This does not invalidate any of the other work of Gardner and Widtsoe, but it does serve to point out differences in the characteristics between soils.

Bodman and Edlefson (6) presented rather fundamental observations on soil moisture movement and the basic functions of forces acting on soil moisture. More recently, Philip (58) (59) (60) presented several mathematical interpretations of the theory of infiltration, but his developments were somewhat difficult to follow. A more practical mathematical manipulation of Darcy's equation has been presented in several of Hall's papers (28) (29), in which more simplified mathematics was employed to define infiltration into soils. Hall's

paper on one-dimensional infiltration was limited, however, to an expression for the depth of penetration of the saturated surface. This is relatively unimportant in irrigation practice, because as Bodman and Colman point out, the depth from the soil surface to the bottom of the shallow layer of saturated soil remains fairly constant.

Infiltration of water into soils

A number of investigators have studied the effects of various factors influencing infiltration into soils, but the results usually apply only to the soils under consideration. This is true particularly in cases where chemical as well as physical factors are involved, such as in the irrigated saline soils in the western United States. Scofield (68) reported in great detail the effects of soil chemistry on water movement through soils, and others (5) (27) (50) have determined the effect of various infiltration patterns on the resultant salt accumulation and salt distribution in soils. Because this dissertation was concerned with only the mechanics of flow, consideration was not given to other modifying factors such as salinity.

A large number of factors affect infiltration, as pointed out by Lewis and Powers (46), who discussed the effects of a number of variables on infiltration rates. In an earlier paper, Lewis (43) stressed the importance of knowing infiltration rates, and discussed results of infiltration tests with single-ring infiltrometers. Studies of a great number of soils by Free, Browning and Musgrave (24) involved the determination of infiltration rates on 68 different soil sites, and a statistical evaluation of the manner in which measureable soil factors affect infiltration.

Their results showed that the general form of the infiltration equation $I = bt^a$ was applicable; and that b varied from unity to 0.0087 and a from 0.04 to 0.82. Results of the regression analyses showed that the following factors have a positive influence on infiltration:

Total porosity
Non-capillary porosity
Aggregation of soil particles
Organic matter content
pH
Moisture equivalent of the surface soil

Conversely, the following factors have a negative influence on infiltration:

Silt and clay content
Clay content
Dispersion ratio
Moisture equivalent of subsoil
Volume weight
Suspension

These analyses and the statistical treatments have served as a general reference for many workers in this field. Krimgold and Beenhouwer (41), for example, used these data as a basis for a general classification of soils into five categories of infiltration characteristics. Unless field determinations are possible, this is the only manner in which the data can be treated--that is, a general qualitative approach, rather than a strict quantitative treatment. Even though Free, Browning and Musgrave conducted an exhaustive study on 68 soils, it is quite improbable that the infiltration rates are the same on these soils today, and is certainly unlikely that these results, other than the generalizations, would apply to other soils.

The technique of measurement of infiltration has been only partially investigated. A number of years ago, Lewis and Neal (45) conducted

infiltration studies on soil cylinders of varying diameter. Although they found a general equation for infiltration as a function of soil porosity, they were free to admit that they had difficulty in getting comparable results.

More recently, Burgy and Luthin (15) investigated the validity of results from single and double ring infiltrometers in a non-stratified soil at or near field capacity. Their results showed conclusively the high degree of variability one would encounter with the ring infiltrometers. They found that six single-ring infiltrometers randomly spaced gave an average value that was within 30 percent of the true mean. Even when an arbitrary rejection technique was applied to the data, the adjusted ring rates were only within approximately 25 percent of the true rates. The authors pointed out, however, that these adjusted rates might be considered quite close in such a variable system as the soil. Thus, as the authors implied, the ring infiltrometer is an instrument or a technique that will produce results for a point location in a usually variable medium. Some descripancy still exists, however, in the physical dimensions and techniques employed in using the ring infiltrometer even for a single point.

Aronovici (3) recently reported the results of a model study of ring infiltrometers, in which he was able to observe the wetting patterns in soil placed in a glass-front tank. His study pertained particularly to the effects of variations in soil profile, ring depth and ring diameter on infiltration velocity, and illustrated quite effectively the influence of these parameters on infiltration from rings. Aronovici found that the infiltration velocity decreased with an increase

in the infiltrometer depth and with an increase in ring diameter. Also, as the initial soil moisture content increased, the rate and magnitude of infiltration velocity decreased, as might be expected. The relationship between ring diameter and infiltration velocity was curvilinear; that is, the rate of decrease of infiltration velocity was about 1.3 cm. per hour per inch of increase in diameter up to four inches, but decreased only 0.05 cm. per hour for each increase in diameter beyond four inches.

An interesting result of the wetting front observations was the relation between the diameter of the ring and the horizontal distance from a vertical projection of the ring to the wet-dry soil interface. This distance was almost the same regardless of the ring diameter, and appeared to be the primary reason for the inverse relationship between infiltration velocities and ring diameter.

These studies have served to emphasize the need for standardization of technique for infiltration measurements. Inasmuch as the single-ring infiltrometer is convenient and most widely used, standardization of technique becomes even more important. Thus, it is imperative that the researcher realize the limitations of infiltration data and techniques. In a sense, the above reviews justified the use of a general infiltration equation in the following theoretical developments. On the other hand, the use of such infiltration data was bound to result in a general development that should be applied with some caution and discretion.

Movement of water into soil from furrows

The movement of water into soils from furrows is complicated by

the fact that the dimensions of the soil surface are variable, the water is moving across this surface at some velocity, and the nature of the surface changes from one irrigation to the next, due to degradation and aggregation in the bottom of the furrow. Aronovici (2) mentioned that furrow silting, erosion, soil-particle rearrangement and deterioration of soil structure were contributing factors in altering infiltration patterns during the season. In evaluating the reliability of the ring infiltrometer as an index of irrigation furrow infiltration, Aronovici stated that neither ring infiltrometers nor permeameter measurements on soil cores gave rates equivalent to furrow infiltration rates. The ratios of furrow to ring infiltration rates varied from 1:1 to 9:1, depending on site conditions and duration of observations; but in all cases, furrow infiltration was always higher than ring infiltration. Aronovici (4) later stated that cylinder infiltrometers were not at all applicable to furrow studies, and strongly suggested the use of the Hamilton furrow infiltrometer.

Considerable differences in individual furrow performance are usually found. This will be true especially in furrow irrigation in orchards, when the center furrows perform differently than those adjacent to trees. Aronovici (2) stated that the reduction in wetted front area of the center furrow (and consequently a reduction in infiltration) was caused by the influence of water moving out from furrows on either side. This was essentially the influence of furrow spacing, although many authors do not treat it as such. Another significant difference in furrow infiltration is due to mechanical

compaction of the soil in the bottom or sides of the furrow.

One of the more important aspects of Aronovici's results was the fact that the furrow width or total wetted surface area appeared to have no direct bearing on the infiltration rate from a furrow on a wetted area basis. He reasoned that the lateral flow of water from the furrow is more dependent upon the water contact with furrow sides and capillary flow laterally than the width of the furrow. Instances were cited where infiltration rates were higher in narrow furrows than in broad furrows.

The Hamilton furrow infiltrometer to which Aronovici referred was described in a recent paper by Bondurant (10). Bondurant's statement of the problem was similar to this author's, in that a need exists for determining infiltration before irrigation water is available on the farm, and that the cylinder infiltrometers are difficult to correlate with furrow infiltration rates. His paper described in detail a furrow infiltrometer, its operation, and some field infiltrometer studies. Bondurant claimed that a comparison of data from the furrow infiltrometer and from inflow-outflow measurements showed a close agreement in most of his trials, but the data shown in his paper revealed a rather poor agreement and only a general correlation. The infiltrometer, however, has the advantage of being useful for any shape of furrow and also takes into account the differences in permeability and areas of the sides and bottom of the furrow.

Bondurant also found a relationship between the stream size and wetted area, for furrows of a given slope. According to his analysis, the following stream size, slope and stream width relationship was obtained:

$$Y = 5.35\ X^{0.285}$$

where Y is the stream width in inches

X is the stream size in gallons per minute divided by the slope in percent

The above relationship was a result of studies in the Republican Valley on V-shaped furrows with side slopes averaging about 4 to 1, and will likely be different in areas of different soils and different furrow shape.

One possible error in Bondurant's paper that was common in a number of other papers also, was an assumption that the water entering the soil from a furrow is distributed over an area equivalent to the length of the furrow infiltrometer (one foot) times the furrow spacing. It is possible that the actual area through which water passes is smaller than the area indicated by the furrow spacing, depending upon the soil. This would tend to increase the field intake rate over that which is usually shown.

In an earlier study, Bondurant (9) verified the poor correlation between ring infiltrometers and inflow-outflow measurements, particularly when the surface soil was not the least permeable horizon. His studies on three major soil types showed that on a sandy loam soil, in which the least permeable horizon was the 6" - 9" depth, the intake rate as determined from the single ring infiltrometer was not a close approximation of the intake rate obtained by surface flow measurements. The furrow intake rate divided by the percentage of furrow covered by the irrigating stream was more nearly the same as the intake rate obtained with single ring infiltrometers. Where the surface soil was

the least permeable horizon, the average intake rates obtained by the two methods were very nearly the same.

The Soil Conservation Service has used an intake rate correlation between cylinder infiltrometers and furrow intake rates in the Northern Great Plains for about three years, in spite of the usually poor correlation. Phelan (57) stated that it has been used purely as a guide in planning farms upon which it was impossible to make furrow intake studies, and made no claim for the accuracy of the correlation. He further stated that the curves were developed in the middle range with intake rates of about one inch per hour and stream sizes between 5 and 15 gallons per minute. Additional work is underway to consider the effect of slope on the correlation.

A number of studies have been made on seepage from ditches and infiltration from furrows. One of the earliest studies was that made by Loughridge (47) in orchards near Riverside, California. He observed wetting patterns in the soil from trenches six feet deep dug across furrows and trees, to give a trench 90 feet long and 3 feet wide. Water was conveyed over the trench with small wooden flumes.

Loughridge observed the difference in wetting patterns from shallow and deep furrows (the depth of water in the furrow was about one-half inch in each case), and found that the depth of percolation and spread of water were far greater under the deep furrow--the ratio being about 2 to 1. He concluded that the real advantage of deep furrows lies in increasing the height of soil through which water from furrows would have to rise by capillarity to reach the surface, thus decreasing evaporation loss and increasing the amount of water retained

by the soil. These conclusions were modified by subsequent work of others (5) (50) (76), however, particularly when salt concentrations in the furrow bed are likely.

Loughridge's studies were also limited by the fact that a very small stream of water was used, resulting in a slow rate of advance of water down the furrows. Under these conditions, he described the form of the curve made by wet soil from the head of the furrow to the end: the depth of percolation was 26 feet at a distance of 30 feet from the head ditch. The curve ascended abruptly toward the surface at a point one-fourth the length of the furrows from the head ditch. From this point to the end of the furrow the depth of penetration was quite small, and was nearly uniform to the end of the furrow. This type of wetting pattern would result in an inefficient distribution of water.

Browning and Milam (14) investigated the use of small contour furrows for conservation of soil and water on sloping pastures in West Virginia, and cited most of the literature available at that time (in 1940). They cited Conti's work, the results of which showed a vertical penetration of water four times as rapid as lateral penetration in soils of uniform compaction; and Whitfield and Fly's work, the results of which showed that the wetted area of contour furrows in heavy clay loam soil extended about 10 inches on each side of the furrow. In Browning and Milam's study, the results showed conclusively that water did not move laterally as far as 12 inches during the 12 to 24 hour tests. They observed quite a variation in the time for water to reach the tensiometers placed six inches away

from the furrows; but usually water reached the downhill ones first, as would be expected, due to the more rapid movement of water in a downhill direction. Cross sections of the wetted soil showed that the wetted area assumed an inverted cone pattern.

One of the more exhaustive field studies of seepage from ditches was reported recently by Rohwer and Stout (65), and should be applicable to furrow irrigation problems. Their studies were concerned mainly with the relative seepage of the sides and bottom of canals, and the factors influencing seepage rates. Methods of measuring seepage were also discussed, with the comment that the inflow-outflow method was preferred because of the longer section of channel available for observation. In general, they found that the actual losses from canals were far less than the maximum possible, due to partial sealing of the bed material. They also stated that seepage was only loosely correlated with depth of water in the canal, and that the effect of water temperature on seepage was quite small.

Individual trials showed considerable soil influences on seepage. For example, in Holtville silty clay loam, side seepage exceeded bottom seepage; but in Meloland fine sandy loam, side seepage was less than bottom seepage. This difference was attributed to differences in soil permeability or in underlying strata. In another case at Davis, California, seepage rates from the bottom of a trench decreased with time. The total seepage increased with time, emphasizing the effect of seepage through the sides of the canal. However, tests in January of the following year showed that the seepage rate from the bottom of the trench exceeded that from the sides and

ends--contrary to previous findings. Rohwer and Stout reasoned that the changes that caused this reversal must have occurred in the sides.

In pool experiments, they mentioned that flow velocities as low as 0.05 feet per second increased the rate of percolation. If this was true, the absence of stream velocity might cause some errors with the furrow infiltrometer, and some adjustment might be necessary to consider water velocity, particularly if the shape of the furrow were affected by the velocity.

Muskat (52) discussed in great detail the flow of fluids through porous media and presented specific solutions for drainage from ditches and seepage from canals into sands with deep or shallow water tables. He derived several equations for the seepage flux, Q, from ditches; assuming that the potential can be expressed as (K/u) (p-rgy). If the porous medium was of very great thickness, the maximum width of the sheet of liquid seeping down into the porous medium was $B_1 = Q = B + 2H$, where B_1 was the width of the sheet of seeping liquid, Q was the seepage flux, B was the width of the stream, and H was the depth of water. He also presented equations for the free surface streamlines, which define the value of B_1.

When the normal ground water level was at a relatively shallow depth, the streamlines assumed a horizontal rather than a vertical trend. In this case, a complex variable relation defined the problem, and after suitable manipulation of the equations for the free surface streamlines, the equation $B = Q + 2H$ was written. Thus here, also, a knowledge of the width and depth of the ditch will give the seepage flux out of it. In the first case, the equipotentials at great depths

were horizontal parallel lines; in the latter case, the equipotentials at great depths were curves depending on the seepage flux and the depth of water in the ditch.

Perhaps a more precise determination of seepage of water into sands with deep-lying water tables was given by the equation $Q = B + 2HK/K'$, where K and K' are the complete elliptic integrals of the first kind with moduli K^*, $1-k^{*2}$. Muskat suggested that the calculation is most readily carried out by assuming Q/H, calculating the associated K^*, and then the value of B/H to which the value of Q/H corresponds. In this case, K^* was given by the equation $K^* = \cos \frac{\pi mH}{Q}$, where 1/m was the average side slope of the ditch. The maximum or asymptotic width of the downward seeping sheet of water was then $B_1 = Q = B + 2HK/K'$. It is necessary in using these equations that, in the numerical interpretation of the equivalence between the flux Q and the lengths such as B, one must multiply the latter by $\bar{k}$, which Muskat took as unity.

The use of these data from Muskat were limited more or less to saturated flow, and may not apply to cases where interference of the wetting pattern from an adjacent furrow is probable. However, use of the simple equation $B_1 = B + 2H$ might serve to define the extent of lateral movement of water from furrows in homogeneous sandy soils where no interference exists. For example, if the width of a furrow stream were 16 inches and the water depth were 2 inches, the width of the seeping stream would be about 20 inches, or 10 inches on each side of the center line of the furrow. This remains to be verified, however, by future studies of unsaturated flow in soils from furrows.

The movement of water from irrigation furrows has been reported by a number of authors. Taylor (72), in advocating the use of closer spaced furrows, recommended a spacing somewhat less than twice the depth of rooting of the plant. He also stated that the wetting front was sharp in dry soils and more gradual in wet soils, as would be expected, and even less sharp for lateral movement.

Day and Luthin (20) analyzed the theory of flow from a system of parallel irrigation furrows in a permeable soil overlying a deep gravel substratum, by using the method of images. They derived equations for the potential at any point in the soil and for the value of the stream function along any chosen streamline. For the vertical limiting streamlines, $\Psi = \pm 2\pi q$, which lie on vertical planes midway between furrows. The total flux, Q, was equal to $4\pi qK$, where q was a flux coefficient whose value could be determined from one of the equations mentioned.

Their studies also included a model study to verify the theoretical developments. Measured values of seepage flux in this part of the study agreed within eight percent of the calculated value, thus validating the developed equations for seepage flux. Tensiometer measurements also indicated approximate agreement with theory.

Variations in the soil profile also affect the pattern of water movement from furrows, particularly the effect of soil stratification and sand lenses. Photographs of wetting patterns in soil (1) showed a definite increase in horizontal movement of water when the wetted area encounters a clay layer or a coarse sand layer. In the latter case, the overlying soil must be nearly saturated before water moves into the sand. Similarly, if cracks in the soil are filled with sand, free

water will not enter the cracks until the adjacent soil is nearly saturated, unless the cracks enter the furrow. This same conclusion was reached by van't Woudt (74).

Haise (27) also used a photographic technique to determine flow patterns in irrigated coarse textured soils. His studies were conducted with a 64-inch long by 38-inch high by 24-inch wide lysimeter box with a plate glass front, in which coarse sand had been placed. Two furrows eight inches high and 36 inches from center to center and 24 inches long, were made in the soil; and during the tests, water was maintained at a constant head in the furrows. During some of the tests, indigo carmine dye was injected at intervals along the furrow perimeter, as a means of tracing the streamlines.

The most important observation of these studies was the fact that soon after capillary wetting of the ridge was completed, the direction of water movement was downward at all points. This had considerable bearing on the movement of salts into and away from the furrow ridge. It was found that the direction of moisture movement was independent of textural differences, even though the rates of water movement varied widely between soils.

After twenty minutes of irrigation, the flow lines were essentially normal to the submerged surface of the furrow; and as shown by the dye patterns, the flow pattern resulting from the water entering the soil in each furrow was symmetrical at any given time.

Haise stated that it would be expected that altering any one of the imposed conditions (head of water in the furrow, shape of furrows and ridges, etc.) would alter the general configuration of the flow

pattern. As shown by his illustrations, furrow spacing would have an important effect also.

Regarding the movement of dye in the soil, Haise found that the direction of water movement as indicated by dye movement in soils already wet to approximately field capacity was less definite than in soils in an air-dry condition. This was due to an apparent lag of the dye behind the wetting front, which is explained in some of Bodman and Colman's work and later by Gardner (77). As a result of these model studies, Haise recommended that fertilizer should be placed in the ridge several inches above the level of water in the furrow, thus preventing excessive leaching of the soluble fertilizers to lower depths.

Field and model studies of water movement from furrows into beds have been concerned mainly with the movement and accumulation of salts in the beds, but afford a reasonable examination of the factors affecting water movement into soil from furrows. McGeorge and Wharton (50) corroborated Haise's data in their studies of salt movement from furrows into beds of different shapes. They found the presence of heavy salt accumulations in the subsoils directly under the beds, indicating a large amount of lateral movement both from the furrow toward the center of the bed and downwards or upwards, depending of the direction of water flow. Salt concentrations were always the least in the furrows and highest in the center of the beds.

Wadleigh and Fireman (76) also reached this same conclusion in studies to determine proper sampling techniques for salinity measurements. They found a continual increase in soil salinity from underneath

the furrow to underneath the row and up to the surface of the soil in the ridge, which reveals the pattern of water movement. The salt accumulation under the row was also much greater under the "wet" irrigation treatment than under the "dry".

More recent studies were published by Bernstein and Fireman (5), which also corroborated the work mentioned above. They used a 32-inch wide by 26-inch high model, and tremied air dry soil into place between two parallel glass plates held 7/8 inch apart. Distilled water was applied to shaped furrows with a constant level device.

They also found that when the shape of the bed was bilaterally symmetrical and both furrows similarly irrigated, the wetting pattern was symmetrical. The wetting fronts moved approximately ten times more rapidly in loam than in clay; clay took 6.7 times as long for the wetting fronts to meet and 4.7 times as long for complete wetting across the bed surface. In the final analysis, however, the salt distributions were remarkably similar.

Generally, the results showed that the more perpendicular the wetting front was to the bed surface, the greater the lateral and the smaller the upward components in the direction of movement of the wetting front, and the less salt was deposited in the surface of the bed. In all cases, however, the angle between the tangent to the wetting front and the soil surface of the bed was not a right angle. The angle increased as the bed height decreased; the angle being 46°, 53°, and 75° for the 6", 4 1/2", and 3" beds, respectively. These results and the others cited showed conclusively that the pattern of water penetration into furrow beds was affected not only by soil

conditions but also by the shape of the furrow and the bed. This becomes quite important when salinity problems are likely to arise.

One of the more recent projects having a direct bearing on flow of water into soils from furrows has been conducted under the leadership of W. H. Gardner. In a recent progress report (77), Gardner sited the results of studies of dye tracers for determining the movement of water through soils, and concluded that dye-track velocities cannot be used to represent average incremental water velocities.

For these studies, rectangular ceramic plates were made from Palouse silt loam soil, into which dye was introduced at specific intervals along the face of the plate. It was shown that the rate of entry and advance of the wetting front obeyed the empirical equation $dQ/dt = At^B$ and $S = Et^F$, but that the dye only approximated the average flow rate for a saturated flow condition. Dye introduced into the block just back of the wetting front was observed to catch up with the wetted front, which suggested that through cascading motion it was passed over the top of water containing no dye. Thus, dye movement was not easily related to rate of flow--but was used to trace out streamlines in both saturated and unsaturated flow. In any respect, it was improbable that any given soil sample would yield identical water movement data on successive runs.

The results of Rowe (66) in contributing to this project were particularly enlightening. He used a model of two rectangular glass plates held one centimeter apart, and used a constant head apparatus to measure flow and maintain the head in the furrows. The procedure used by Rowe was the same as that used in this study, except that he

used soil sifted dry through a #20 sieve, whereas fine sand was used in this study.

Rowe's data appeared to fit the equation $Q = At^B$ for infiltration; thus he expressed the results of the model study by showing the effects of various factors on the values of A and B. The relative positions of the curves plotted from the data were very nearly the same for both laboratory and field data on ten soils.

The effect of initial soil moisture content on the parameters A and B were as follows:

In Ephrata sandy loam, as the moisture content increased,

A decreased and B decreased

In Ritzville silt loam, as the moisture content increased,

A increased and B decreased

In general, there was no definite trend in the values of A with variation in initial moisture content; the values of B decreased, resulting in an expected decrease in total infiltration with time.

The effect of the depth of water in V-shaped furrows, for Quincy sandy loam soil was as follows:

Depth	A	B
3.5 cm	1.442	0.9775
6.0	1.673	0.9786
8.2	2.404	0.9610

Thus, it was apparent that there was a slight trend in A with variations in hydrostatic head. No definite trend in values of B with variations in head were evident.

The effect of the area of contact of water at constant head in flat-bottom furrows was as follows for Ephrata sandy loam soil:

Area of Contact	A	B
10.60 cm^2	2.176	0.8404
21.46	2.926	0.8470
31.46	4.898	0.8304

Although no statistical analyses were employed, it was evident that the value of A increased with an increasing area of contact, whereas the value of B did not change appreciably.

From these results, it then appeared possible that the infiltration from furrows could be described by an equation in the form of $F \cdot At^B$, where At^B represents the infiltration from a standard measurement, such as that with a furrow infiltrometer. The function F would then be a function of head of water in the furrow, the area of contact and the furrow spacing.

As these data indicated, it was no longer necessary to postulate the form of the infiltration equation for furrows. Once the values of F are known, the infiltration of water into soil from furrows can be readily determined.

Rowe also found that the rate of advance of the wetted front in the vertical direction did not greatly exceed that in the horizontal direction. The greatest difference occurred in the coarser soils, as could be expected; and the data indicated that the gravitational field was small in comparison with the capillary field as long as the water source was maintained and the moisture gradient was fairly large.

Where the soil is sufficiently isotropic, the depth to the wetted front may then be estimated from observations of the distance of lateral advance of the wetted front.

The equations $S = Dt^E$ and $U = Ft^H$ appeared to apply in defining the position of the wetting front with time, where S was the horizontal distance and U was the vertical distance. For Quincy sandy loam, the equations found were $S = 1.037\ t^{0.585}$ and $U = 1.068\ t^{0.596}$, from which it was evident that the lateral advance was very nearly equal to the vertical advance. Rowe then used the equations $Q = At^B$ and $S = Dt^E$ to derive a simple relationship between total infiltration and lateral movement of the wetting front. This equation was $Q = CS^K$ where $C = A/D^K$ and $K = B/E$.

More recent work by Nagmoush (54) corroborated Rowe's work. Nagmoush also found that the value of the time exponent B decreased with increasing hydrostatic pressure and A increased with increasing hydrostatic pressure. He also observed that the vertical rate of advance of the wetted front did not exceed greatly the horizontal, as long as water was applied.

Nagmoush also found that it was possible to convert one dimensional flow in soils to two and three dimensional flow, using simple conversion factors. Averages of data on Palouse silt loam and a fine sand resulted in the following equations:

One dimension	$Q = At^B$	$S = Et^F$
Two dimensions	$Q = 2.1\ At^{1.52B}$	$S = 0.78\ Et^{0.81F}$
Three dimensions	$Q = 2.5\ At^{1.64B}$	$S = 0.34\ Et^{0.83F}$

These constants depended on the texture of the soil involved; but served to illustrate the fact that regardless of the geometry of the system, the general equation for infiltration could still be written.

It was noted that the effects of furrow spacing were not considered in this study, nor was furrow shape. It was quite likely that the wetted area of a furrow might be less significant than the top width, and it was evident that the relation would depend also on the relative permeabilities of the sides and bottom of the furrows.

In summarizing this section of the review, it appeared likely that furrow dimensions will affect the rate of water movement into soils from furrows. Although the general equation of the form $Q = At^B$ may be used to define total infiltration and vertical and horizontal advance of the wetting front, the constants A and B depend upon soil texture and structure, initial soil moisture content, head of water, and the furrow dimensions. Because the value of B did not depend on furrow dimensions, as reported by Rowe and Nagmoush, it may be postulated that an equation in the form of $Q = F \cdot At^B$ may be employed to determine the infiltration from any given furrow geometry in a particular soil situation. This was the basic postulate in the later developments of this study.

<u>Principles and design of furrow irrigation systems</u>

In many cropping systems, the most widespread method of irrigation is by furrows. Brown (13) stated that more than 80 percent of the sugar beets in California are furrow irrigated, and emphasized the fact that no other method requires more judgement or more skill in

irrigation management than furrow irrigation. His popularized article presented three basic essentials for furrow irrigation:

1. Furrows should be close enough together so that wetted areas meet.
2. Water should be kept in the furrows for the time necessary to obtain the desired penetration.
3. The length of the furrow should be such that the difference in penetration between upper and lower areas shall not be excessive. He did not define his criteria, "excessive".

He also gave some general recommendations for furrow length, depending on soil type.

Lawrence (42) suggested that furrows be spaced to fit crops and standard machinery, and also suggested that wide, flat bottom furrows can be used on uniform grades of less than 0.5 percent. Furrow grades of 2.0 percent or more may result in excessive erosion, but this depends on the flow of water in the furrow and the soil type. Lawrence stated that the size of the stream should be controlled to fit the furrow grade and soil conditions, such that the maximum non-erosive stream would reach the end of the furrow in about one-fourth the time it takes to irrigate the crop.

These recommendations agreed essentially with those of Criddle (7) and Criddle, Davis, Pair and Shockley (18). These two reports gave in detail the procedure for determining the length of furrows, sizes of streams and spacing of furrows, but involved the common problem that water must be already available and the land must be graded and leveled

to perform the tests. Thus, the methods cited are more adapted to the evaluation of irrigation systems than to the design of a furrow irrigation system.

Criddle stated at the outset that increasing the size of the stream in bare V-type furrows on steeper grades did not materially increase the rate at which water infiltrates into the soil. Others have found that this relation did not hold on flatter slopes in lighter soils nor where the furrows were broad or grass covered. In fact, many workers in this field disagreed with his statement altogether.

Criddle explained the analysis of results of field tests, in which rate of advance curves were determined for furrow streams of various sizes. He cited the fact that the final analysis for the permissible limit for erosion rests somewhat on personal judgement. Regarding furrow spacing, the row crop involved usually fixes the spacing of the furrows. One should realize, however, that in homogeneous soils, the horizontal width of the wetted bulb of soil is frequently about the same as the height of the bulb. Under these conditions, the correct furrow spacing is somewhat less than the root zone depth of the crop.

The authors of both publications stated emphatically that the stream front should reach the lower ends of the furrows within approximately one-fourth of the total time needed to refill the soil in the root zone. This procedure would reduce the average deep percolation loss for the full length of the furrow to about five percent of the water stored in the root zone. A faster rate of advance would decrease loss, but would also create problems in labor and soil erosion.

The maximum allowable stream, as Criddle mentioned, appears to be a matter of good judgement. However, as a general rule, the equation $Q = 10/S$ may be used as an approximation; where Q is the furrow stream in gallons per minute and S is the furrow slope in percent.

The final analysis of the problem, as outlined by Criddle, consisted of plotting the rate at which different size streams advance, and determining the maximum size stream and maximum time that can be allowed for it to reach the end of the furrow. In this manner the maximum allowable length of furrow can be determined.

Furrows present conditions most favorable to erosion, in that loose, cultivated soil is exposed to a concentrated flow of water. On the other hand, the frequent cultivation creates roughness in the channel which may tend to lower the velocity of flow. Taylor (71) used the work of Gilbert on small channels to postulate the effect of slope, discharge and aggregation on furrow erosion; and to present in mathematical form the capacity for traction. He concluded that the slope should be kept to a minimum, that the furrow width should be large in relation to the depth, cover should be used where steep slopes are unavoidable, and narrower furrow widths and greater depths should be used when the cross slope increases.

In a more popular article, Taylor (70) stressed a number of advantages of broad furrows, particularly the fact that it was a more effective water conducting channel with less susceptibility to erosion and clogging. He recommended an effective bottom width of 20 to 24 inches on flat land and about half this width on hillside orchards. These advantages would depend on the properties of the soil, however,

and cannot be considered applicable to all soils and all crops.

Later work by Israelson, Clyde, and Lauritzen (36) corroborated Taylor's work and provided the values of constants in an equation suggested earlier by Gardner. This equation was in the form of $E = kS^nQ$, where E is the rate of soil erosion from a furrow with slope S. The authors found values of k and n in the order of 2.8 and 2.0, respectively, for silty clay loam; and 4.4 and 1.5, respectively, for sandy loam soil.

They also found that erosion was higher from V-shaped furrows than from flat furrows, due to the differences in velocity of flow. Above slopes of 3.2 percent to 3.5 percent, however, the stream in the rectangular channel concentrated in its eroded channel and formed a V-shaped channel. Thus the authors concluded that furrow slopes of two percent and higher were excessive and caused harmful erosion when streams of ten gallons per minute, were run into each furrow.

Evans and Jensen (22) conducted similar studies in North Dakota, and developed the equation $E = 0.48\ S^{2.3}Q^{1.5}$ for furrow erosion. In this case, Q was the runoff flow in gallons per minute, which might be less likely to represent total erosion in the furrow than total inflow into the furrow. In observing cultivated and undisturbed furrows, Evans and Jensen found that the undisturbed furrows suffered less soil loss than the disturbed furrows, the rate of advance in undisturbed furrows was about twice as fast as in disturbed furrows, and the infiltration rate of the undisturbed furrows was lower during the first hour.

The fact that soil erosion may occur in furrows is an important facet in the field of irrigation hydraulics, for erosion would affect

not only the infiltration rate but also the furrow shape, dimensions, and hydraulic roughness.

Perhaps the most detailed design procedure for furrow irrigation systems has been prepared by the Soil Conservation Service (73). This engineering handbook summarized the adaptations, limitations and conservation features of irrigation furrows. The recommended design procedure was outlined as follows:

1. Determine the average intake rate. (For this purpose, curves were shown as a guide, and related the average seasonal intake rates for coarse to very fine soils).
2. Increase the average intake rate to allow for runoff from the end of the furrow (10 to 15 percent).
3. Determine the average water application head per 100 feet of length. (Curves relating water application head to intake rate and furrow spacing were shown).
4. Multiply the water application head required per 100 feet of length by the recommended length of run and divide by 100.
5. Check for erosive water application heads. The value obtained should be 1/4 to 1/3 less than the erosive head limit. (From $Q = 10/S$).

The handbook further provided recommendations for furrow spacing for the best ratio of lateral and vertical penetration. These recommendations were based on a grouping of soil types, and were intended primarily as a guide.

It was quite evident that the above design procedure is not infallible, but was intended as a reference guide to be used with

discretion by service personnel. These data provide some means of designing an irrigation system, however, in the event that water is not available or the soil has not been leveled.

Several Australian workers have contributed to studies on furrow irrigation, in designating what they term a "primary flow" system. Lyon and Pennefather (49) described the generally low efficiency (33 percent) of furrow systems and stated that higher efficiencies (70 to 80 percent) were attainable through good design and operation. They regarded the size of flow per furrow as the most important factor and showed a relation between flow rate per furrow and the volume water applied to the soil surface. At low flow rates, the water applied was quite high; as the flow rate increased the water applied decreased, until a minimum water application was reached. As the flow rate increased from this point, the water application remained constant. Many other workers disagreed with this hypothesis, because of some rather broad assumptions.

Vasey (75) derived the equation for this curve as follows:

1. The volume of water applied by ideal furrow = wdL/12.

   where w is the furrow spacing

   d is the depth of water in inches

   L is the furrow length

2. By turning the water off when it reaches the bottom end of the furrow (primary flow), the volume of water = Qt.

3. Thus the average depth, $d_{ave} = 12\ Qt/wL$.

4. Then plotting d_{ave} and Q, a curve was drawn that showed a minimum value of d_{ave} for large rates of flow, which was designated as d_1.

5. If the required application was greater than d_1, the flow should not be reduced, but the other dimensions of the system should be changed.

The errors associated with this hypothesis were due to the fact that water storage in the furrow was neglected and because it is seldom practicable to turn the water off when it reaches the bottom end of the furrow. The shape of the curve depends also on the rate of advance function, and may assume a form quite unlike that shown by the authors.

In discussing primary flow, Lyon and Pennefather stated that the necessary conditions for this system can be attained by lengthening the watering run, increasing the width and roughness of the furrow, cultivating deeper, impeding the flow with crops, decreasing the slope or reducing the flow. They further recommended that furrow grades should be uniform and that furrows should be made to suit the large flows required in "flat grade watering".

Philip (61) also advocated the primary flow system in discussing the general mechanics of the advance of water in the furrow. He suggested that the following relations be established in future work on furrow irrigation:

1. The relation between wetted perimeter of furrow and equivalent soakage area in an infiltrometer.
2. The relationship between furrow flow and friction losses.
3. The relation between furrow shape and time of irrigation (changing shape during the season).

These relations would be extremely useful, whether or not the primary flow concept is accepted.

Theoretical analysis of furrow irrigation

Oroszlany and Wellisch (55) proposed an unusual method for furrow design, based on the following requirements: a closed-end furrow system, such that the total water applied equalled the total volume of water required to wet the soil to a uniform depth; the infiltration of water was uniform along the length of the furrow; and the advancing water in the furrow reached the end of the run at the time the flow was cut off. They derived equations for the flow variables T, the duration of time of application; q, the flow in the furrow; and l, the furrow length.

They assumed that the rate of advance could be expressed by the relation $x = aq^{k}t^{B}$, where a was a function of the soil characteristics; and assumed that the effect of soil properties on the movement of water could be characterized by one coefficient. This was questioned however, for not only infiltration rates but also furrow erosion and roughness affect water movement, and these affects vary throughout the irrigation season.

An interesting analysis was presented, however, which bears further investigation. Results of their analyses showed that average field slopes (for ranges of 0.0001 to 0.006) had no direct influence on water advancement. They also mentioned that if the wetted section at the beginning of a furrow was greater than average, the advancement of water was slower and the constant a would decrease. This lower value of a caused a higher than actual value for the infiltration rate. Thus they compensated the error resulting from the introduction of a lower value for the wetted area by a higher than actual infiltration rate. Theoretically, however, this conclusion was not valid, for this

assumed a linear relationship between infiltration rate and volume of surface storage in the furrow, which may not be correct.

The authors prepared a table, based on their equations, that permitted an easy solution of the discharge-length of run-time relationship. They suggested applying a flow of one liter per second to eight or ten furrows, and recording the time required for the water to travel 50 meters. Then using a table with this corresponding time, one found the discharge and total time of application corresponding to the actual length of furrow and depth of water to apply. The fact that the authors mentioned that the constant a did not change appreciably during the irrigation season, and that the tables were unsatisfactory when a small flow was introduced over soil with high infiltration or vice-versa, raised considerable doubt as to the validity of the solutions shown.

Theoretical analysis of border irrigation

A number of authors have attempted to define the flow of water in irrigated borders, with varying degrees of success and acceptance. Several authors stated that their analysis for borders applied also to furrows; but it was unlikely that this was the case; for wetting patterns, infiltration phenomena and flow in the furrows are considerably different from that in borders.

Lewis and Milne (44) derived an equation for rate of advance down border strips, based on the assumption of constant depth of water and varying rate of infiltration. The final form of the equation was as follows:

$$cx = - \int_{0}^{t_x} y\ (t_x - t_s)\ x'\ (t_s)\ dt_s + qt_x/L$$

which was solved when the function y was a solution of a linear differential equation of the n th order with constant coefficients.

Several examples were given. If y, the infiltration function, was defined by $y = b\,(1 - e^{-rt})$, then

$$x = \frac{q}{LR\,(b + c)} \left[t - \frac{1}{k}\,(1 - e^{-kt}) \right]$$

where $k = r\,(b + c)/c$.

If y was defined by $y = at + b\,(1 - e^{-rt})$, then

$$x = \frac{q}{La} \left[1 - e^{-\beta t} \cosh \delta t + \left(\frac{a}{c\delta} - \frac{\beta}{\delta}\right) e^{-\beta t} \sinh \delta t \right]$$

These equations do not appear to have a wide acceptance by system designers, possibly because of their mathematical complexity and because the infiltration data are forced to fit a predetermined functional relationship. Also, the effect of slope and surface roughness were not readily discernable; because they were reflected in the depth of water, which was estimated beforehand. Their analysis, on the other hand, has been widely accepted by researchers and has stimulated a mathematical approach toward field irrigation analyses.

Israelson (37) presented a rather simplified approach to border analysis and rate of advance of water in a border strip. He also assumed a constant depth of water as it flows over the soil. Letting A represent the area covered with water at any time t, after water was turned on, then

$$q\,dt = y\,dA + IA\,dt$$

where y is the average depth of water in inches, I is the rate of infiltration into soil of wetted area in in/hr, and t is the time after water was turned on in hours.

Then rearranging and integrating,

$$t = 2.303\ (y/I)\ \log q/q - IA$$

Thus, a rather simple equation was the result. The errors involved in this analysis were increased, however, by the assumption of a constant infiltration rate and a uniform depth of water. The slope and roughness of the border were reflected in the depth of the water, as in Lewis and Milne's analysis.

Israelson recognized the fact that furrow irrigation presents a more difficult problem, in that the water wets only part of the soil surface. He cited this as an advantage because it lessens the puddling of heavy soils and cultivation can begin sooner after irrigation than with borders.

Hall's (30) analysis of border flow closely paralleled the analysis in this dissertation. Hall considered that the volume of water in storage above the soil surface was equal to $V_{si} = b\ (d_o c + e)\ x_i$; where c was a constant that describes the shape of the water surface, e was a depth correction termed the puddle factor, d_o was the depth of water at the head of the check, and x_i the distance the water has advanced down the surface of the check.

The infiltration function, y(t), was defined as the total quantity of water per unit area which has entered the soil t units of time after water was applied initially. The increment of volume applied to the soil ΔV_{ai} was then given by

$$\frac{\Delta V_{ai}}{b} = 1/2 \left[(y_i - y_{i-1}) + (y_{i-1} - y_{i-2}) \right] \Delta x_1 + 1/2 \left[(y_{i-1} - y_{i-2}) + (y_{i-2} - y_{i-3}) \right] \Delta x_2 + \ldots + 1/2 \left[(y_2 - y_1) + (y_1 - 0) \right] \Delta x_{i-1} + k y_1 \Delta x_i$$

where k was a constant describing the shape of the wetting front in the soil under the element of distance Δx_i. Then, by letting $a_i = (y_i - y_{i-2})/2$, and by summing the volumes of water in the soil and in surface storage, the mass balance for the check was:

$$Q_o \Delta t/b = a_i \Delta x_i + a_{i-1} \Delta x_2 + \ldots. + a_2 \Delta x_{i-2} + (ky_1 + cd_o + e) \Delta x_i$$

Thus, a solution for Δx_i was obtained by using a simple numerical method, which Hall illustrated with an example in his paper. An analysis of possible errors in this method showed that errors in estimating e, c, k or n have much less effect on the result than errors in Q_o or y(t). Likewise, Q_o was the most important for determining the first increments of distance while y(t) was more important in determining later increments of distance, or for longer furrow runs.

Hall also compared measured advance down a border with that calculated by assuming various values for c and k. He found that the curve for c = k = 0.75 fell approximately on the experimental points, demonstrating the validity of the developed equations. He concluded that this method of computing rate of advance was well within the accuracy of infiltrometer data.

Bouwer (12) presented a somewhat different approach to flow in borders which was somewhat laborous in that a number of equations were solved simultaneously to determine the infiltration of water into the soil. Considerable errors would be present if infiltration changed rapidly with time and if the varying depth of water on the surface were not considered. However, the method offered some advantages in its simplicity and could produce more accurate results by easy manipulation of the time and distance variables.

Bouwer suggested that the method was applicable to furrow systems, assuming that the width of the wetted front in the soil was a multiple of the row spacing. He did recognize the problem in doing so, however, for he stated that some refinement can be obtained if the effect of stream width on infiltration was known.

Ostromecki (56) reviewed the equations proposed by Skotnicki, Zakaszewski, Kostiakow and Michalowski, which dealt with the calculation of the time required to flood irrigation checks. He pointed out that these equations were limited to a condition of a low water table (several meters below ground level); and because these equations assumed a constant rate of infiltration, the practical applications were not always quite justifiable.

Ostromecki then proposed a differential equation for the solution of the time of flooding, based on a variable rate of infiltration defined by the equation $W = W_1 T^{a+1}$. His equation was developed in a manner similar to Hall's, in that he equated the volume of water introduced into the check in a finite time interval Δt to the sum of the increments of volumes of water in surface storage and soil moisture storage, in order to calculate the increment of distance, ΔX, that the water has traveled in the check. However, in order to derive his equations, he apparently assumed that water flows into the lower end of the check, and fills the check with successive horizontal increments of water depth. This premise, in the writer's opinion, deviated considerably from field practice and may result in a considerable error in the calculation of the volume of water stored above the soil surface. Otherwise his technique appeared valid. He

did not validate the equation with any empirical field studies, however, and merely compared this equation with that of the four other workers mentioned.

Although all of the above methods appeared to have merit, it was doubtful that they could be applied to furrow irrigation unless the stream shape-infiltration function was known. Because this function depends on the soil properties and the flow regime, the Hamilton furrow infiltrometer may provide a satisfactory means of measuring furrow infiltration rates which could then be substituted into the equations presented. In any case, the adoption of any mathematical technique of preducting rates of advance of water in furrows will depend on its simplicity, its accuracy, and the availability of field data.

METHODOLOGY AND DERIVATION OF EQUATIONS

Any approach to a rate of advance equation for irrigated furrows may be subject to error and a varying degree of applicability. However, the mass conservation approach, as advocated by Hall, Israelson and Ostromecki, appealed to this author as a method less subject to error than others and as a method fairly easily validated by empirical studies.

Of all the methods proposed for determining the rate of advance in borders, as discussed in the review of literature, Hall's appeared to offer the most promise as an accurate, simple solution. Not only was infiltration considered as a variable function of time, but the water surface profile was also considered in determining the storage of water in the border. Thus, one may consider that Hall's equation was mathematically correct; that the equation itself need not be validated, but that the infiltration and storage functions need evaluation. This approach leads more toward the empirical study of these functions than the study of the equation itself.

The purpose of this dissertation was then: (1) to adapt Hall's approach to furrow irrigation for the derivation of a single equation for rate of advance, (2) to validate the equation in field studies, and (3) to shed some light on the relative contributions of the infiltration and surface storage functions.

Derivation of the equation

The method used to obtain the advance of the water front was essentially a numerical integration. When water flows into a furrow

at a rate of Q cubic feet per second, part of this volume of water enters the soil at an intake rate $i = i(t)$, a function of time after wetting. The rest of the water fills a volume V_s above the surface of the soil. For a given roughness and furrow shape, and water surface slope at the head of the furrow; a depth of water, d_o, will be reached such that the rate of flow down the furrow at the head end is equal to the inflow rate Q.

The infiltration function y(t) was defined as the total quantity of water per unit length of furrow which has entered the soil t units of time after water was applied initially and continuously; such that $y(t) = \int_o^t i(t)dt$.

The relationship between total infiltration and surface storage is given by the curves in Figure 1 with time as a parameter. Downward from a horizontal line representing the soil surface, a series of points were plotted on a vertical axis, representing to scale the total volume of infiltration at the end of successive, equal increments of time. At any distance X down the furrow, the volume of water applied to the soil was determined only by the time elapsed since water first reached that point.

If it is presumed that on the average the infiltration characteristics were uniform for the length of the furrow, the horizontal lines then represent the total volume of water in the soil at the corresponding instants in time after water reaches the point considered. At the end of the first time increment, Δt, water will have reached X_1 and the volume of water applied at $X = 0$ will be y_1. At the end of the second time increment, the volume of water in the soil at $X = 0$ will be y_2,

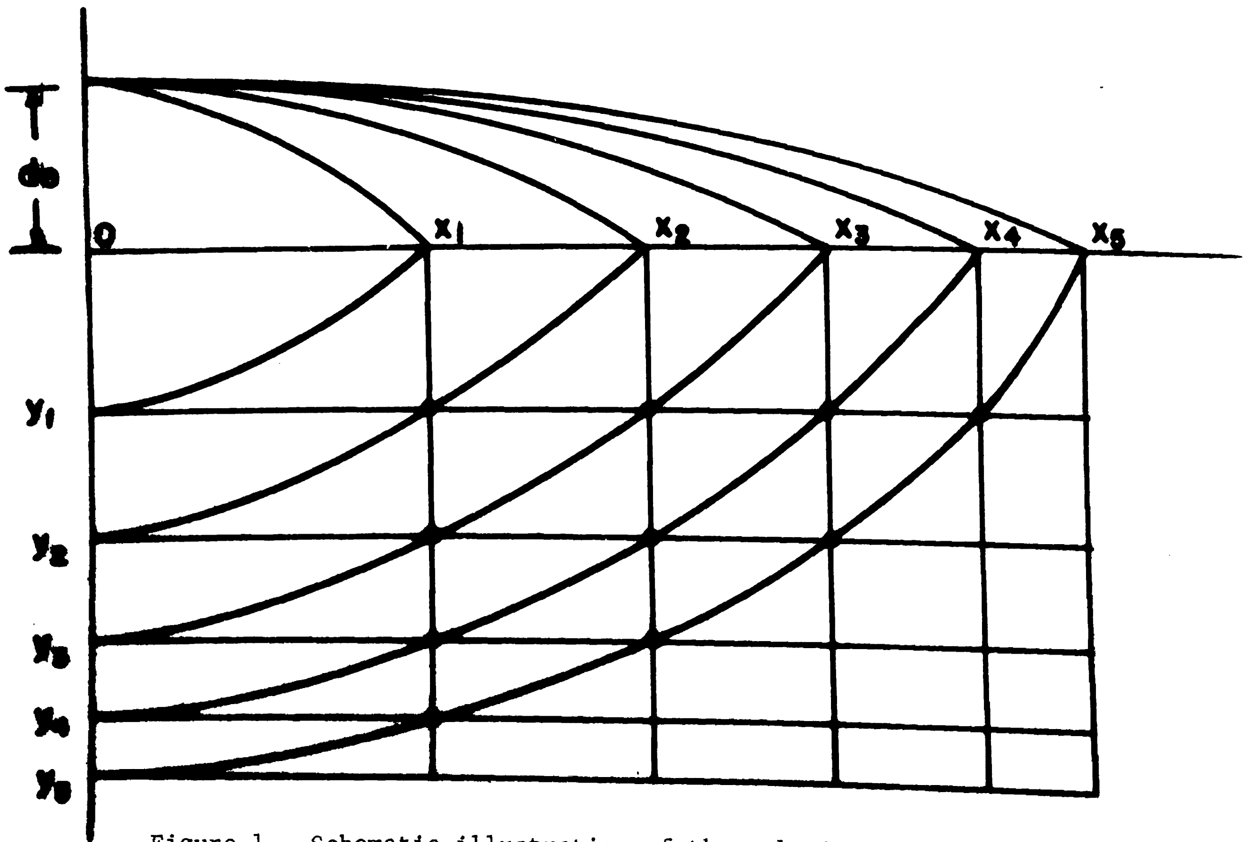


Figure 1. Schematic illustration of the relation between total infiltration, surface storage, and distance down a furrow; where y_i represents infiltration volume, X_i represents distance down the furrow and d_o represents the depth of flow at the upper end of the furrow.

the volume of water in the soil at X_1 will be y_1, and the water will have reached X_2. Thus the curve passing through the points $(0, y_2)$, (X_1, y_1) and $(X_2, 0)$ represents the total volume of water in the soil as a function of distance down the furrow at time $t = 2\,\Delta t$. Other such curves for $t = 3\,\Delta t$, $t = 4\,\Delta t$ and $t = 5\,\Delta t$ are also shown to illustrate the method for constructing these curves. The area between any two successive curves is then equal to the total volume of water applied to the soil during the time interval Δt.

In addition to the volume of water stored in the soil as described above, there is a storage of water represented by the depth of water in the furrow. Depending on the slope, roughness and shape of the furrow, there is a minimum depth d_o necessary at the head of the furrow to pass the flow Q down the furrow. This depth may be obtained directly from Manning's equation or from flow equations that may be developed later to more adequately describe the flow phenomena in small rough channels.

The depth of water necessary for flow past successive points down the furrow will decrease, however, since the total flow past these points decreases. The water depth thus becomes a function of the distance down the furrow. While the depth of water at each point can be computed, a simpler and more general approach was to assume that the type of function represented by the water surface was the same for all instants of time. With this assumption, the ratio of the actual volume of surface storage to the volume of the circumscribing parallelopiped is a constant c, which from reasoning should be greater than one-half but less than one.

The value of c would depend not only on the shape of the water surface but also on the shape of the furrow. For example, if the equation of the water surface happened to be a cubical parabola with vertex on the X-axis at the point in question, the value of the constant ratio is 0.75 for a rectangular shaped furrow; 0.375 for a triangular shaped furrow, 0.321 for a semicircular shaped furrow, and a dual constant for a trapezoidal furrow. The advantage in expressing the volume in terms of c lies in the fact that c can always be computed for any particular furrow shape if enough is known of the geometry.

The volume of water calculated in the above manner was only that which was necessary for the required flow to occur at the roughness and slope of the channel, and did not include the volume of water which must be applied to fill the pockets and minute depressions before flow can occur. Thus for purposes of surface storage, a correction must be applied to represent the volume of water which would remain in the furrow after the water was turned off, assuming zero infiltration. This average volume correction was termed the puddle factor, denoted by e. It is somewhat dependent upon surface roughness and consequently the volume of flow and water stability of soil aggregates, but for most soil conditions, should be a fairly constant value.

The volume of water in storage above the soil surface at any time t_i, is then equal to

$$V_{si} = \left[c \cdot f(d) + e \right] X_i \qquad (1)$$

The increment of surface storage volume which occurs during any time interval is equal to the difference between the surface storage volumes at the beginning and end of the time interval.

$$\text{Thus} \quad \Delta V_{si} = \left[c \cdot f(d) + e \right] \Delta X_i \tag{2}$$

The increment of the volume of water stored in the soil is equal to the area between two successive total application curves. In Figure 1, for the fifth time increment, this is the area whose corners are y_4, X_4, X_5 and y_5. The area except the last three cornered element below ΔX_5 can be determined by the trapezoidal rule. The last element was estimated in the same manner as the surface volume by assuming that the shape of the curve in this last element was a constant. The ratio of the actual cross sectional area to the area of the rectangle circumscribing it will be a constant, k, whose value should be between one-half and one. The increment of volume applied to the soil ΔV_{ai} is then given by

$$\begin{aligned} \Delta V_{ai} = {} & 1/2 \left[(y_i - y_{i-1}) + (y_{i-1} - y_{i-2}) \right] \Delta X_1 + \\ & 1/2 \left[(y_{i-1} - y_{i-2}) + (y_{i-2} - y_{i-3}) \right] \Delta X_2 + \dots + \\ & 1/2 \left[(y_2 - y_1) + (y_1 - 0) \right] \Delta X_{i-1} + k y_1 \Delta X_i \end{aligned} \tag{3}$$

To simplify equation (3), one may assume that in most cases the function $y = at^n$ is applicable, as pointed out by others in the review of literature. In fact, as long as y is an algebraic function of t (i.e. nontrigonometric or transcendental), this postulate does not affect the validity of the analysis; it merely is a more simplified form. For example, if $y = at^n + bt$, there would be only one more term to include; or if $y = y(t)$ is expansible in a power series in t, the

method, though cumbersome, would still yield a workable solution.

Then, assuming that $y_1 = a(\Delta t)^n$; $y_2 = a(2\,\Delta t)^n$; $y_3 = a(3\Delta t)^n$; $y_i = a(i\,\Delta t)^n$,

$$\Delta V_{ai} = 1/2\left[a(i\,\Delta t)^n - a\left\{(i-2)\quad\Delta t\right\}^n\right]\Delta X_1 + 1/2\left[a\left\{(i-1)\quad\Delta t\right\}^n - a\left\{(i-3)\quad\Delta t\right\}^n\right]\Delta X_2 + \ldots\ldots + 1/2\left[a(2\,\Delta t)^n\right]\Delta X_{i-1} + ka(\Delta t)^n\quad\Delta X_i \tag{4}$$

Simplifying equation (4) by factoring;

$$\Delta V_{ai} = \frac{a(\Delta t)^n}{2}\left[\left\{i^n - (i-2)^n\right\}\Delta X_1 + \left\{(i-1)^n - (i-3)^n\right\}\Delta X_2 + \ldots\ldots + 2^n\quad\Delta X_{i-1} + 2\,k\quad\Delta X_i\right] \tag{5}$$

By substituting a factor defined by

$$g_i = i^n - (i-2)^n \text{ where } i \geq 2,$$

$$\Delta V_{ai} = \frac{a(\Delta t)^n}{2}\left[g_i\Delta X_1 + g_{i-1}\quad\Delta X_2 + \ldots + g_2\Delta X_{i-1} + 2k\,\Delta X_i\right] \tag{6}$$

By the law of conservation of matter, the quantity of water flowing into the furrow during any time increment must be equal to the sum of the increments of storage produced. Using equations (2) and (6), the mass balance for the furrow during any time increment is, for $i \geq 2$;

$$Q(\Delta t) = \frac{a(\Delta t)^n}{2}\left[g_i\Delta X_1 + g_{i-1}\Delta X_2 + \ldots\ldots + g_2\Delta X_{i-1} + 2k\Delta X_i\right] + \left[c\cdot f(d) + e\right]\Delta X_i \tag{7}$$

Presuming that the shape of the furrow is either parabolic or V-shaped, the volume of water in surface storage can be expressed as a function of d^2. Also, since the total intake function is likely to be characterized by cylinder or furrow infiltrometer techniques, the intake function should be modified by a factor F to permit the use of

the equation for all conditions of furrow shape, roughness, spacing, depth of water, etc.; such that $y_i = F\,a\,(i\,\Delta t)^n$. Thus equation (7), including the above changes and rearranged, becomes

$$\Delta X_i = \frac{Q(\Delta t) - \frac{Fa(\Delta t)^n}{2}\left[g_i \Delta X_1 + g_{i-1}\Delta X_2 + \ldots + g_2 \Delta X_{i-1}\right]}{Fa(\Delta t)^n k + cd_o^2 + e} \quad (8)$$

For X_1 the solution is simply

$$\Delta X_1 = \frac{Q(\Delta t)}{Fa(\Delta t)^n k + cd_o^2 + e} \quad (9)$$

The value of ΔX_1 is obtained from equation (9) and substituted into equation (8) for i = 2 to obtain ΔX_2. This value is substituted in turn in equation (8) for i = 3 to obtain ΔX_3.

The g_i are calculated directly from the empirical total infiltration function and are shown for various values of n in Table I. While not necessary, the solutions of equation (8) can be determined easily with electronic computers or with the form shown by Hall in his paper.

Equation (8) was obtained with accepted laws and equations of hydraulics. However, certain assumptions were made in order to reduce the labor of computations and to provide for a more general, acceptable equation. These postulates primarily concerned the constants F, c and k. Additional factors affecting the accuracy of the results were the experimental accuracies with which the infiltration functions were determined and the accuracy of the estimates of the puddle factor and furrow roughness. None of these factors should be expected to remain constant during the irrigation season or from year to year, except possibly as average values.

On soils of good permeability, the volume of water stored in the soil will usually be much larger than the volume of water in surface

Table I

$$g_i = i^n - (i - 2)^n$$

n	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}
.04	1.0281	.0449	.0289	.0216	.0173	.0144	.0124	.0110	.0098
.08	1.0570	.0919	.0603	.0455	.0368	.0311	.0269	.0237	.0213
.12	1.0867	.1409	.0943	.0721	.0589	.0500	.0435	.0387	.0348
.16	1.1173	.1922	.1310	.1015	.0837	.0716	.0626	.0560	.0508
.20	1.1487	.2457	.1708	.1340	.1115	.0961	.0847	.0761	.0692
.24	1.1810	.3017	.2136	.1698	.1427	.1237	.1099	.0992	.0906
.28	1.2142	.3602	.2601	.2091	.1772	.1551	.1386	.1257	.1154
.32	1.2483	.4213	.3100	.2524	.2159	.1902	.1711	.1561	.1440
.36	1.2834	.4851	.3638	.2999	.2588	.2298	.2080	.1908	.1768
.40	1.3195	.5519	.4216	.3517	.3066	.2743	.2497	.2303	.2145
.44	1.3566	.6216	.4838	.4086	.3594	.3240	.2969	.2753	.2575
.48	1.3946	.6944	.5507	.4710	.4180	.3794	.3499	.3262	.3067
.52	1.4340	.7705	.6222	.5387	.4827	.4416	.4097	.3839	.3627
.56	1.4743	.8501	.6992	.6127	.5540	.5106	.4768	.4493	.4265
.60	1.5157	.9332	.7817	.6933	.6327	.5876	.5521	.5231	.4989
.64	1.5583	1.0204	.8701	.7812	.7195	.6730	.6363	.6063	.5810
.68	1.6021	1.1108	.9647	.8766	.8150	.7681	.7307	.6998	.6738
.72	1.6472	1.2056	1.0660	.9805	.9198	.8734	.8361	.8052	.7790
.76	1.6935	1.3047	1.1744	1.0933	1.0350	.9901	.9539	.9234	.8976
.80	1.7411	1.4082	1.2903	1.2157	1.1616	1.1194	1.0850	1.0562	1.0316
.84	1.7901	1.5164	1.4142	1.3485	1.3002	1.2624	1.2313	1.2050	1.1826

storage. It therefore appeared that some error in estimating e, c, k or surface roughness would have much less effect on the result than errors in Q or y(t). It was also noted that while Q will be the most important factor for determining the first increment of distance, y(t) will be more important in determining later increments of distance. This is an advantage, however, because more tolerance can then be allowed for short runs than for longer runs. Where long runs would be more efficient (low infiltration rates), the infiltration function should be subject to less error in measurement.

Thus, an equation for rate of advance in irrigation furrows has been written. The remainder of this dissertation will then describe the results of certain field and laboratory tests, conducted to demonstrate the applicability of the equation and to discern the errors and effects of estimating e, c, k and F.

DESCRIPTION OF FIELD AND LABORATORY STUDIES

To test the applicability of the furrow equation and to determine the effects of some variables on the coefficients in this equation, appropriate measurements were made in the field during the summer of 1958. In addition, the equation was evaluated using data from other workers.

A preliminary model study was also conducted in the greenhouse, in an attempt to evaluate the effects of furrow shape, spacing and water depth on the rate of infiltration into the furrow. This will be described later, as it affects only a part of the problem of non-uniform flow in furrow.

The field studies were conducted on the Marshall Wanzer ranch in Tulare County near Farmersville, on a Cajon fine sandy loam soil; and on the experiment fields of the University of California at Davis on Yolo silty clay loam soil.

Field studies in Tulare County

The field work in this area was conducted in cooperation with Mr. Alan George, Farm Advisor, who selected the fields and assisted in the collection of field data. Two separate fields were selected on the Wanzer Ranch; both were planted to cotton in the middle of April, after a pre-planting application of water. The two fields, hereinafter called the northeast and the southwest fields, had the following treatments:

Northeast Field

Planted	Cotton, April 18
Cultivated	May 15, June 10, June 21
Fertilized	May 26, 80 lbs. N
Irrigated	June 12, 30, July 17, 31, August 13, 22
Crop history	Cotton, Cotton, Field Corn, Sweet Corn, Cotton, Cotton, Cotton

Southwest Field

Planted	Cotton, April 16
Cultivated	May 7, 13, June 10, June 21
Fertilized	May 21, 80 lbs. N
Irrigated	June 13, July 1, 18, 30, August 8, 22
Crop history	Cotton, Cotton, Corn, Cotton, Cotton, Corn, Cotton

Each field had been recently graded, the northeast field had an average slope of 0.195 percent for 400 feet and an average slope of 0.068 percent from 400 to 650 feet. The southwest field had an average slope of 0.086 percent for the entire length of 520 feet, but the field contained numerous slight depressions that had not been removed during grading.

To evaluate the effects of changing soil conditions and foliage conditions during the irrigation season, the trials were conducted during the first, third and fifth irrigations. Ditch water of about the same quality was applied at each irrigation; in no case was salinity a problem in the irrigation operation.

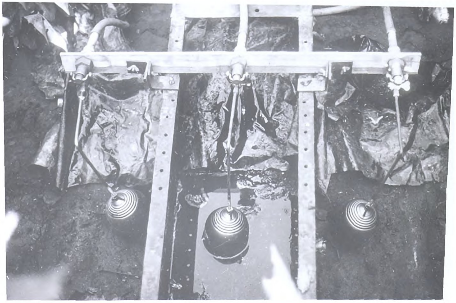
Before each irrigation, the infiltration rates of the soil were determined with the Hamilton furrow infiltrometer (as described by Bondurant). Float valves were used to maintain a constant head of water in the furrow section and the buffers; and a Friez FW-1 water level recorder was used to record the water level in a calibrated five-gallon pail which served as a water storage tank. These instruments are shown in Figure 2. The furrow section was lined with plastic film, and measurements were started when the furrow section was full of water and the plastic was removed. Disturbance of the soil by water flowing from the valves was prevented.

At least two infiltrometer measurements were made immediately prior to each rate of advance measurement in each field in an area adjacent to the test area. These measurements were conducted over a period of time sufficient to insure that infiltration had reached a constant value.

To evaluate the influence of flow rate (volume/time) upon rate of advance, measurements were made with five flow rates, representing a range from very low to very high for the soil and length of run conditions encountered. Five adjacent furrows were irrigated with the same flow rate; 25 furrows were irrigated in total. Because the two fields were irrigated from a head ditch at the upper end of the fields, it was necessary to combine various sizes of siphons or spiles to obtain the five flow rates desired.

For the first irrigation, combinations of 3/4", 1", 1 1/2" and 2" aluminum siphons were used to introduce water into the furrows. These were primed by the irrigator and the time at which flow started in

Water supply tanks and stage recorder.



Furrow infiltrometer and float valves.

Figure 2. Furrow infiltrometer in operation.

each group of furrows was noted. The rate of advance was then determined by noting the position of the wetting front in the furrow with respect to stakes placed every 50 feet down the field. The flow of water into alternate furrows from the siphons was measured with a calibrated bucket and a stopwatch. Because this was a difficult method, sometimes leading to questionable accuracy; the head on the siphon was determined by leveling, and the flow calculated from rating curves for the siphons. The flow rates then used for later calculations were averages of the two methods employed.

During the third and fifth irrigations, spiles were used to introduce water into the furrows from the head ditch. These were placed in the ditch bank and allowed a much more precise measurement of the flow with the bucket. Two to three determinations of the flow rate were then made on alternate furrows, and the average of these determinations employed in the later calculations.

Toward the end of each trial, the depth of water in each furrow was determined and observations were made on the shape and width of each furrow.

In two cases--the first irrigation in the northeast field and the third irrigation in the southwest field--some of the data were discarded because of major changes in the flow condition. Breaks in the head ditch upstream resulted in excessively varied flow, sufficient to warrant exclusion of the data. For all of the other trials, the flow rates were presumed to be fairly constant.

Field studies at Davis

The studies at Davis were conducted in a small area which had been planted to milo in June, and which was irrigated for the first time at the middle of July. The measurements were made in much the same manner as those in Tulare County, except that gated pipe was used to introduce water into the furrows. Two studies were made here--on July 14 and August 28.

On the first date, three flow rates were introduced into three groups of three furrows each; on the second date, three flow rates were introduced into three groups of four furrows each. Flow measurements were again made with a calibrated bucket and a stopwatch, and the position of the wetted front in the furrow noted in 50 ft. intervals for the length of the field.

Furrow infiltrometers were operated at the same time as the irrigation, on adjacent furrows, with the same equipment as previously described.

Toward the end of each irrigation, water depth and furrow width were measured and recorded. After the second irrigation, the shape of each furrow was determined by the method of cross sections; that is, the difference in elevation between the water surface and the furrow bottom was measured at one-inch intervals across the furrow.

Furrow model studies

To investigate several of the furrow parameters that might influence the infiltration phenomenon, two model tanks were constructed. The tanks were about six feet long, three feet deep and 0.1 feet thick; with 1/4-inch plate glass on the front, through which

wetting patterns were observed. Both front and back of the tanks were strongly reinforced to prevent warping or twisting, and the base of each tank was equipped with leveling screws. A small perforated tube wrapped with fiberglass mat was installed at the bottom of each tank, to permit the escape of entrapped air in the soil during tests.

The plywood back of each tank was removable to facilitate placing the sand in the tank and to allow the sand to later dry out at an accelerated rate.

Initially, the tanks were tipped forward, with the glass front down, and the backs were removed. Air dry sand was then placed in the tank in uniform horizontal layers, to eliminate any horizontal stratification when the tanks were then tipped to their original position. The sand has been classified as an Oso Flaco fine sand, which is a dune sand with a fairly uniformly graded particle size distribution and with nearly spherical shaped particles.

The sand was leveled in the tanks, the back was replaced and the tank tipped back and leveled. Several wetting and drying cycles were performed to settle the sand. Drying was accelerated by removing the back and blowing air over the soil surface for 24 to 48 hours, or until the entire depth of sand was air-dry. The surface of the sand was protected by a layer of fiberglass to avoid any disturbance by air movement, as shown in Figure 3.

Furrows were made in the wet sand by slicing out of the sand the size and shape of the furrow desired. The furrow sides were then lined with several thicknesses of fiberglass mat and coarse screening, to maintain the shape of the furrow when water was later introduced.

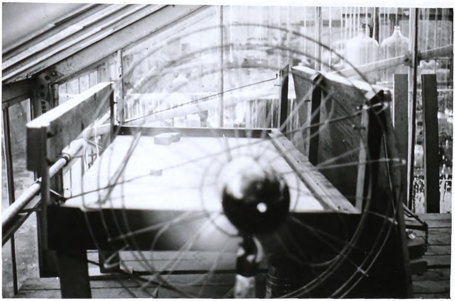


Figure 3. A view through the drying fan showing the back of a model tank which had been tipped forward for drying.

Water was supplied to each furrow from a 4-inch diameter plastic cylinder approximately 24 inches high, using the principle of Mariotte's bottle to supply water and to maintain a constant water level in the furrow. All the water used was cold tap water, the temperature of which did not change during the period of the study. The water was chlorinated in the cylinders to prevent any microbial growth in the sand.

The cylinders which were calibrated and read to the nearest 9 cc. (.05 inch depth), were attached to a manifold of positive action valves with tygon tubing. This arrangement permitted entry of water into as many as seven furrows simultaneously. Figures 4 and 5 show the arrangement of the tank and the cylinders. Immediately after water was admitted to the furrows, the position of the wetting front and the depth of the water in the supply cylinders were recorded at specific time intervals. This was done by marking the glass front of the tank and the side of the cylinders with a wax pencil.

Since it was difficult to prevent entirely any deflections in the front or back of the tanks, measurements were made to determine the magnitude of such deflections. The depth of sand was determined at the start and toward the end of the study. In both tanks the maximum variation in sand depth was about 9 percent of the average depth, while the average variation was about four percent of the average depth.

The specific variables studied were as follows:

Furrow shape

a. triangular--6" deep, 1:1 side slopes

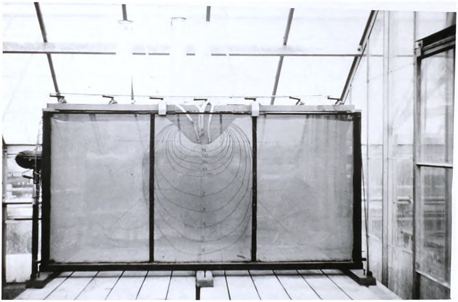


Figure 4. Front view of a model tank immediately after a measurement, showing the location of the water supply cylinders and the valves.

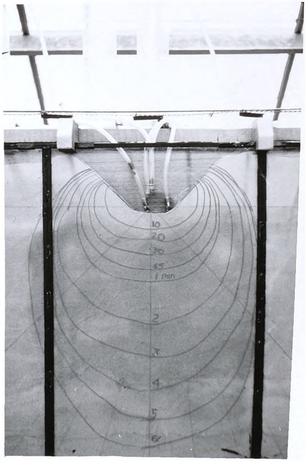


Figure 5. Close-up view of the front of a model tank, showing the furrow and the method of marking the positions of the wetting front.

b. trapezoidal--6" deep, 1:1 side slopes, 4" bottom width

Furrow spacing

a. 18 inches

b. 36 inches

c. 72 inches

Water depth

a. 2 inches

b. 5 inches

After initial settlement of the soil in the tank had taken place, the sand was allowed to come to an air dry condition and the tests were then performed. For the 72-inch spacing, one furrow was made in the center of the tank, and several separate tests were conducted for purposes of replication. For the 36-inch spacing, half furrows were added at each end of the tank, and again several separate tests were conducted. For the 18-inch spacing, two more furrows were added, making a total of three complete and two half-furrows in the tank. In this case, the three furrows provided some replication, and additional tests were not performed.

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PRESENTATION AND ANALYSIS OF DATA

The data described in the previous section will be presented in the order of the development of this study, or in the order of the apparent need for these data. First, the applicability of the furrow equation will be treated; that is, a comparison will be made of the observed rate of advance and a theoretical rate of advance for all the studies conducted.

Secondly, parts of the equation will be analyzed to determine the magnitude of the separate factors involved. Here, the results of the furrow infiltrometer data and their apparent fit to the existing field conditions will be shown, as well as the results of the furrow model studies conducted in the laboratory. The results of measurements of furrow size and shape and the subsequent calculation of hydraulic roughness will then be presented--all in an attempt to provide more knowledge on the behavior of water flow in small channels and the resulting storage of water in the furrow channel.

Applicability of the furrow equation

After each field study had been conducted, the infiltrometer data were plotted and the equations for total infiltration were calculated. In general, these equations assumed the form $I = At^n$. In some instances, the slope of the curves for about the first 15 minutes of the infiltrometer run was steeper than the curve for the remaining time; but rather than introduce the problem of using two separate equations for infiltration, one single equation was calculated which represented the total infiltration for the remaining time. This should introduce on

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only a small error, because the flow of water in the furrow usually requires a considerable length of time, and the equations used should be representative of conditions existing throughout most of the trials.

In each study, at least two separate infiltrometer determinations were made. Two equations were thus obtained by the slope-intercept method, and an average of the two was used for the study. The resulting average equations are shown in Table II.

Table IIA

Infiltration Equations for Cajon Fine Sandy Loam,

Wanzer Ranch, Farmersville, California

	Northeast Field		Southwest Field	
Irrigation	Equation	D_i	Equation	D_i
First	$I = 0.0342\ t^{0.56}$	0.280	$I = 0.0908\ t^{0.31}$	0.278
Third	$I = 0.0142\ t^{0.704}$	0.135	$I = 0.0751\ t^{0.375}$	0.155
Fifth	$I = 0.0174\ t^{0.468}$	0.120	$I = 0.0562\ t^{0.332}$	0.150

Table IIB

Infiltration Equations for Yolo Silty Clay Loam,

Davis, California

Irrigation	Equation	D_i
First	$I = 0.0341\ t^{0.625}$	0.17
Second	$I = 0.0321\ t^{0.549}$	0.15

In each of these tables, I is expressed in cubic feet per foot length of furrow, D_i represents the depth of water in the infiltrometer in

feet, and t represents elapsed time in minutes.

Thus, for each study a standard measurement of infiltration was obtained and an equation for total infiltration as a function of time was determined. Inasmuch as these data were determined immediately preceeding an irrigation, the equations should represent the field conditions of moisture content and soil aggregation encountered during the irrigation.

Two glaring errors are involved in the above assumption. First, the area of soil isolated by the infiltrometer was not subject to erosion, so the furrow essentially retained its shape and dimensions. A furrow in which water is flowing, however, is subject to soil erosion; consequently its shape and size will change depending on its roughness, aggregate stability and aggregate size, etc. Thus, the furrow used for determining infiltration rates may or may not be representative of furrows in which water is flowing.

Secondly, the depth of the water in the infiltrometer may differ considerably from that in a flowing furrow. If the infiltrometer depth is greater, it may be presumed that the total infiltration will be greater than that in a flowing furrow.

In view of the fact that <u>some</u> determination of infiltration is necessary, and the fact that no better method was available; these two discrepancies have to be ignored. This is not serious, however, because as other authors have pointed out, the shape of the furrow and the depth of water in the furrow affect only the constant A in the equation $I = At^n$. Thus, if a factor F, which is a function of various furrow parameters, were applied to the infiltration equation; a su

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suitable equation for infiltration from furrows in which water is flowing should result.

The equation for rate of advance, as derived in a previous section, was as follows:

$$\Delta X_i = \frac{Q\Delta t - 1/2Fa(\Delta t)^n\left[(g_i\Delta X_1 + g_{i-1}\Delta X_2 + \ldots. + g_2\Delta X_{i-1})\right]}{Fa(\Delta t)^n k + cd_o^2 + e}$$

In each trial, the depth of water flowing in the furrows was measured; and assuming some reasonable furrow shape from observations, the volume of water in storage in the furrow could be calculated. In the northeast field on the Wanzer Ranch, the slope of the field changed abruptly at a distance of 400 feet from the upper end. For this reason, the depth of water changed in proportion to the square root of the ratio of the two slopes; and for purposes of calculating the rate of advance, as soon as water had reached station 4 + 00, the term representing storage in the denominator of the equation was appropriately revised.

In most cases a value for the puddle factor e was assumed to be within the range of 0.001 to 0.003 cu. ft. per ft. These values are based upon cursory observations of stationary roughness in the furrows. With the field slopes encountered in the field studies, errors in estimating the puddle factor should not affect the accuracy of the equation significantly.

Assuming that the infiltration function adequately represented the true infiltration of water into the soil, that the measured depth of water in the furrow was reasonably accurate, that the puddle factor was reasonably representative, and that the flow rates were accurately

determined; the only remaining unknowns in the equation were c, k, F and X_i.

For the analyses, c was assumed equal to unity, because field observations indicated that a constant depth of water in the furrow was reached shortly after the wetting front had passed. No data were available from which any other value could be justifiably selected. The constant k and the furrow shape factor F were then combined to reduce the number of remaining variables in the equation; thus only F and X_i remain unknown.

For each flow measurement for each study, a factor F was assumed and X_1 was calculated. Then by trial and error, a value of F was reached whereby X_1 (calculated) was equal to X_1 (observed). This resulting value of F then remained constant throughout the calculations for the remaining X_i. Once this initial step was performed, the calculations proceeded rather speedily, for the denominator of the equation and most of the numerator remained constant. Several sample calculations are shown in the appendix.

The time Δt selected for the calculations of rate of advance was either 10 or 20 minutes, depending on the length of time the measurements were made. For eight of the trials, two separate calculations using both 10 and 20 minute intervals were made. There was no difference in rate of advance due to these different time intervals.

Comparisons of calculated rate of advance and observed rate of advance for all of the field studies are shown in figures 6 through 12. In all cases, the calculated rate of advance was almost

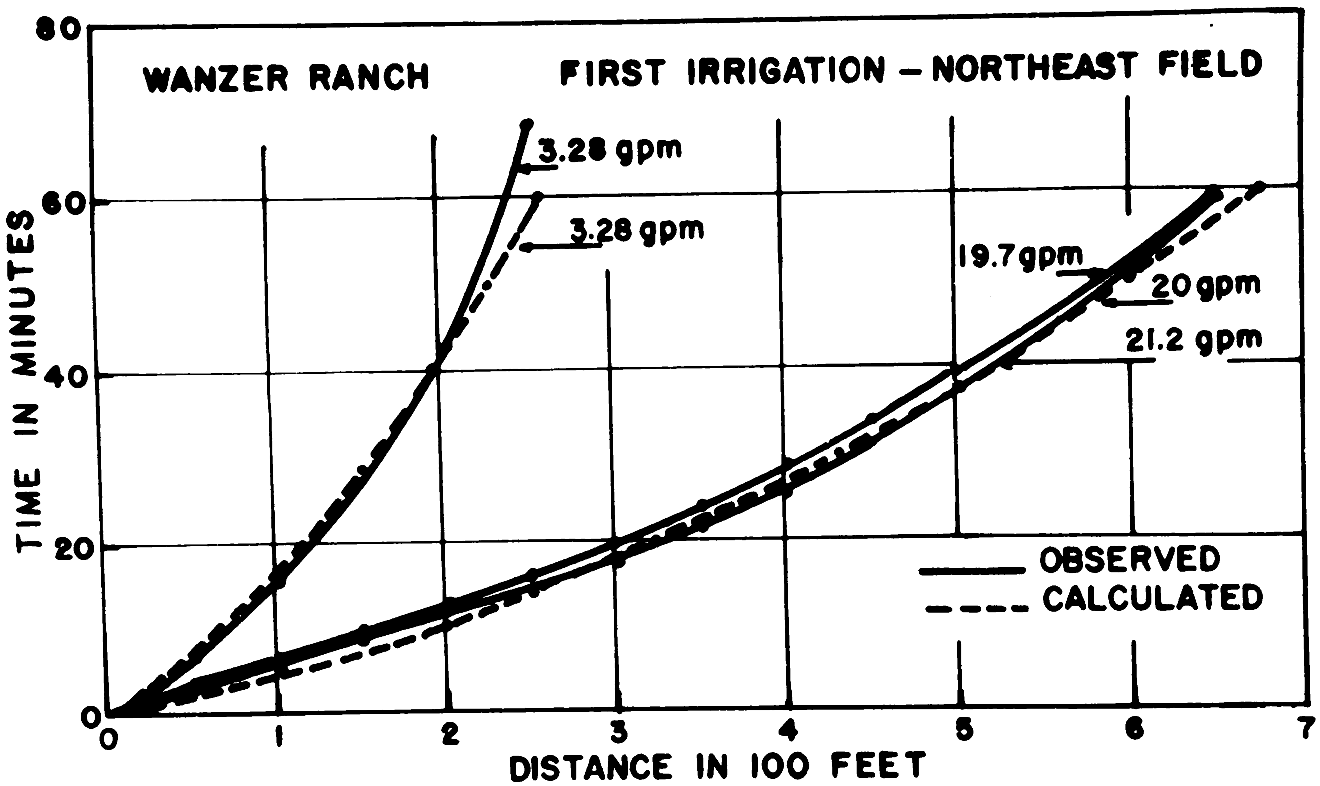

Figure 6. Comparisons of observed and calculated rates of advance of water in furrows, for indicated flow rates.

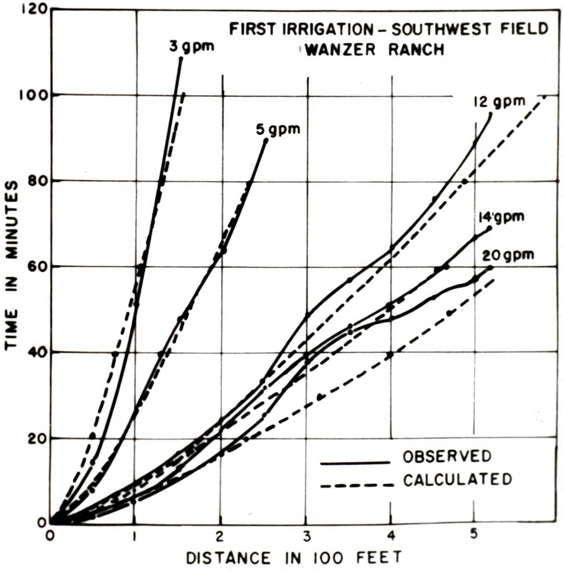

Figure 7. Comparisons of observed and calculated rates of advance of water in furrows, for indicated flow rates.

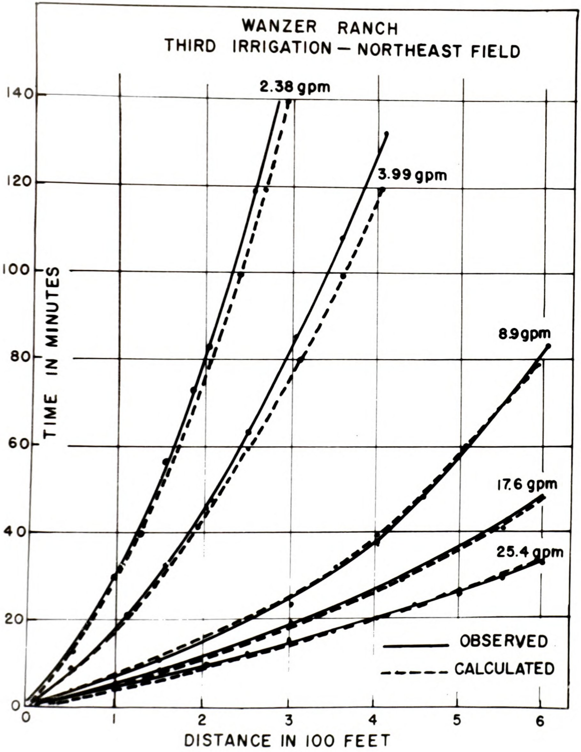

Figure 8. Comparisons of observed and calculated rates of advance of water in furrows, for indicated flow rates.

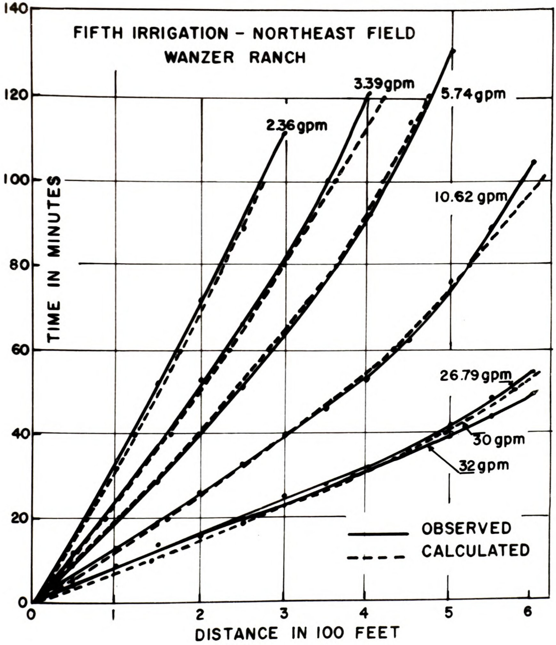

Figure 9. Comparisons of observed and calculated rates of advance of water in furrows, for indicated flow rates.

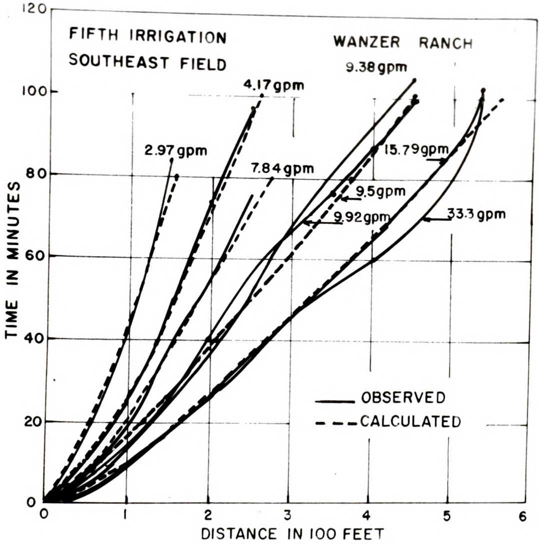

Figure 10. Comparisons of observed and calculated rates of advance of water in furrows, for indicated flow rates.

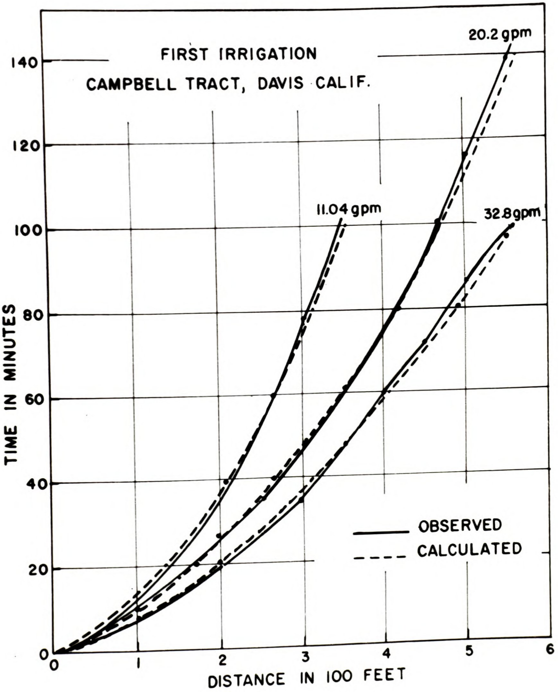

Figure 11. Comparisons of observed and calculated rates of advance of water in furrows, for indicated flow rates.

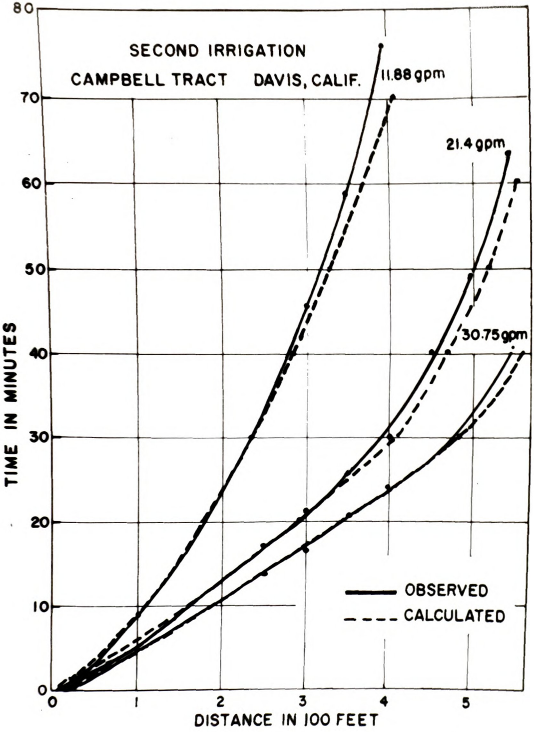

Figure 12. Comparisons of observed and calculated rates of advance of water in furrows, for indicated flow rates.

equal to the observed rate of advance, indicating a rather high degree of predicting accuracy of the equation. The discrepancies in figures 7 and 10 were due to a small rise of about 0.03 feet in field elevation from station 2 + 50 to station 3 + 00. This was not taken into account in the predicting equation, but it evidently affected the observed rate of advance considerably.

It was interesting to note in these two cases that the predicted distance down the furrow was nearly equal to the observed distance after the flow had become more stabilized on the downstream side of this ridge. This might indicate that the equation has a practical use in fields where grading or leveling has been done improperly, or where minor changes in grade may occur.

From the results of these seven studies one may conclude that an equation may be available for accurately predicting the rate of advance of water in furrows. Of perhaps even greater importance is the fact that the equation defines the research areas in which additional work is necessary, and also designates the relative importance of the variables affecting flow and the conditions under which the importance may change.

To test the equation under more severe conditions of data availability, information gathered at an irrigation training conference in 1950 at Davis was selected and analyzed. These data, over which the author had no control, consisted of rate of advance measurements and inflow-outflow measurements for three rates of flow. The furrow inflow-outflow measurements were used for plotting the total infiltration as a function of time. The infiltration equation for each flow rate was then determined.

The outflow measurements using the above method are usually made at a distance of 100 feet from the upper end of the furrow. The instantaneous infiltration rate is then assumed equal to the difference in flow rate between the upper end and the outflow section, divided by the average of the times that water has flowed past each of these two sections. The resulting infiltration rate then represents an average or an integrated rate over the 100-foot length, rather than an instantaneous rate at a particular point. For this reason, the determined infiltration rate was reduced by an arbitrary factor, similar to the F factor previously mentioned, for use in the rate-of-advance equation.

The results of these calculations are shown in Figure 13. A fairly good correlation between the observed and calculated rates of advance was again evident. Thus, the equation may be expected to perform satisfactorily under conditions of limited data and limited field contact.

A similar conclusion may be drawn from Figure 14, which also represents a condition of limited field data--in this case, gathered by another graduate student. These data were treated rather uniquely, because three flow rates were used and only one inflow-outflow measurement was made, for which the flow rate had not been indicated. An infiltration equation was determined from the inflow-outflow data and used in the calculations for rate of advance of the three different flows.

It was evident in Figure 14 that the calculated rates of advance for the 11.0 and 23.9 gpm flow rates differed considerably from the

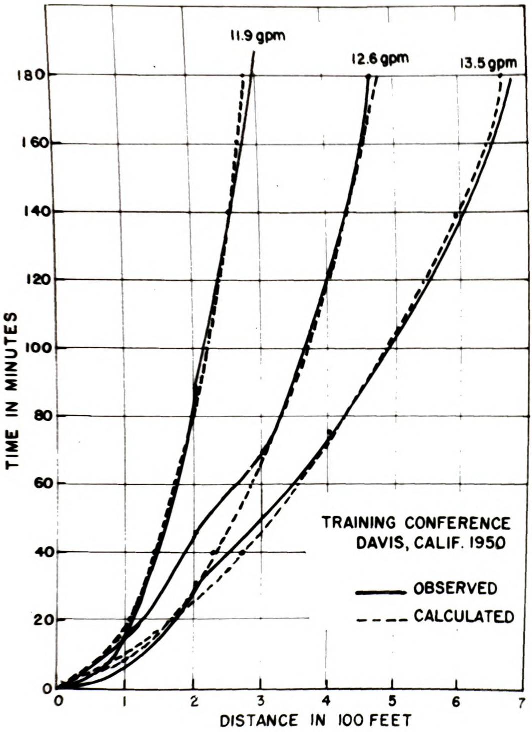

Figure 13. Comparisons of observed and calculated rates of advance of water in furrows, for indicated flow rates.

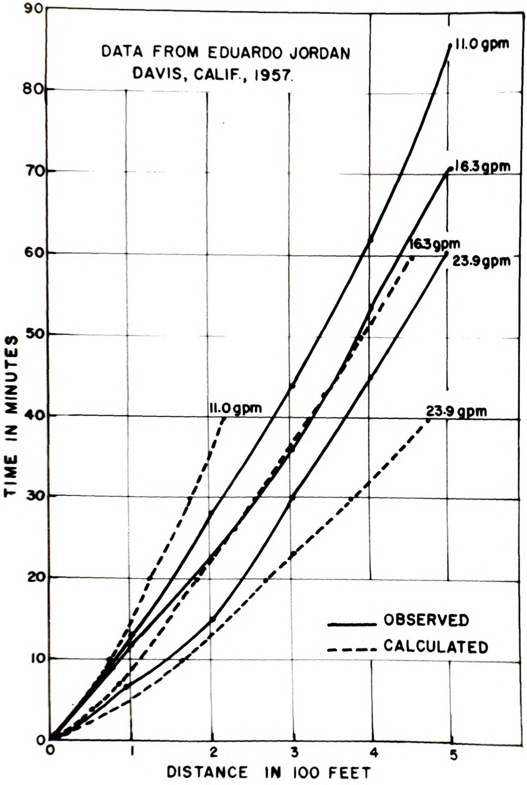

Figure 14. A comparison of observed and calculated rates of advance of water in furrows, for indicated flow rates, using limited infiltration data.

observed, whereas the calculated rate of advance at 16.3 gpm agreed fairly well with that for the observed rate of advance. Later, the major professor for the graduate student stated that the inflow-outflow measurements had been made in the furrows in which 16.3 gpm was flowing. This was a timely statement, for it verified the fact that the rate of advance equation will produce satisfactory results only if valid data are used in the equation.

The rate of advance equation thus appears to be capable of predicting an advance of water down a furrow with a fairly high degree of accuracy. Studies on two different soil types at different times during the irrigation season indicate that the equation is valid under a range of field conditions. Before full use can be made of this equation, parts of it will need further analysis.

Furrow infiltration

One of the hypotheses stated in the initial development of the rate of advance equation and of this study was that the infiltration of water from a furrow (a two dimensional system) as a function of time was related linearly to the depth of water in the furrow, the furrow shape and size and the furrow spacing. The model study was conducted to evaluate this hypothesis, and to determine the relationship between these factors.

Data from the field studies will be analyzed later, to evaluate the effectiveness of the furrow infiltrometer and its relation to existing furrow conditions.

Duplicate measurements of total infiltration of water from simulated furrows in the model were averaged and the total infiltration

was plotted as a function of elapsed time. The results are presented in figures 15 and 16, in which the factors of furrow shape, depth of water and furrow spacing are identified.

The initial parts of the curves represent that time in which the furrows were being filled with water to a predetermined depth, which was a relatively short time compared to the total length of time of the measurements. The remainder of the data represent the total infiltration function after the depth of water was stabilized. Only the latter condition was analyzed and interpreted because the initial transitory condition would not necessarily represent the variables under study.

Straight lines were drawn through the plotted points by eye. The equations for these straight lines were then determined. The fact that the resulting curves are straight lines on rectangular coordinates was of little consequence--this merely represented a final condition where the infiltration rate into the sand was equal to the hydraulic conductivity of the sand. As expressed by Hansen, this represented the condition of a head loss per unit length (ht/y) that became so small that the hydraulic conductivity was the only governing factor.

The equations that were determined were in the form $I = At^n + B$, where n equalled unity and B represented the volume of water required to fill the furrow and the volume of water added to the soil during the time that ht/y was significant. For this analyses, however, the values of B were discarded, because this represents an initial condition which had little bearing on the relationships to be evaluated.

Thus, the equations selected were in the form $I = At$, from which it was evident that the effects of the variables could be expressed by

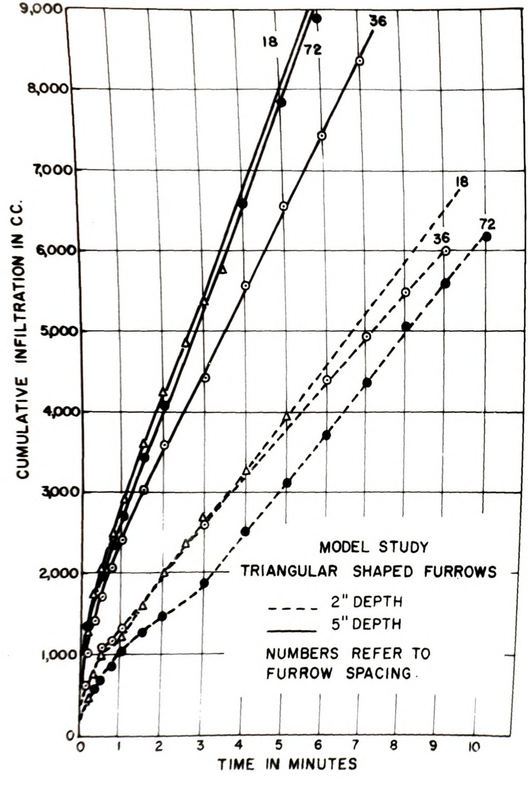

Figure 15. Total infiltration of water from model furrows, as a function of elapsed time.

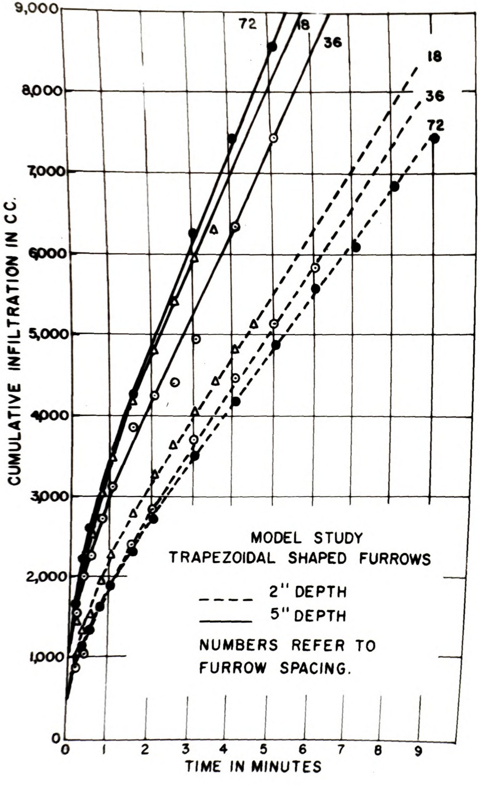

Figure 16. Total infiltration of water from model furrows, as a function of elapsed time.

the values of A--the slope of the line representing total infiltration. The effects of the three variables are shown in Table III.

Table III

Effects of Furrow Parameters on the Rate of Infiltration

Rate of Infiltration in cc/min

Shape of furrow	Furrow Spacing 18 in. water depth 2 in.	18 in. water depth 5 in.	36 in. water depth 2 in.	36 in. water depth 5 in.	72 in. water depth 2 in.	72 in. water depth 5 in.
Triangular*	11.78	22.90	10.18	17.60	11.22	24.05
Trapezoidal	13.10	18.95	12.69	17.60	11.40	19.85
Average	12.44	20.92	11.44	17.60	11.31	21.95

*Corrected for difference in the thickness of the tanks, where the thickness of the tank for triangular furrows was 0.928 times that for trapezoidal furrows.

A multiple regression analysis was applied to these data, which represented 12 separate conditions or combinations of the various furrow parameters. For this analysis, X_1 represented wetted parameter, X_2 represented top width, X_3 represented water depth, X_4 represented furrow spacing and Y represents the slope of the total infiltration curve. The resulting regression equation was as follows:

$$Y = 3.2019\ X_1 - 3.3739\ X_2 + 0.5065\ X_3 + 0.0075\ X_4 + 6.1148$$

The correlation coefficient for this equation was $R_{y.1234} = 0.9163$, which was significant at the one percent level. Table IV shows the correlations of infiltration rate with X_i.

Table IV

Correlations of Infiltration Rate with Furrow Parameters

	Wetted Perimeter X_1	Top Width X_2	Depth X_3	Spacing X_4
Correlations of Y with X's	0.7935	0.7179	0.9119	0.0367
Standard regressions of Y on X's	3.2500	-2.6338	0.1646	0.0367

Since the value of $R_{y.1234}$ was little larger than $R_{y.3}$, small advantage was gained by the multiple regression so far as estimating infiltration rate was concerned. One might as well use the simple linear regression of infiltration rate on depth of water. If the shape and spacing are ignored, the total regression would then be

$$Y = 2.83 X_3 + 6.03$$

for the data gathered in these studies.

The regression coefficients of the multiple regression showed that the wetted perimeter and top width were more effective in forecasting infiltration rate than depth of water. Thus even though the infiltration rate was highly correlated with depth, the contribution of an increasing depth to an increasing rate was small in comparison to the furrow size and shape. This was consistent with potential theory, which shows that an increase in head exerts only a small influence on the total potential.

From these results, one may conclude that: (1) infiltration rate was linearly related to depth of water and to the wetted perimeter and top width of the furrow, (2) furrow spacing had little effect on infiltration rate, even when the wetted soil masses tended to interfere,

(3) the relative potency of wetted perimeter and top width in estimating infiltration rate was much greater than that of water depth, and (4) the depth of water was highly correlated with infiltration rate, and a simple linear regression could be used with fair accuracy.

These conclusions were based upon rather restricted conditions, where the wetted perimeter and top width were directly related to water depth, and where no soil stratification existed. In a layered soil, or where the permeability of the sides of a furrow is different than that of the bottom of the furrow, these relations just developed may not exist and the above conclusions may not be valid.

To test these theories under field conditions, data taken from the studies at the Wanzer Ranch and at Davis were analyzed. Assuming that the rate-of-advance equations were valid, the factor F should represent some measure of the infiltration phenomenon in flowing furrows in comparison to that in the furrow infiltrometer. This factor thus provides some basis for these analyses. Ratios of depth of water in the flowing furrow to the depth of water in the furrow infiltrometer were calculated, and plotted with the factor F that was found to result in a fairly accurate rate of advance prediction. This relation is shown in Figure 17, from which it was evident that as the depth of water in the furrow increased in relation to the depth of water in the infiltrometer, the value of F also increased. In all cases, the infiltration rate in the flowing furrow was equal to or less than the infiltration ratio measured in the infiltrometer.

If F was a reliable measure of actual furrow infiltration rates, these data also indicated that the condition of the furrow (time of

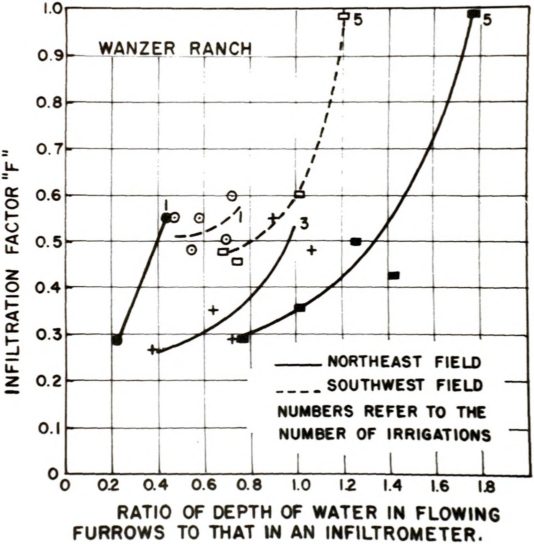

Figure 17. Relation between the ratio of depth of water in a furrow infiltrometer to the depth of water in a flowing furrow and an infiltration factor F, showing seasonal variability.

season) had a considerable bearing on the relation of the infiltration rates in the furrow to that in the infiltrometer. If this was correct, the effects of soil surface sealing by the velocity of flowing water varied throughout the season, such that the soil surface in a furrow had a tendency to seal more easily later in the season than earlier.

The rather meager data from the studies at Davis indicated the opposite--that the factor F increased with a decrease in the ratio of depth in the furrow to depth in the infiltrometer.

Although the results of all of these comparisons were rather inconclusive, it appeared probable that the infiltration rate of a furrow was related to the depth of water in a furrow infiltrometer; but that this relationship was affected greatly by the condition of the soil in the furrow and by soil texture and structure. The non-linear relationship of F and d_f/d_i indicated that the infiltration from the sides of the furrows might be higher than that of the bottoms. This effect, and the effects of tractor wheel compaction and surface sealing thus prevented direct application of the results of the model study to the conditions of these field studies.

In any event, much additional work will be necessary before the furrow infiltrometer can be used successfully to accurately predict the infiltration from a flowing furrow. Qualitatively, the infiltrometer may prove a useful tool, but for a rigorous qualitative analysis, many factors need consideration.

Furrow shape and hydraulic roughness

Because infiltration varies with wetted perimeter, top width, depth of water, and the relative permeabilities and areas of the bottom and

sides of the furrow; and because the storage of water in a furrow has an influence on the rate of advance; it was desirable to develop some relationship between stream size, furrow shape and water depth.

Bondurant attempted such a correlation in the Republican Valley in Nebraska, and found the following relationship:

$$Y = 5.35\ X^{0.285}$$

where Y is the stream width in inches and X is the stream size in gallons per minute divided by the slope in percent. One can hardly expect, however, that these data would apply to other conditions of soil texture and structure and hydraulic roughness.

When data for two irrigations at Davis were expressed in similar fashion, no such relationship existed. Using stream size and slope data from Davis in Bondurant's equation resulted in calculated stream widths that were nearly 70 percent greater than those measured in the field.

Certainly some relation between stream size or stream velocity and furrow size, shape and width existed; but this relation was likely affected by aggregate size and stability and hydraulic roughness of the furrow. Thus Bondurant's equation must be treated as a special case which may not be applicable to other soil or cropping conditions.

Studies of changes in furrow shape were conducted at Davis on Yolo silty clay loam soil, in the same area in which the rate of advance studies were made. Furrow cross sections were measured before any irrigation after the furrows were made; and after each of two successive irrigations. Typical results of these measurements are shown in Figure 18.

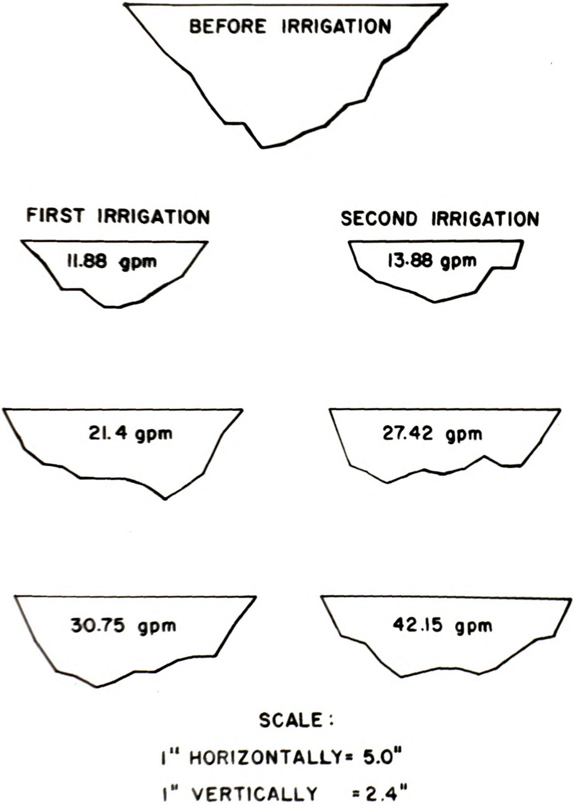

Figure 18. Typical furrow cross sections, showing the effects of stream size and number of irrigation on furrow shape.

Initially, the furrows were V-shaped furrows, with side slopes of about 2:1. Flows of about 12 gallons per minute did not alter this shape appreciably, but a slight flattening of the sides was noticeable. Flow rates of about 25 gallons per minute created a trapezoidal shaped furrow with a distinctly flatter bottom, but with about the same side slopes. Higher flows did not change this trapezoidal section appreciably.

It appeared that once the change in furrow shape has taken place, additional irrigations did not influence the resulting shape to any extent, as shown by the lack of difference between the first and second irrigations. Similar observations were made on the Wanzer Ranch on the sandy loam soil.

Thus, the shape of an irrigated furrow could be presumed to be a function of soil type, soil structure, aggregate stability, furrow flow or furrow velocity, the initial furrow shape and the number of irrigations. After the initial irrigation without any intervening cultivation, it is probable that the only factors that would influence furrow shape are furrow flow to a small extent and furrow roughness, including that roughness caused by vegetative trash in the furrow. Furrow flows that would be erosive would certainly alter the shape, but this condition should be avoided at all times.

Based on these data, one might conclude that the prediction of a furrow shape based on soil conditions and furrow flow is possible. These studies showed that the prediction may be more difficult for the first irrigation than for subsequent irrigations, and showed also that furrows tended to form trapezoidal or parabolic shapes with

increasing flow, in silty clay loam soil. No definite relationship between furrow size and shape and flow rate was apparent in these studies.

These same measurements were used also as a means of evaluating hydraulic roughness in furrows. As small, earth-lined channels, furrows represent a condition whereby the characteristics of the channel change with time, soil conditions, cropping conditions, and flow rate. Because of the influence of these factors, the rate of advance of water down the furrow due to surface storage in the furrow can be extremely variable and subject to a multitude of conditions.

The purpose of this part of the study was to determine the magnitude of hydraulic roughness and the effect of flow rate on roughness. Presumably, the relation between roughness and velocity can be expressed in a manner similar to the classical expressions for friction in pipes as a function of Reynolds Number. That is, the friction loss is a function also of e/d, which represents the magnitude of small projections in relation to the diameter of the pipe.

In furrows, the roughnesses (mainly clods) are sufficiently large in relation to furrow depth to warrant such an approach. However, at high flow rates, the velocity of flow tends to smooth the furrow and dissipate the cloddiness, which reduces the roughness of the furrow. On the other hand, high flow rates alter the shape of furrow to a generally less efficient hydraulic section, as shown previously. Also, the leaves of some crops, such as potatoes and sugar beets, may hang into the furrow to create some retardance on the surface of the water.

Thus, the flow regimes in irrigation furrows are extremely varied and rather difficult to evaluate. The problem of flow characteristics

in small channels under conditions of moving boundaries itself is a relatively new concept, especially when the change in the boundary is a function of the flow. Some data are presented herein, however, as a means of introducing the problem and adding to the knowledge of this phenomenon.

At Davis, the same furrows which were measured for rate of advance were used for determinations of hydraulic roughness. The technique used involved the measurement of flow into each furrow, the measurement of the cross-sectional area of each furrow, and the determination of the slope of the water surface. Water was directed into twelve furrows in three flow rates for a sufficient length of time to insure uniform flow in a 50 ft. length of furrow, which was marked with stakes about 100 feet from the head end of the furrows. As soon as the flow had stabilized in this section, small metal markers were inserted in the side of each furrow to mark the water level in the furrow at each end of the section. The flow was then turned off and the measurements of the furrow cross-section and water surface slope were made several days later.

This procedure was followed because measurements of furrow cross sections when water was flowing were extremely inaccurate. The rather mushy, soft bottom almost prohibited measurements of depth and the furrows were easily disturbed. Although the method used was subject to some inaccuracy, it was probably more accurate than others.

The cross-sectional shape of each furrow at both ends of the test section was plotted and the wetted perimeter and area determined. These were then averaged to arrive at a representative area and wetted

perimeter for each furrow. By substituting the known parameters of flow rate, area, wetted perimeter and slope into Manning's equation, the roughness factor n was then calculated. Summaries of this analysis are shown in Appendix III.

The results of this analysis are shown in Figure 19, which expresses the calculated n as a function of furrow velocity for two irrigations. No disturbance of the soil took place between irrigations. It seems quite evident that the hypothesis expressed earlier was correct; that is, the hydraulic roughness was a function of flow rate, or rather, the flow velocity. As the velocity of flow increased, the roughness coefficient decreased, probably due to a smoothing of the clods in the furrow. Because the same relationship existed for the second irrigation as for the first, it appeared that the aggregates in the furrow either no longer existed or had already stabilized, and that the crop of milo had no effect on the roughness.

The slope of the line in Figure 19 was almost minus one. For these conditions n may be expressed as $n = CV^{-1}$. If this expression is substituted into Manning's equation, the following equation results:

$$1 = \frac{1.486}{C} R^{2/3} S^{1/2}$$

Considering that S was constant, and C was constant, then the hydraulic radius was a constant and did not depend on the velocity or the flow rate. One may conclude from this that for these soil conditions, the hydraulic radius was independent of the velocity or of the flow rate, and that the soil conditions were such that a constant relation between area and wetted perimeter existed for all flow rates.

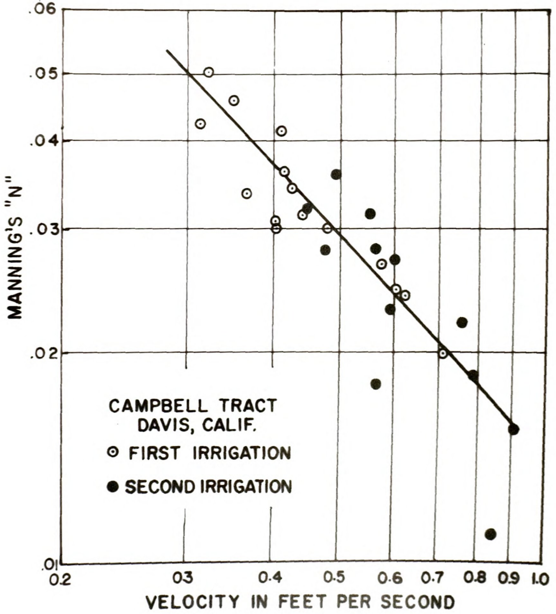

Figure 19. Relation between velocity of water in furrows and Manning's roughness coefficient, for Yolo silty clay loam.

Thus, if the general furrow shape as a function of flow rate can be determined; it becomes possible to estimate the depth of water in the furrow for any given flow, and to calculate the volume of water in storage in the furrow. Additional studies are certainly needed to verify this conclusion, however.

Another interesting facet of this study was the fact that initial roughness appeared to have little effect on the value of the calculated roughness coefficient. Due to compaction by the tractor when the furrows were made, the furrows were alternately smooth and extremely rough. However, the effects of this initial cloddiness or roughness were not evident in the calculated value of n except for minor trends at low flow rates and at high flow rates. On the average, the values of n for the rough furrows were 12 percent higher than those for the smooth furrows, for both irrigations. This was within the experimental error, however.

Although the studies at the Wanzer Ranch were not intended for the evaluation of hydraulic roughness, the data collected have proved of some use in this respect. Measurements of flow rates and depth of water in the furrows were made, and used primarily in the rate of advance equation. Inasmuch as the calculated rate of advance very nearly approximated the observed advance, it was presumed that the quantity of water in surface storage had been estimated fairly accurately, and that the volume of water per foot of furrow was equal to the area of the channel.

Most of the furrows in this sandy loam soil approached a trapezoidal or parabolic shape, even at low flows. Thus, in order to

calculate the values of the roughness coefficient, the hydraulic radius was assumed equal to the depth of flow. Errors in the order of 20 percent may result from this assumption, so the results should be treated with caution and interpreted only as possible trends.

Substituting the depth for hydraulic radius, the slope of the soil surface for the water surface, and the estimated surface storage per foot of furrow for area into Manning's equation; n was calculated. The results are shown in figures 20 and 21, which express the calculated n as a function of velocity and flow rate, respectively.

These results were approximately the same as those for the studies at Davis, in that increasing the velocity decreased the hydraulic roughness of the furrow. In Figure 20, the slope of the line was approximately -0.75, and n was then expressed as $n = CV^{-0.75}$. When this expression was substituted into Manning's equation, the hydraulic radius became a function of the velocity to the 3/8 power, and velocity a function of the square of the slope.

This relationship between n and V would presumably permit a trial and error solution for water depth if the shape of the furrow were known. In fact, the resulting equation $Q = kAR^{8/3}\ S^2$ could be used quite simply for this determination.

Figure 21 expresses the relation between n and the flow rate, Q. Here, $n = gQ^{-1/3}$, which if substituted into Manning's equation resulted in the equation $Q = mA^{3/2}\ RS^{3/4}$. If a known slope is assumed, these two equations for flow rate may then be solved simultaneously for the two unknowns R and A, for any flow rate.

These results and conclusions would certainly not apply to other soils, but indicate that it may be possible to apply this method of

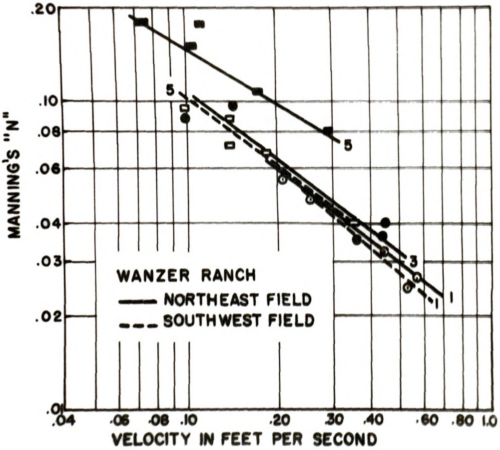

Figure 20. Relation between velocity of water in furrows and Manning's roughness coefficient, for Cajon fine sandy loam.

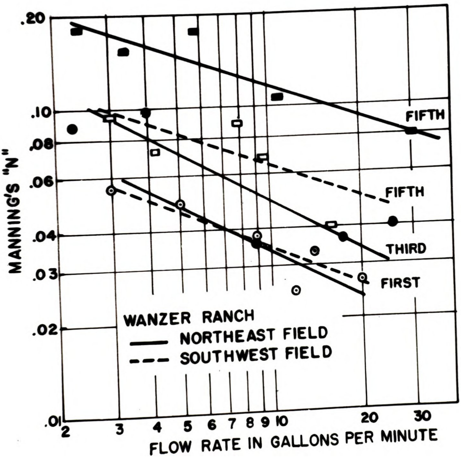

Figure 21. Relation between flow rate in furrows and Manning's roughness coefficient, for Cajon fine sandy loam.

analysis to other soils if these relationships between V, Q, and n are known. The fact that no relationship existed between Q and n for the Yolo silty clay loam invalidated this last statement, but the results from the studies at the Wanzer Ranch provided enough justification for additional studies of these effects.

Figure 21 also points out that the relation between Q and n changed during the irrigation season, and shows that the value of n tended to increase as the season progressed. This conclusion agrees with the unpublished work of Mech at Prosser, Washington, in which he showed increases in the value of n during an irrigation season for sugar beets. He reasoned that this was due to the increased vegetative growth extending into the channel and to the secession of cultivating and ditching. Crops such as alfalfa and wheat showed a fairly uniform n throughout the season.

Although the vegetative growth of cotton did not extend much into the furrow, the shedding blossoms and the weeds which were hoed fell into the furrow, creating the same effect.

From these two studies of furrow roughness, it was apparent that the introduction of a non-erosive furrow stream resulted in some stable shape and size of furrow which remained relatively unchanged during the irrigation season. Predictions of furrow area and hydraulic radius for any flow rate may be possible, but additional studies on other soil conditions will be necessary. The effect of vegetation extending into the furrow and vegetative trash in the furrow changed the hydraulic roughness during the irrigation season, but had little effect on the roughness of the furrow itself.

Determinations of surface storage in the furrow are much more important than infiltration volumes on soils of low permeability. In this situation, some error in estimating the infiltration function will be less critical than errors in estimating hydraulic roughness and furrow area. On the other hand, on soils of good permeability, some errors in estimating e, c or n will have much less effect on the result than errors in flow rate or infiltration rates. Accurate estimates of surface storage may be more critical at higher rates of flow, if the volume of water in the furrow becomes greater in proportion to infiltration volume. This will depend considerably on the existing soil conditions in the furrow.

Thus, a need exists for evaluating these two components of the rate of advance equation (infiltration and surface storage) as a function of soil physical properties, to determine the allowable errors of measurement and the relative significance of the two factors.

SUMMARY AND CONCLUSIONS

A general mathematical expression, based on the conservation of mass, was derived to define the flow of water in irrigated furrows. Although the principle of mass conservation cannot be argued, the individual components of the expression can. This study was initiated to present a mathematical expression of flow in furrows, and to determine the factors that affect the application of the equation; specifically, to evaluate the phenomenon of infiltration from furrows and to evaluate the hydraulic factors that affect the storage of water in the furrow.

The conclusions of this study were based on field measurements at two soil locations during the irrigation season of 1958, and on measurements of infiltration in a furrow model tank. These conclusions are summarized as follows:

1. An equation for accurately predicting the advance of surface water in irrigated furrows was derived. Field studies conducted in two different soil areas with two different crops during an irrigation season proved the reliability and accuracy of the equation under variable conditions of soil and flow rates.

2. Comparisons of observed and calculated rate of advance showed that the equation may be applied to fields of non-uniform slopes or slightly irregular slopes. The equation also performed well with rather limited data, provided that valid measurements were used.

3. Studies of furrow infiltration in a sand model resulted in infiltration equations in the form $I = At^n$ where I is the total infiltration after time t. The effects of water depth, furrow shape

and furrow spacing on this equation were evaluated by regression analysis, which verified the hypothesis that these factors were related linearly to infiltration rate.

4. This analysis showed that water depth only slightly affected the infiltration rate, but was highly correlated with infiltration rate. Wetted perimeter and top width affected infiltration rates to a much greater degree than the water depth.

5. Furrow spacing had little effect on the infiltration rate from a single furrow, and was not correlated with infiltration rate.

6. The resulting multiple regression equation was highly significant in predicting infiltration rates; however, a simple linear regression of infiltration rate on water depth proved just as accurate. One might thus conclude that infiltration rates determined with a furrow infiltrometer might be used satisfactorily for estimating infiltration rates for furrows in which water is flowing at the same or any other depth.

7. Field measurements with the Hamilton furrow infiltrometer indicated that this instrument might serve well as a tool for qualitative analyses, but that considerably more work is necessary before it can be used in a strictly quantitative manner.

8. A furrow factor F, applied to the infiltration equations determined with the infiltrometer, appeared to satisfactorily describe any differences in infiltration between infiltrometer and a flowing furrow. As the depth of flowing water increased, the value of F also increased; but this increase and the magnitude of F were affected by the time of the season or the condition of the furrow.

9. The movements, distribution and deposition of sediments in a furrow appeared to affect the relation between the infiltrometer infiltration and that from a flowing furrow. These effects, combined with differences in permeability between the bottom and sides of furrows, prevented a direct application of data from the tank models and also created problems in the use of the furrow infiltrometer.

10. Studies of furrow shapes at Davis showed that changes from a V-shape to a trapezoidal or parabolic shape were likely to occur during the first irrigation after furrows are formed. Subsequent irrigations did not alter the shape appreciably.

11. The rate of flow of water into a furrow affected the shape considerably. Up to a certain point, increasing flow tended to result in a furrow with a flatter bottom. These studies also indicated that prediction of furrow shape may be possible, if factors such as soil texture, soil structure, aggregate stability, furrow flow and initial shape can be evaluated. Bondurant's equation for furrow shape did not appear applicable to the soils evaluated in this study.

12. Calculations of hydraulic roughness of furrows showed that roughness was a function of the flow velocity, such that higher velocities resulted in lower values of Manning's "n". This was probably due to a smoothing of the clods or soil obstructions in the furrow. The relation between roughness and flow velocity appeared to remain constant during the irrigation season, and was affected to only a slight degree by the initial roughness of the furrow. The magnitude of "n" and its relation to flow velocity appeared to be about the same for the two soils studied.

13. The hydraulic roughness of a furrow was inversely related to velocity, in the studies at Davis, and the hydraulic radius was essentially constant and independent of the flow rate. Studies at the Wanzer Ranch showed, however, that on a sandy loam soil the relation between Manning's "n" and flow rate, together with the relation between "n" and flow velocity resulted in two simultaneous equations involving Q, A, R and slope, thus, if the slope and flow rate are known, the area and hydraulic radius of the furrow may be calculated. This conclusion needs further verification for other soil conditions, however.

14. For the same flow rate, the value of hydraulic roughness increased during the irrigation season. This was probably due to the effects of overhanging vegetation and trash in the furrows. The over-all values of n varied from about 0.01 to 0.18 depending on flow velocity.

The most significant conclusion of this study was the fact that a simple equation, based on conservation of mass, may be used to accurately predict the rate of advance of a water front in an irrigated furrow. This equation may then provide a means whereby an irrigation system can be better designed or evaluated, and should result in a much better understanding of the contributions of the infiltration and flow phenomena.

A rather striking but inconclusive part of the study was the fact that for the two soils studied, the shape of the furrow channel tended to become stable for a certain rate of flow. This leads to the possibility that hydraulic radius may either be constant or may be

estimated if the flow rate and slope are known. If this conclusion can be verified, solutions of the rate of advance equation can be made on the basis of infiltration alone, or for general textural soil groupings. This would certainly enhance irrigation system design and would result in an ultimate use of recognized design techniques based on sound engineering principles.

RECOMMENDATIONS FOR FUTURE WORK

Future research in the field of the hydraulics of irrigation systems should be concerned with two aspects: the flow of water from irrigation furrows into the surrounding soil and the hydraulics of flow in small, rough channels.

The former involves the determination of the influence of furrow shape, size, spacing and water depth on the infiltration of water into stratified, heterogeneous soils. Particular emphasis should be placed on infiltration theory, but considerable field work should be done to evaluate the effects of flow velocity and sediment deposition or removal on the infiltration phenomena.

Some improvements in the techniques of measuring infiltration are quite desirable. Standardization of instruments and procedures are vitally needed for infiltration studies. Some method of measuring the flow rate in an irrigated furrow would also be extremely useful, for such a tool would provide a means of collecting not only infiltration data but also data concerning the hydraulics of the furrow channel.

The ultimate goal of any such infiltration studies should be toward a more complete understanding of the geometric factors affecting infiltration into soils. This work, combined with research on other modifying factors, would certainly enhance the development of more efficient furrow irrigation systems.

The hydraulics of flow in small rough channels can be divided into two phases: a study of the characteristics of flow in small channels with fixed boundaries and artificial roughness, and studies of flow

regimes in small channels under conditions of moving boundaries. The latter deserves particular immediate attention, because this affects also the infiltration characteristics of the furrow.

The relationships between flow rate, flow velocity, furrow shape, furrow size and hydraulic roughness certainly need to be established for many soil conditions. The results of this study indicate the possibility that in a certain soil, a definite hydraulic radius and area may exist for a given flow velocity or flow rate. If this is true, studies on this aspect are needed immediately to simplify the design procedures that would then follow.

These studies could well be conducted in a variable slope flume in which different soils can be placed, using limited field studies to verify any theories developed in the laboratory. The problem could perhaps be effectively approached by the use of dimensional analysis.

Studies of channels using artificial roughness, including that caused by vegetation, would be an invaluable aid in determining the effects of seasonal plant growth and roughness geometry on furrow flow characteristics. These studies should be undertaken to supplement any progress made in evaluating the effects of furrow flow on furrow shape and aggregate size.

The most important work in the future involves the integration of all these physical factors into a mathematical tool whereby the distribution efficiency of furrow systems can be made optimum. Engineers should recognize that this tool will provide the key for optimum design of irrigation systems and efficient, economic water use and distribution; and will provide the only basis upon which

automation may be applied to surface irrigation systems. Future studies should be directed toward this definite goal, and should be developed on a broad fundamental basis if irrigated agriculture is to survive the technical evolution in agriculture and the increasing demand for water resources.

APPENDIX

I. Sample Calculations of Rate of Advance in Furrows

A. First Irrigation on Wanzer Farm, Northeast Field

Given: $Q = 3.28$ gpm

$I = 0.0342\ t^{0.56}$

Depth of flow = 0.08 ft.

Furrow area = 0.0353 sq. ft.

$\Delta t = 10$ min.

$$\Delta X_i = \frac{Q\ (\Delta t) - \frac{Fa(\Delta t)^n}{2}\left[g_i \Delta X_1 + g_{i-1}\Delta X_2 + \ldots + g_2 \Delta X_{i-1}\right]}{Fa(\Delta t)^n + cd_o^2 + e}$$

Assume F = 0.22. Then

$$\Delta X_1 = \frac{3.28/448.6 \cdot 10 \cdot 60}{0.22 \cdot 0.124 + 0.0353 + 0.001} = \frac{4.38}{0.0636} = 69 \text{ ft.}$$

$$\Delta X_2 = \frac{4.38 - 0.01365\ (1.4743 \cdot 69)}{0.0636} = 47.2 \text{ ft.}$$

$$\Delta X_3 = \frac{4.38 - 0.01365\ (0.8501 \cdot 69 + 1.4743 \cdot 47.2)}{0.0636} = 41.3 \text{ ft.}$$

$$\Delta X_4 = \frac{4.38 - 0.01365\ (0.6992 \cdot 69 + 0.8501 \cdot 47.2 + 1.4743 \cdot 41.3)}{0.0636} = 36.8 \text{ ft.}$$

$$\Delta X_5 = \frac{4.38 - 0.01365\ (0.6127 \cdot 69 + 0.6992 \cdot 47.2 + 0.8501 \cdot 41.3 + 1.4743 \cdot 36.8)}{0.0636} = 33.5 \text{ ft.}$$

$$\Delta X_6 = \frac{4.38 - 0.01365\ (0.5540 \cdot 69 + 0.6127 \cdot 47.2 + 0.6992 \cdot 41.3 + 0.8501 \cdot 36.8 + 1.4743 \cdot 33.5)}{0.0636} = 31.0 \text{ ft.}$$

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

B. First Irrigation on Campbell Tract, Davis, California

Given = $Q = 32.8$ gpm

$I = 0.0341\ t^{0.625}$

Furrow area = 0.208 sq. ft.

$\Delta t = 20$ min.

$$\Delta X_i = \frac{Q(\Delta t) - \frac{Fa(\Delta t)^n}{2}\left[g_i \Delta X_1 + g_{i-1}\Delta X_2 + \ldots + g_2 \Delta X_{i-1}\right]}{Fa(\Delta t)^n + cd_o^2 + e}$$

Assume F = 1.08. Then

$$\Delta X_1 = \frac{32.8/448.6 \cdot 20 \cdot 60}{1.08 \cdot 0.222 + 0.208 + 0.002} = \frac{87.8}{0.4500} = 195 \text{ ft.}$$

$$\Delta X_2 = \frac{87.8 - 0.12\ (1.5423 \cdot 195)}{0.4500}$$

$$\Delta X_3 = \frac{87.8 - 0.12\ (0.9874 \cdot 195 + 1.5423 \cdot 115)}{0.4500} = 96 \text{ ft.}$$

$$\Delta X_4 = \frac{87.8 - 0.12\ (0.8369 \cdot 195 + 0.9874 \cdot 115 + 1.5423 \cdot 96)}{0.4500} = 82 \text{ ft.}$$

$$\Delta X_5 = \frac{87.8 - 0.12\ (0.7483 \cdot 195 + 0.8369 \cdot 115 + 0.9874 \cdot 96 + 1.5423 \cdot 82)}{0.4500} = 72 \text{ ft.}$$

II. Summary of Rate of Advance Calculations

A. Wanzer Ranch

No. of Irrigation	Field	Q, gpm	F	Surface storage, ft^2	Depth in infil., ft.	Depth in furrow, ft.
1	NE	3.28	0.22	0.0353	0.28	0.08
		19.7 21.2	.55	.0652	0.28	.11
1	SW	3	0.55	0.033	0.278	0.13
		5	.48	.044	.278	.15
		12	.55	.051	.278	.16
		14	.50	.071	.278	.19
		20	.595	.079	.278	.20
3	NE	2.28	0.26	0.050	0.135	0.05
		3.99	.29	.063	.135	.096
		8.9	.35	.055	.135	.086
		17.6	.55	.089	.135	.12
		25.4	.48	.126	.135	.144
5	NE	2.36	0.29	0.073	0.12	0.09
		3.39	.36	.073	.12	.12
		5.74	.425	.114	.12	.17
		10.62	.50	.140	.12	.15
		30.0	1.00	.232	.12	.21
5	SW	2.97	0.48	0.067	0.15	0.10
		4.17	.46	.067	.15	.11
		7.84	.60	.126	.15	.15
		9.5	.60	.118	.15	.15
		15.79	1.00	.102	.15	.18

B. Campbell Tract, Davis

No. of Irrigation	Q, gpm	F	Surface storage, ft^2	Depth in infil., ft.	Depth in furrow, ft.
1	11.04	0.63	0.076	0.17	--
	20.2	.72	.175	.17	--
	32.8	1.08	.208	.17	--
2	11.88	0.70	0.061	0.15	0.11
	24.4	.40	.130	.15	.14
	30.75	.50	.157	.15	.12

III. Summary of Hydraulic Roughness Calculations

A. Campbell Tract, Davis, Second Irrigation

Slope = 0.2 percent

Furrow No.	Q, gpm	Area, ft^2	Wetted perimeter, ft.	Velocity, ft./sec.	n
1	11.88	0.066	0.833	0.40	0.030
2	11.88	.084	.938	.31	.042
3	11.88	.066	.818	.40	.031
4	11.88	.072	.901	.37	.034
5	21.4	.112	1.084	.43	.034
6	21.4	.107	1.021	.45	.033
7	21.4	.136	1.147	.35	.046
8	21.4	.128	1.169	.38	.041
9	30.75	.097	.991	.71	.020
10	30.75	.112	1.050	.61	.024
11	30.75	.118	1.047	.58	.027
12	30.75	.167	1.282	.41	.042

B. Campbell Tract, Davis, Third Irrigation

Furrow No.	Q, gpm	Area, ft^2	Wetted perimeter, ft.	Slope, percent	Velocity, ft./sec.	n
1	13.88	0.037	0.717	0.206	0.84	0.011
2	13.88	.069	.904	.288	.45	.032
3	13.88	.065	.868	.262	.48	.028
4	13.88	.054	.819	.176	.57	.018
5	27.42	.102	1.108	.278	.60	.027
6	27.42	.124	1.145	.270	.49	.036
7	27.42	.108	1.118	.252	.56	.028
8	27.42	.103	1.106	.206	.59	.023
9	42.15	.104	1.098	.224	.90	.016
10	42.15	.125	1.135	.238	.75	.022
11	42.15	.120	1.186	.206	.79	.018
12	42.15	.170	1.553	.264	.55	.032

C. Wanzer Ranch

Irrigation	Field	Q, gpm	Area, sq.ft.	Wetted perimeter, ft.	Velocity ft./sec.	n
1	NE	3.28	0.035	0.08	0.21	0.059
		20.0	.065	.12	.68	.023
1	SW	3	0.033	0.13	0.20	0.055
		5	.044	.15	.25	.049
		12	.051	.16	.52	.025
		14	.071	.19	.44	.033
		20	.079	.20	.56	.026
3	NE	2.28	0.051	0.05	0.10	0.089
		3.99	.063	.096	.14	.098
		8.9	.055	.086	.36	.036
		17.6	.089	.12	.44	.036
		25.4	.126	.144	.45	.040
5	NE	2.36	0.073	0.09	0.07	0.182
		3.39	.073	.12	.10	.155
		5.74	.114	.17	.11	.180
		10.62	.140	.15	.17	.110
		30.0	.233	.21	.29	.081
5	SW	2.97	0.067	0.10	0.10	0.095
		4.17	.067	.11	.14	.072
		7.84	.126	.15	.14	.089
		9.5	.118	.15	.18	.069
		15.79	.102	.18	.34	.040

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