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INFILTRATION CHARACTERISTICS OF FURROW IRRIGATION IN A HEAVY-TEXTURED SOIL

(with a summary in dutch)

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD
VAN DOCTOR IN DE LANDBOUWWETENSCHAPPEN
OP GEZAG VAN DE RECTOR MAGNIFICUS, MR. J. M. POLAK,
HOOGLERAAR IN DE RECHTS- EN STAATSWETENSCHAPPEN
VAN DE WESTERSE GEBIEDEN,
TE VERDEDIGEN TEGEN DE BEDENKINGEN
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DOOR

C. J. GRASSI

H. VEENMAN & ZONEN N.V. - WAGENINGEN 1972

Dit proefschrift met stellingen van

CARLOS JULIAN GRASSI

landbouwkundig ingenieur, geboren op 7 augustus 1923 te Bahia Blanca, Argentinië, is goedgekeurd door de promotor, Ir. J. Nugteren, hoogleraar in de Irrigatie.

De Rector Magnificus van de Landbouwhogeschool,
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STELLINGEN

I

De coëfficiënt p van de voortschrijdingsfunctie bij vorenbevloeiing neemt significant toe met een toename in debiet.

(Dit proefschrift)

II

Het verdient aanbeveling, gelet op de variaties die zich voordoen in de coëfficiënten p en de exponenten r van de voortschrijdingsfuncties van herhaalde proeven, om ten behoeve van het ontwerpen van irrigatiesystemen de voortschrijding van het water op het veld statistisch verantwoord te bepalen.

(Dit proefschrift)

III

Er is geen garantie dat de parameters van de infiltratievergelijking voor het eerste stadium onveranderlijk zijn wanneer opeenvolgende irrigaties worden uitgevoerd in voren met gelijkblijvende oppervlakte ruwheden.

(Dit proefschrift)

IV

De lengte van de vore beïnvloedt de parameters van de Kostiakov infiltratievergelijking voor het tweede stadium.

(Dit proefschrift)

V

Herhaalde giften van geringe hoeveelheden water kan de bevochtigingstijd van de wortelzone verminderen in gronden, met een geringe infiltratiecapaciteit, die korte tijd na de bevochtiging neiging tot scheuren vertonen.

VI

De balansvergelijkingen zoals voorgesteld door LEWIS en MILNE (1938) en PHILIP en FARREL (1964) zijn niet betrouwbaar voor het voorspellen van de voortschrijding van water bij oppervlakte irrigatie omdat zij slechts gebaseerd zijn op een schatting van de dikte van de waterlaag gedurende de voortschrijding.

VII

De verdampingsformule van Blaney en Criddle is niet gevoelig genoeg om de maandelijkse variatie in verdamping te beschrijven voor de klimatologische omstandigheden van de Zuid-Amerikaanse tropische gebieden.

VIII

Menselijke factoren, meer dan de natuurlijke omstandigheden, bepalen het welslagen van irrigatie-projecten in Latijns-Amerikaanse landen.

IX

Technische hulpprogramma's van ontwikkelende landen zullen effectiever zijn indien meer aandacht geschonken wordt aan het oprichten van ondersteunende organisaties.

X

Technische deskundigen in ontwikkelende landen zouden niet mogen worden toegestaan andere foto's te nemen dan voor hun werk nodig is.

Proefschrift van C. J. Grassi
Wageningen, 28 juni 1972.

CONTENTS

1. INTRODUCTION

The purpose of this thesis is to determine the infiltration pattern of soil water and to analyse the infiltration function of furrow irrigation in a tropical soil, with the conditions of heavy texture and shallow depth. This implies that a comprehensive knowledge of the mentioned physical process can provide a better basis for design criteria of surface irrigation, as well as for the irrigation practices at the farm level.

The main purpose of irrigation is to restore water to the root zone, making the water available to the crops. This purpose may be accomplished by means of several irrigation procedures that can be grouped as: overhead, surface, and sub-surface irrigation.

Surface irrigation is characterized by the fact that land surface is used to convey water from the head ditch to the point where the water infiltrates into the soil. When the whole land surface is subsequently covered with a shallow depth of water remaining stagnant during infiltration, the method is referred to as basin irrigation. Otherwise, when the water flows over strips of land it is called borderstrip irrigation, and when water flows through small channels partially covering the land surface, it is called furrow irrigation. Borderstrip and furrow irrigation are defined as flow irrigation.

In order to supply the depth of water needed to wet the soil root zone, the water has to be in contact with the land surface for a certain length of time. The length of the required time depends on the soil characteristics which affect infiltration rate and the capacity to absorb water.

Three time stages may be distinguished in the practice of flow irrigation: a wetted or advance period to cover the length of run, a period during which the entire length of the run is covered with water, and a recession period, after terminating the supply from the head ditch, during which the water recedes over the length of run. The three stages have to be considered when the contact time between the water and the land surface is being determined.

Under a good irrigation practice the soil moisture deficit is restored in the root zone, with a minimum loss of water by deep percolation and, with a minimum waste by run-off at the end of the run. Therefore, the ideal practice for the problem under consideration, calls for a uniform depth of water to be put into the soil along the length of the furrow.

The hydraulics of shallow flow, combined with the study of soil infiltration capacity, have provided design procedures with optimal aim to secure high efficiency of irrigation under actual field conditions. During the last thirty years, a great effort has been made in the development of theoretical, semi-theoretical, and empirical approaches. The theoretical analysis, used to reach the solution of surface irrigation design, has been based on assumptions which are often not found in the field. Experiences in the western United States have produced data tabulations that do not generally fit tropical soil conditions.

Between the theoretical analysis and the very simplified procedures, there is a broad field to be covered by research. A comprehensive study of the variables involved in the practical determination of the infiltration capacity can provide a stronger foundation to reach the solution of such problems.

In the hydraulics of shallow flow, there is not a great difference between borderstrip and furrow irrigation. Considerable differences exist, however, when infiltration capacities are compared. This thesis does not cover the hydraulics of flow during the advance and recession periods. Its purpose is to deal with furrow infiltration capacity and infiltration pattern during the wetting front advance period, and during wetting of the root zone.

The field trials and laboratory determinations on which this thesis is based were conducted on tropical soils in an irrigation project in Venezuela. The data collected in these field trials are analysed statistically, in order to develop empirical relations of the advance and infiltration functions, and to obtain more generalized equations. Furthermore, on the basis of these equations, infiltration pattern and irrigation efficiency are analysed for each of the tested stream flows, surface roughnesses, furrow lengths and initial soil moisture contents. Special consideration is given to the infiltration equation parameters and their variability due to the effect of several factors.

Because of the objectives of this thesis, no attempt is made to develop a theory. But theories, proposed by others, have been used and were checked with experimental data.

2. ASPECTS OF INFILTRATION

2.1. INFILTRATION FUNCTION

Infiltration rate, which is synonymous to intake rate, can be defined as the rate of penetration of water into the soil profile when the land surface is covered with a shallow depth of water.

Infiltration has the dimension of velocity ($L\,T^{-1}$), as the depth (L) of water taken in by the soil in a unit of time (T); or as the quantity of water absorbed by a unit area of land surface per unit time ($L^3T^{-1}L^{-2}$), respectively. If the same units are used in both cases, the expressions are dimensionally equivalent ($L\,T^{-1}$). The common way to express the first form of the intake rate is mm hr^{-1} or mm min^{-1} in the metric system, and in inch hr^{-1} in the English system. In the second form, it is usually expressed as liter sec^{-1} m^{-2} or liter min^{-1} m^{-2} in the metric system, and ft^3 sec^{-1} ft^{-2} or in gallons min^{-1} ft^{-2} in the English system.

When water is applied to an area to restore the water content of the soil, it may happen that the quantity of water absorbed increases less than proportional with time. By plotting the accumulated depth of infiltrated water I_{cum} against the time t, a type of curve like the one shown in Fig. 1 will result. On the other hand, if the infiltration rate I is plotted against time t, the curve will have the shape as shown in Fig. 1. Both curves depict a decrease in the infiltration rate with time. Many soils show a decreased infiltration rate after a certain period of infiltration. This infiltration rate is called the basic infiltration rate.

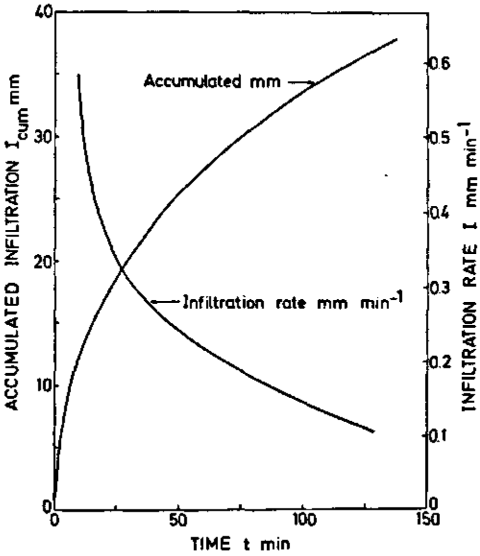

FIG. 1. Accumulated infiltration I_{cum} and infiltration rate I, as a function of intake time t.

From soil moisture relations during infiltration, **Bodman** and **Coleman** (1944) distinguished four zones in the mass of soil below the land surface: (i) a zone approaching saturation to a depth of up to 1.0 to 1.5 cm; (ii) a zone where the water content decreases rapidley with depth; (iii) a zone called the transmission zone, where the water content is nearly constant and roughly at three-quarters of saturation; (iv) a zone with a great and sharp decrease in water content, called the wetting zone, which ends abruptly at the wetting front.

2.1.1. *Theory*

The theory of infiltration is based on an analysis of the movement of soil water under unsaturated conditions. During infiltration, the liquid phase and the gaseous phase coexist in the mass of soil, except in the contact zone between soil and water on the land surface.

The discussion that follows is mainly related to the downward movement of water, but it is recognized that, with some adjustments, it can be applied to horizontal infiltration or infiltration at any angle ranging from vertical to horizontal.

The capillary theory, and the analogy with heat and electricity flow, were fundamental to the early attempts to explain soil water movement and infiltration rate. On the basis of the capillary theory, several scientists in papers as reviewed by **Gardner** (1967) proposed semi-empirical equations that describe the phenomena. **Philip** (1957) in a series of papers gave a stronger basis to the infiltration theory by solving the flow equation for downward gravity-aided infiltration:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial \theta}{\partial z}\right] - \frac{\partial k(\theta)}{\partial z} \tag{2.1}$$

Under conditions:

$$\theta = \theta_0 \quad t = 0 \quad z > 0$$
$$\theta = \theta_s \quad z = 0 \quad t \geqslant 0$$

where:

θ is the soil water content by volume fraction ($L^3\,L^{-3}$)
θ_0 is the initial soil water content by volume fraction ($L^3\,L^{-3}$)
θ_s is the surface water content by volume fraction ($L^3\,L^{-3}$)
$D(\theta)$ is the diffusivity coefficient as a function of θ (L^2T^{-1})
t is the time (T)
$k(\theta)$ is the hydraulic conductivity as function of θ ($L\,T^{-1}$)
z is the spatial coordinate, positive in the downward direction (L)

Philip's solution of this equation is based on infinite power series for accumulated infiltration. For practical purposes, the first two terms are considered sufficient for downward water movement:

$$I_{cum} = S\,t^{1/2} + C\,t \tag{2.2}$$

The coefficients of both terms are functions of soil water diffusivity and the initial and surface water content of the soil. The coefficient S is called sorptivity and has special significance at the early stage of infiltration; it represents the initial capacity of the soil to store and release water. The coefficient C is related to the capacity of the soil to transmit water, becoming important in later stages of infiltration. According to Philip's recommendations, the values of S and C can be approximated from actual determinations of the I_{cum} values at $t = 1{,}000$ sec and $t = 10{,}000$ sec respectively.

By differentiating Eq. 2.2 with respect to time, the infiltration rate equation can be obtained:

$$\frac{dI_{cum}}{dt} = I$$

Then:

$$I = \frac{S}{2}\,t^{-1/2} + C \tag{2.3}$$

2.1.2. *Empirical equations*

Several empirical equations have been proposed to express the infiltration rate as a function of time, a relation that can be represented by a curve of hyperbolic shape. The KOSTIAKOV equation (1932) expresses the infiltration rate at one point:

$$I = a\,t^{b} \tag{2.4}$$

where:

I is the infiltration rate (L T^{-1}) in mm min^{-1} of mm hr^{-1}

t is the infiltration time (T) in min or in hr

a is a coefficient which represents the infiltration rate at $t = 1.0$; expressed in mm $\text{min}^{-(1+b)}$ or mm $\text{hr}^{-(1+b)}$

b is a dimensionless exponent. It is always negative with values ranging from 0 and -1.0.

By integrating Eq. 2.4 between the limits $t = 0$ and $t = t$, the accumulated intake depth I_{cum} can be obtained:

$$I_{cum} = \int_0^t I\,dt$$

$$I_{cum} = \int_0^t a\,t^{b}\,dt$$

$$I_{cum} = \frac{a}{b+1} t^{b+1} \tag{2.5}$$

Eq. 2.5 may also be represented by

$$I_{cum} = A\,t^{B} \tag{2.6}$$

where

$$A = a/(b+1) \text{ and } B = b+1$$

Generally, equations 2.4 and 2.5 fit most of the conditions of surface irrigation practices very well. However, there are some cases in which intake rate reaches a constant value within the period of infiltration; if so, Eq. 2.4 becomes

$$I = a\,t^{b} + c \tag{2.7}$$

where
c is a constant infiltration rate for $t = \infty$.
The accumulated intake I_{cum} becomes then:

$$I_{cum} = \frac{a}{b+1} t^{b+1} + c\,t \tag{2.8}$$

With $b = -0.50$ Eq. 2.8 is equivalent to the Philip equation (2.2).

Other empirical equations have been developed, like Gardner's and Widtsoe's presented by CHRISTIANSEN *et al.* (1966) and the HORTON (1933) equation, extensively used in hydrology.

The Kostiakov equation has been used extensively in irrigation and soil sciences, mainly because of its practicality; both parameters can be obtained by simply plotting the experimental data on double logarithmic paper. At the present time, several equations used in the design of surface irrigation methods involve the parameters of the Kostiakov equation, especially the exponent b or B. Thus, in this thesis, the discussion will refer to this infiltration equation, and the dependence of these parameters on different variables will be given special consideration.

Average infiltration rate is the ratio of accumulated intake, divided by the intake time:

$$I_{av} = \frac{I_{cum}}{t} \; (LT^{-1}) \tag{2.9}$$

By substituting Eq. 2.5 in Eq. 2.9 a point average equation is obtained:

$$I_{av} = \frac{a}{b+1} t^{b} \tag{2.10}$$

Then I_{av} is the average rate of intake of water that has entered the soil in a period t.

The basic intake rate I_b is another quantity which deserves consideration because of its importance in irrigation design. According to the US Department of Agriculture, Soil Conservation Service, basic intake rate is the instantaneous value, when rate of change of intake for standard period is 10% or less of its value.

The time at which $I = I_b$ is found by equating the first derivative of Eq. 2.4 to Eq. 2.4 times 0.1:

$$\frac{dI}{dt} = -0.1\, I$$

Then

$$a\, b\, t^{b-1} = -0.1\, a\, t^{b}$$

and

$$t_b = -10\, b \tag{2.11}$$

If Eq. 2.11 is substituted in Eq. 2.4, I_b is obtained:

$$I_b = a\,(-10\, b)^{b} \tag{2.12}$$

Equations 2.11 and 2.12 are generally valid if consistent units are used, mm hr^{-1} or mm min^{-1}.

2.2. FACTORS AFFECTING INFILTRATION

According to Philip's theoretical analysis, the infiltration rate of a homogeneous and isothermal soil depends on the capacity of the soil to store and to transmit water.

Both parameters of Philip's equation are functions of many factors. These factors result from a diversity of quantitative values commonly found in the field. Unfortunately, because some of those factors are extremely dynamic, they change with soil and water management. Thus it has not yet been possible to come up with a figure for infiltration capacity pertaining to some specific soil classification taxonomic unit, except when a rough estimate of the basic infiltration rate is being obtained, or when a qualitative expression such as high, moderate or low is used.

Infiltration can be evaluated by the flow equation which is valid for saturated as well as for non-saturated conditions. The factors affecting infiltration can therefore be grouped as follows: factors affecting the hydraulic gradient, and factors affecting the hydraulic conductivity and diffusivity. For a comprehensive discussion of the factors involved they are grouped according to the inherent characteristics of the soil and related to soil and water management practices as follows: (1) soil physical characteristics; (2) soil profile characteristics; (3) soil moisture characteristic; (4) irrigation method and water management; (5) other factors.

2.2.1. *Soil physical characteristics*

Soil macroporosity is the primary factor affecting hydraulic conductivity at the near saturated stage and thus also infiltration rate. Porosity depends on texture and structure. Water passes more readily through the soil profile in a coarse soil with greater noncapillary porosity than in a heavy soil in which capillary pores are predominant.

The influence of structure and structure stability is also important. Soils stable to wetting and drying, and subject to a regular crop sequence and good soil management have a greater chance of maintaining an open surface permeable to water.

Clay content, the mineralogical composition of clay and the composition of the exchange complex, are other factors to be considered, e.g. soils with high montmorillonitic or illitic clay content shrink and swell on alternate drying and wetting.

Soil-binding agents as organic matter and inorganic oxides are instrumental in aggregate formation and thus, in maintaining a high hydraulic conductivity. Intake rate may be reduced by the breakdown of the structure of a very thin soil-surface layer. Particularly when clear water is used for irrigation, disruption of aggregates and slaking produce a surface seal that reduces water penetration. Impact of droplets from sprinkler irrigation may yield the same results. Otherwise, the settlement of transported sediment, eroded at some upstream section and resettling of water-carried sediments elsewhere in the same surface-irrigated field, may be the cause of surface sealing.

2.2.2. *Profile characteristics*

In non-stratified homogeneous soils, as are found in many arid regions, rate of water intake depends on inherent physical conditions being nearly constant with soil depth. But very frequently, especially in wet climates, the soil profile shows a stratification, and the infiltration capacity may vary considerably for individually differentiated soil horizons.

In case a soil horizon near the surface exhibits the smallest infiltration capacity, the entire process is then governed by infiltration through that layer. However if the limiting strata lay deeper in the soil profile, the intake rate may initially be high depending on the infiltration capacity of the uppermost strata. When the wetting front reaches a less permeable stratum, further water infiltration will be governed by the infiltration of the less permeable layers.

A perched water table might develop on the limiting layer, because in one-dimensional downward movement, water cannot escape laterally. This could happen not only on top of layers with a very low absolute value of permeability, but also as a consequence of relative permeability, when this is much higher in the upper layer than in the lower one.

The soil profile characteristics play important roles in determining furrow width and furrow spacing. As HENDERSON and HAISE (1967) point out, if a less permeable stratum is located at some depth in the profile, the initial infiltration rate will depend on the wetted area, but once a watertable starts developing on the top of the restricting stratum, the furrow spacing will become unimportant.

2.2.3. *Soil moisture characteristic*

The soil moisture characteristic, or water retention relation, is an important factor in infiltration. This factor has been analysed theoretically and has been tested under laboratory and field conditions. The water retention relation is now considered as a physical characteristic for each type of soil. Therefore, water content needs to be included as one of the parameters in an infiltration experiment.

The US Bureau of Reclamation Land Classification Handbook (1953) suggests two infiltration trials: a dry and a wet trial. A good approach is, undoubtedly, to run the infiltration test near the soil moisture content at which irrigation water will normally be applied; for instance, the one that represents 50% of the total available moisture. This rule is especially valid for heavy soils that shrink and crack upon drying, because a relationship appears to exist between shrinkage and soil moisture depletion.

2.2.4. *Irrigation method and water management*

The irrigation method affects the access of water to the soil, the depth of water flowing or standing on the land surface, and the uniformity of application. In sprinkler irrigation, water penetrates into the soil immediately on reaching the surface. In surface flow irrigation, water flows over the land in various depths through channels of different sizes and shapes with different hydraulic gradients and thus with different effective areas for infiltration.

An important difference between border and furrow flow patterns, exists in relation to the wetted area. Border irrigation practically covers the whole area with a shallow depth of water, while furrow irrigation covers it partially. Because the wetted area is smaller in furrow irrigation, the total amount involved in infiltration is also smaller than in border irrigation.

The hydraulic conditions of the furrow, which depend on stream flow, size of the furrow, slope, shape and surface roughness, have an effect on the wetted perimeter and on the wetted entry area. Thus, the summarized infiltration rate is dependent on the hydraulic conditions of the furrow. A possible coalescence from adjacent furrows, due to lateral movement of the wetting front may consequently also effect infiltration rates.

2.2.5. *Other factors*

Influence of temperature on infiltration rate is to be expected since temperature affects both viscosity and surface tension. The effect of temperature on infiltration has not been proved so far, to the author's knowledge, but it is expected to be small in practice.

Another factor worth noting is air entrapment during flooding. Air stays in the soil voids, and cannot escape under extensive flooding. With furrow irrigation in which case the land surface is only partially covered with water, air entrapment is less important on most soils.

3. INFILTRATION CHARACTERISTICS IN FURROW IRRIGATION

3.1. Furrow infiltration pattern

Water infiltrates through the wetted perimeter of the furrow cross-sectional area. The interface between wetted and dry soil moves then downwards from the wetted perimeter as a wetting front with circular or elliptical cross-section.

In unsaturated soil, water movements are caused by capillarity and gravity. Horizontal and upward movement are caused by matric potential gradients. Vertical and downward movements depend on both matric and gravitational potential gradients. The whole moistening of the upper layers of the soil mass in the ridges between the furrows is caused by lateral and upward capillary movement.

In deep predominantly sandy soils, downward movement due to gravity may be dominant, and in that case the wetting front extends very deep before lateral movement reached the centre line between furrows. If so, the water may be turned off to avoid deep percolation below the root zone, but as a result an area of dry soil will be left between furrows. A longer period to attempt complete moistening of the soil root zone could result in high losses by deep percolation.

Furrowing generally decreases the relative area of contact between land and water, as compared with border strip or basin irrigation. In closely spaced deep furrows the length of the wetted perimeter may be equal to the furrow spacing. But in shallow furrows with wider spacing, the wetted perimeter may be half, one third or even a smaller fraction of the furrow spacing. In wider spaced furrows, the infiltration time has to be increased in order to moisten the ridge between furrows even when some deep percolation might result.

The furrow spacing is usually determined by crop and cropping practices, especially if machinery is used. Whereas the wetted perimeter is a consequence of the flow hydraulics determined by the size of flow, the shape and slope of the furrows, and surface roughness. Consequently, the ratio between wetted perimeter or wetted width and the furrow spacing, in general, cannot be adjusted to optimum conditions for wetting of the ridges.

3.2. Advance of the water front along the furrow

If a stream flow Q is supplied to a furrow of infinite length, the advance of the water front in the initial phase will be rapid. Later at some distance which still may be close to the feeder ditch, the rate of advance declines until at a farther distance the water front stops.

The plot of the distance x against time t is called the advance curve, and this relation determines the decrease of the advance velocity dx/dt with time. This behaviour is independent of hydraulic factors and is caused by the decrease of the flow size with distance *x*. When water is let into the furrows for some period, the remaining part of the original stream flow Q is much larger than the infiltrated flow Q_i. Water is then available to run further along. Later the reduction in stream flow clearly affects the advance rate and slows down the water front. Finally, the whole stream flow has penetrated into the furrow bed, the advance virtually stops and the curve becomes asymptotic with a line paralel with the time axis.

Since the rate of advance is a function of the flow size for constant furrow hydraulics and soil, a pattern of advance curves will result if we supply different initial flow sizes Q to a set of furrows with all the other external factors held constant.

3.3 IRRIGATION TIME STAGES

When the water front has advanced along a furrow for a certain distance, the decrease in depth of water from the furrow intake to the water front corresponds to the volume of water stored in the furrow channel over that distance (Fig. 2). Due to the difference in contact time for different sections of the furrow, different volumes of water are taken in by the soil.

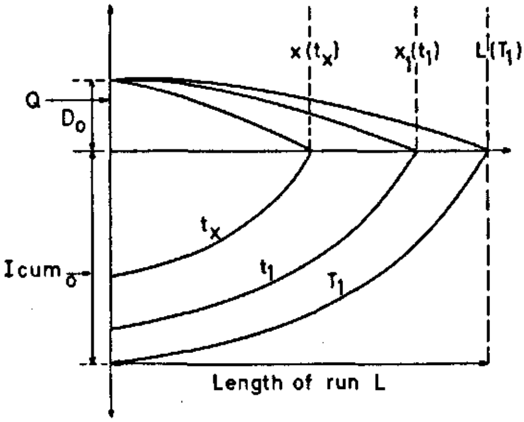

FIG. 2. Water distribution profiles during the advance period: water surface profiles and intake profiles. Both for equal advance time increments.

When the water front has arrived at the far end of the furrow, no water has as yet penetrated the soil there. A volume of water is still in the furrow flowing towards the lower end, but at the upper end the time of contact may not have been enough to wet the root zone. Then, in a sloping furrow, the intake flow must continue at a rate depending on infiltration capacity, until the time needed to restore the deficit of soil water at the lower end has passed. Certainly, in such a case, some unavoidable deep percolation losses will occur at the supply end of the furrow.

In furrows with gentle slope, reduction in supply, relative to infiltration capacity when the water front reaches the far end, would avoid run-off. But this may prevent any infiltration in the final section of the furrow. Even when the stream flow can be somewhat reduced, a tail flow would still be needed to maintain sufficient flow to moisten the far end of the furrow.

The supply can be turned off towards the end of the time period needed to restore water deficit at the far end of the furrows. Water stored in the furrow will flow down. Then, the recession of the surface water takes place from the upper to the lower end of the furrows. Tail water flow stops when recession of surface water reaches the lower end.

In surface irrigation, three stages must be considered: (i) water front advance or furrow wetting period; (ii) a period during which the entire length of the furrow is filled and is subject to infiltration; (iii) a recession period during which a decreasing length of furrow is filled with water.

The infiltration characteristics during the first and second stages will now be discussed.

3.4. FIRST IRRIGATION STAGE: THE ADVANCE FUNCTION

Several authors agree that the advance of the wetting front over the furrow bed can be expressed as an exponential function of the time variable:

$$x = p\, t^r \tag{3.1}$$

where

x is the length of advance at time t

p is an empirical coefficient of the advance function

t is the advance time

r is an empirical exponent of the advance function $0 < r < 1.0$

The advance of the wetting front depends on several factors: stream flow; infiltration function; size, shape and slope of the furrow, and roughness of the entire surface.

Analysing the physical meaning of p and r in Eq. 3.1, NUGTEREN (1969) found that p is an empirical constant depending on the slope S_0, the size of the flow Q, the hydraulics of flow and surface roughness; and that r is related to the physical characteristics expressed in the infiltration function.

Then, Eq. 3.1 becomes

$$x = u f(Q)\, t^r \tag{3.2}$$

From data from Criddle and Wonji, NUGTEREN (1969) also found that for practically acceptable flows, x in m is proportional to Q in liter min^{-1} as:

Slope 2.0% $x = 0.35\, Q\, t^{0.53}$
Slope 0.1% $x = 0.055\, Q\, t^{0.53}$

When x is proportional to Q Eq. 3.2 becomes:

$$x = u\, Q\, t^{r} \tag{3.3}$$

A more general expression is given by:

$$x = u\, Q^{s} t^{r} \tag{3.4}$$

With s probably ranging between 0.8 and 1.0 increasing with the slope (VIERHOUT, 1971). Thus u in Eq. 3.2 will be governed mainly by the slope and by other factors like surface roughness and other hydraulic characteristics of flow along the furrow.

By differentiating Eq. 3.1 with respect to time

$$\frac{dx}{dt} = p\, r\, t^{r-1} \tag{3.5}$$

where

dx/dt is the rate of advance of the water front defined as a function of the advance time

$p\,r$ is the initial velocity of advance into the system at $t = 1.0$.

Hence $dx/dt \rightarrow \infty$ in the asymptotic value for $t = 0$. Depending on the p value, at a certain time the advance velocity becomes too small to be measured, so for practical purposes $dx/dt = 0$ for some time less than infinite.

3.5. INFILTRATION-ADVANCE FUNCTION

The infiltration advance process can be analysed from a simple balance equation:

$$V_{in} = Q\, t = (\bar{D} + \bar{I}_{cum})x\, w \tag{3.6}$$

where

V_{in} is the inflow volume at the advance time t (L^3)

Q is the supply flow into the furrow ($L^3\, T^{-1}$)

t is the time of inflow (T)

x is the length of advance at time t (L)

w is the spacing between furrows, or wetted width or wetted perimeter (L)

$\bar{D}$ is the average depth of water flowing in the furrow at time t (L)

$\bar{I}_{cum}$ is the average depth of water infiltrated along the furrow wetted length at time t (L).

Then, from Eq. 3.6

$$x = \frac{Q\,t}{(\bar{D} + \bar{I}_{cum})\,w} \tag{3.7}$$

To solve Eq. 3.7 an adequate procedure is required to approximate both $\bar{D}$ and $\bar{I}_{cum}$. Coefficients can be used in relation to the depth values D_0 and I_{cum0} at the furrow intake at $x = 0$. The normal depth of water at this point, i.e. the depth of water at $x = 0$ flowing through the furrow, D_o, can be calculated from Manning's equation if the conventional hydraulic characteristics of the channel, slope and surface roughness are known then $C_1 = \bar{D}/D_0$. The accumulated infiltration depth I_{cum_0} for the same point, i.e. $x = 0$, can be calculated from Eq. 2.5, given the infiltration parameters, then the coefficient $C_2 = \bar{I}_{cum}/I_{cum}$.

Eq. 3.7 can be represented by:

$$x = \frac{Q\,t}{(C_1 D_0 + C_2\,I_{cum_0})\,w} \tag{3.8}$$

where

D_0 is the normal depth of water flowing in the furrow at $x = 0$

I_{cum_0} is the cumulative intake at $x = 0$.

Since the first study of LEWIS and MILNE (1938), several approaches have been developed to elaborate Eq. 3.6. Approaching the surface water depth by Manning's equation, HALL (1956) developed a procedure for numerical integration to predict the advance of the water front at regular intervals. CRIDDLE *et al.* (1956) in the US Department of Agricultural Handbook 82 suggests direct measurements of the water advance front and of the furrow intake rate to relate these two factors. PHILIP and FARREL (1964) provided a rational procedure to analyse the infiltration-advance problem in surface irrigation. FINKEL and NIR (1965) designed a graphical method based on actual measurements of inflow and surface water to relate infiltration and advance. FOK and BISHOP (1965) and CHRISTIANSEN *et al.* (1966) developed equations to relate the distance that the front moves with the infiltration equation and the normal depth. WILKE and SMERDON (1965) gave a family of dimensionless curves and regression equations to solve the Philip and Farrel equation.

Lewis and Milne's balance equation expresses water advance for a unit width $w = 1.0$ in differential form.

$$Q\,t = C_1 D_0\,x + \int_0^t I_{cum(t-t)_x}\,x'(t_x)\,dt_x \tag{3.9}$$

where

t is the time that water has been turned onto the land

t_x is the time to reach the distance x

$x'(t_x)$ is the value of dx/dt at $t = t_x$.

Considerable effort has been devoted to solving the integral term of Eq. 3.9. PHILIP and FARREL (1964) rewrote the Lewis and Milne equation as:

$$\frac{\bar{D}\,x}{Q\,t} = \sum_{n=0}^{\infty} \frac{\left\{\frac{-A\,t^{B}}{\bar{D}}\left[\Gamma\,(1 + B)\right]\right\}^{n}}{\Gamma\,(2 + n\,B)} \tag{3.10}$$

where

$\bar{D}$ is the average depth of surface water

Q is the inflow per unit width of border strip or in the furrow inflow

Γ is the Gamma function

n is an integer

A and B are parameters of the Kostiakov equation (2.6).

Convergence of this series, however, is extremely slow. An elaborate analysis was given by ASSED and KIRKHAM (1968) and the equations proposed by them give directly the required results. WILKE and SMERDON (1965) analysed the dimensionless relations of $Q\,t/\bar{D}\,x$ against $A\,t^{B}/\bar{D}$, and derived a family of curves for different B values. By some adjustments of the regression equations, they obtained a function with one parameter that varies with B:

$$\frac{Q\,t}{\bar{D}\,x} = 1.0 + 0.7165\left(\frac{A\,t^{B}}{\bar{D}}\right) \textit{ for } B = 0.5 \tag{3.11}$$

The values of the coefficient of Eq. 3.11 vary with B between 0.8447 (for $B = 0.2$) to 0.6676 (for $B = 0.7$).

To solve Eq. 3.9, FOK (1958) developed a relationship between $\bar{I}_{cum}$ and infiltration characteristics, by integrating the accumulated infiltration (Eq. 2.5):

$$\bar{I}_{cum} \cong \frac{1}{t}\int_{0}^{t} I_{cum}\,dt \quad (L)$$

$$\bar{I}_{cum} \cong \frac{a\,t^{b+1}}{(b + 1)\,(b + 2)} \tag{3.12}$$

Eq. 3.12 expresses the average depth of water that enters the soil in the advance time t. This equation in fact only applies if time and advance are proportional, as occurs with a constant advance of the front. Generally that equation does not fit the advance rate as expressed by Eq. 3.1.

CHRISTIANSEN *et al.* (1966) improved the solution of the infiltration-advance function with the following analysis:

$$I_{cum} = \frac{a}{(b + 1)}\,(t_{t} - t_{x})^{b+1} \tag{3.13}$$

where

t_{t} is the time for the water front to reach a distance x_{t}

t_{x} is the time to reach any point between and including 0 and x_{t}.

Then, the area representing the infiltrated depth of water along the furrow length when the water front reaches point x_1 becomes:

$$I_{cum}x_1 = \int_{o}^{x_1} I_{cum}\, dx = \int_{o}^{t_1} I_{cum} \frac{\partial x}{\partial t}\, dt_x \tag{3.14}$$

In accordance with Eq. 3.5:

$$\frac{\partial x}{\partial t} = p\, r\, t_x^{\,r-1} \tag{3.15}$$

Then if equations 3.13 and 3.15 are substituted in Eq. 3.14:

$$\bar{I}_{cum}x_1 = \int_{o}^{t_1} \frac{a}{(b+1)} (t_1 - t_x)^{b+1}\, p\, r\, t_x^{\,r-1}\, dt_x$$

By solving the binomial $(t_1 - t_x)^{b+1}$ for $t_x/t_1 \leqslant 1.0$ and integrating, KIEFER (1965) provided an exact procedure for calculating the $\bar{I}_{cum}$. By dividing the left hand side of Eq. 3.14 by $x_1 = p\, t_1^{\,r}$ an average depth of infiltration is obtained:

$$\bar{I}_{cum} = \frac{F\, a}{(b+1)(b+2)}\, t_1^{\,b+1} \tag{3.16}$$

where

$$F = r\,(b+2)\left[\frac{1}{r} - \frac{b+1}{r+1} + \frac{b\,(b+1)}{2\,(r+2)} - \ldots\ldots\ldots\right] \tag{3.17}$$

Theoretically the binomial expansion does not converge under all circumstances. For practical values of b and r convergence occurs (VIERHOUT, 1971).

The factor F has been approximated by KIEFER (1965) as:

$$F \cong \frac{b - r\,b + 2}{1 + r} \tag{3.18}$$

If $\bar{I}_{cum}$ from Eq. 3.16 and I_{cum_0} from Eq. 2.5 are substituted into the coefficient $C_2 = \bar{I}_{cum}/I_{cum_0}$, then C_2 becomes:

$$C_2 = \frac{F}{b+2} \tag{3.19}$$

The value of $\bar{D}$, seems a little more difficult to obtain without direct measurements. BISHOP *et al.* (1967) considered that $C_1 \rightarrow 1.0$ for sloping lands, and that, for flat slopes, small advance distances and high intake rates, $C_1 \rightarrow 0.67$.

OSTROMECKI (1960) assumed the profile of surface water to be parabolic, concluding that C_1 may vary from 2/3 to 3/4. According to HALL (1956), C_1 coefficients range from 2/3 to < 1.0. The coefficient C_1 depends on the shape of the water surface profile parallel to the bed: rectangular $C_1 = 1.00$, elliptic $C_1 = \pi/4 = 0.78$, parabolic $C_1 = 2/3 = 0.67$, triangular $C_1 = 1/2 = 0.50$.

FOK and BISHOP (1965) derived an equation for surface storage volume and for average water depth from normal depth D_0 and the exponent r of Eq. 3.1:

$$\bar{D} = \frac{D_0}{1 + r} \tag{3.20}$$

Then, for the values of $0 < r < 1$, $\bar{D}/D_o$ values vary between 0.5 and 1.0.

3.6 INFLOW-INFILTRATION FUNCTION

As advance is related to inflow Q and to infiltration, some relations between the average inflow and the infiltration per unit area may be obtained.

NUGTEREN (1969) derived an equation to calculate the unit inflow as a function of infiltration parameters. Unit inflow q_0 is the average available supply to the furrow per unit area of infiltration A_i. The area of infiltration A_i is obtained by multiplying the wetted width by the length of run x. The wetted width could be the wetted perimeter P; if this is so then the net infiltration area $A_i = P\,x$; or the furrow spacing w for which $A_i = w\,x$, is the gross infiltration area. The unit inflow, for the gross infiltration area becomes:

$$q_0 = \frac{Q}{w\,x} \tag{3.21}$$

In case of proportionality between x and Q if Q of Eq. 3.21 is substituted in Eq. 3.3:

$$x = u\,q_0\,w\,x\,t^r \tag{3.22}$$

or, in general

$$x = u\,(w\,q_0\,x)^s\,t^r \tag{3.23}$$

Solving for q_0 and assuming that $s \approx 1.0$, we obtain:

$$q_0 = \frac{1}{u\,w}\,t^{-r} \tag{3.24}$$

If the infiltration flow Q_i is considered instead of the inflow Q, the unit infiltration flow q_i or average intake for gross infiltration area becomes:

$$q_i = \frac{Q_i}{w\,x} \tag{3.25}$$

The values of both q_0 and q_i decrease with the advance time t up to the end of the run ($t = T_1$). Then, $x = L$ being constant at time $t \geqslant T_1$, the infiltration area A_i as well as q_0 will remain constant.

By presenting the balance equation in differential form it can be seen that for the point $t \leqslant T_1$ the water front advances a distance dx during dt and the inflow volume is $Q\,dt$. Then, according to Nugteren's derivation (Fig. 3),

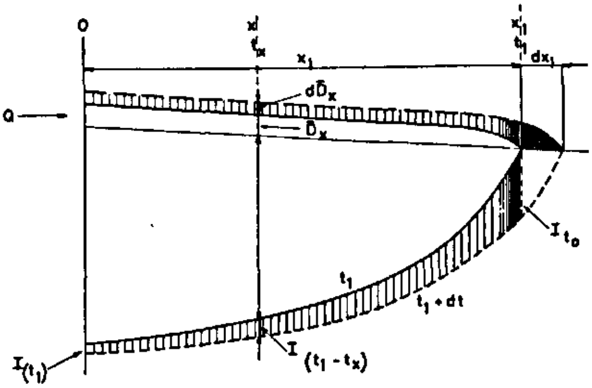

Fig. 3. Water-surface and soil-profile characteristics of a shallow flow over the land surface of uniform slope. From Nugteren (1969).

$$Q\,dt = w\,x_1\,d\bar{D}_{x_1} + w\,\bar{D}x_1\,dx_1 + w\,dt\int_0^{x_1} I\,dx \tag{3.26}$$

By dividing both members by $w\,x_1\,dt$ and substituting $I = a\,(t_1 - t_x)^b$

$$\frac{Q}{w\,x_1} = \frac{d\bar{D}_{x_1}}{dt} + \frac{\bar{D}_{x_1}}{x_1}\frac{dx_1}{dt} + \frac{1}{x_1}\int_0^{t_1} a\,(t_1 - t_x)^b\,\frac{dx}{dt_x}\,dt_x$$

By substitution of $Q/w\,x$ by q_0 (Eq. 3.21), by transposition of two terms and by substituting $dx/dt_x = p\,r\,t_x^{r-1}$, Eq. 3.26 becomes:

$$q_0 - \frac{d\bar{D}_{x_1}}{dt} - \frac{\bar{D}_{x_1}}{x_1}\,\frac{dx_1}{dt} = \frac{1}{x_1}\int_0^{t_1} a\,(t_1 - t_x)^b\,r\,p\,t_x^{r-1}\,dt_x$$

If $\frac{d\bar{D}_{x_1}}{dt}$ and $\frac{\bar{D}_{x_1}}{x_1}$ are neglected and $p\,t_1^r$ is substituted for x_1:

$$q_0 = \frac{a\,r}{t_1^{\,r}} \int_0^{t_1} (t_1 - t_x)^b \, t_x^{\,r-1} \, dt_x \tag{3.27}$$

For linear advance, when $r = 1.0$ Nugteren's derivation becomes:

$$q_0 = \frac{a}{t_1} \int_0^{t_1} (t_1 - t_x)^b \, dt_x$$

Then

$$q_0 = -\frac{a}{t_1} \int_0^{t_1} (t_1 - t_x)^b \, d\,(t_1 - t_x)$$

$$q_0 = \frac{a}{b+1} t_1^b \tag{3.28}$$

Eq. 3.28 is identical to Eq. 2.10 for I_{av}. However, at the beginning of the run, q_0 is greater than I_{av}, because the terms $d\bar{D}_{x_1}/dt$ and $(\bar{D}_{x_1}/x_1)\,(dx/dt)$ are then quantitatively important. At the later phase of advance, the decreased infiltration rate at the upper part of the run dominates the value of q_0, due to the factor $t_x^{\,r-1}$, so q_0 may then become less than I_{av}.

4. LAYOUT OF FIELD EXPERIMENTS

4.1. PLAN OF THE EXPERIMENTS

Furrow irrigation was selected for this research for the following reasons: (i) in practice it is possible to manage the required number of replicates; (ii) the plots are smaller than with borderstrip or basin irrigation due to their reduced width. The required area with sufficient uniformity is therefore smaller; (iii) the flow measurement does not require elaborate equipment; it is done with apparatuses of small size which are easy to operate and are inexpensive; (iv) checking the water content of the soil can be done by sampling, based on few replicates; (v) the flow required is smaller than with other surface irrigation methods and a steady head can easily be maintained at the feeder ditch; (vi) during the furrow wetting period the advance front and the flow section i.e. the depth and the width of the cross-sectional area, can be measured rather accurately.

Besides, furrow irrigation is of relevance and importance in Venezuela, for the irrigation of crops like maize, beans, soy beans, sugar cane, sesame for which the best agricultural soils are used. Consequently, the Algodonal series was chosen for the experiments, because of the area of land that is composed of this series in the Cojedes-Sarare Irrigation Project. In addition, it fitted in with the objectives of the research plan which is carried out at the Experimental Station.

In order to draft the program of the experiments it was considered that infiltration in a furrow, as expressed in the infiltrating flow Q_i, is a function of:

$$Q_i = f(a, b, L, a_f, w, S_0, n) \tag{4.1}$$

where

a and b are the parameters of infiltration equation (2.4)
a_f is the furrow flow cross section (L^2)
L is the furrow length (L)
S_0 is the furrow slope ($L\ L^{-1}$)
n is the furrow roughness condition, that could be expressed by Manning's surface roughness coefficient ($L^{-1/3}\ T$)
w is the distance between furrows (L).

The average slope $S_0 = 0.18\ \text{‰}$, which is representative for the field experiments for the entire project, was adopted as a constant. The spacing and the shape of the furrows which depended on the furrower used were also taken as constants. Thus for the field experiments the variables were: (i) furrow flow cross section a_f (varying with the inflow size Q); (ii) furrow surface roughness n; (iii) furrow length L; (iv) intake rate I (only varying with the initial soil moisture content and the conditions of the furrow during successive irrigations).

To study these variables the experiments were planned in three series:

1. First series of experiments. Variables: inflow Q and furrow roughness n.

2. Second series of experiments. Variables: initial soil moisture content.
3. Third series of experiments. Variables: length of the furrow L.

4.1.1. *First series of experiments*

i. *Variables*	*Number of treatments*
Inflow size	4
Surface roughness	3

ii. *Constants*

Physical characteristics of the soil and quality of the water
Initial soil moisture content
Length, spacing, slope, shape and size of the furrows.

In the first series of experiments the nominal flow to each furrow was as follows:

Treatment 1 $Q = 0.50$ liter sec^{-1} (30 liter min^{-1})
Treatment 2 $Q = 1.00$ liter sec^{-1} (60 liter min^{-1})
Treatment 3 $Q = 1.50$ liter sec^{-1} (90 liter min^{-1})
Treatment 4 $Q = 2.00$ liter sec^{-1} (120 liter min^{-1})

The actual flow in Treatment 1 differed from the nominal one, due to the set-up for water delivery into the furrows, and the available head in the feeder ditch. This combination of treatments was repeated three times with different roughnesses: (i) Bare soil with a rough surface; this was the first irrigation after the land had been prepared; (ii) Bare soil somewhat smoothed by previous water applications; this was the third irrigation. (iii) Bare soil with a smooth land surface after several water applications; this was the fourth irrigation.

During the first irrigation, the water moved forward while destroying clods by slacking, whereas in the following irrigations the water advanced while closing the surface cracks. This closing of cracks was partly due to erosion and redeposition of material, but mainly to the expansion of the colloids upon wetting.

For practical purposes during the third and fourth irrigations there were no differences in roughness conditions. The surface was cracked before irrigation but otherwise smooth, contrasting notably with that of the first irrigation. In order to get further results of practical importance, and considering that the roughnesses of the third and fourth irrigations were identical, the aspect of flow reduction was introduced in the fourth irrigation. Upon the arrival of the water front at the end of the furrow during the fourth irrigation in treatments 1 and 2, and when 78.5% of the furrow length was covered in treatments 3 and 4 the flow was reduced to:

Treatment 1 $Q_r = 0.15$ liter sec^{-1} (9.0 liter min^{-1})
Treatment 2 $Q_r = 0.28$ liter sec^{-1} (16.8 liter min^{-1})
Treatment 3 $Q_r = 0.59$ liter sec^{-1} (35.4 liter min^{-1})
Treatment 4 $Q_r = 0.64$ liter sec^{-1} (38.4 liter min^{-1})

4.1.2. *Second series of experiments*

i. *Variables*	*Number of treatments*
Initial soil moisture content	3

ii. *Constant*
Inflow size
Physical characteristics of the soil and quality of the water
Length, spacing, slope, shape, and size of the furrows.
Surface roughness.

The relevant variable was studied because the soils of the Project show variations in bulk density and crack upon drying, which affects the infiltration characteristics of the soils. The values of the soil moisture content on a weight basis, taken as an average of the upper 45 cm soil strate, were as follows:

Treatment 1: Low soil moisture content: 16.3%
Treatment 2: Moderately moist: 19.3%
Treatment 3: High (nearly saturated): 27–34%

In the sequence of irrigations during the whole experiment this series corresponds to second irrigation with an average constant inflow $Q = 0.51$ liter $\sec^{-1}$ (30.6 liter $\min^{-1}$), with a range between 0.46 liter $\sec^{-1}$ and 0.57 liter $\sec^{-1}$.

4.1.3. *Third series of experiments*

i. *Variables*	*Number of treatments*
Length of the furrow	3

ii. *Constants*
Inflow size
Physical characteristics of the soil and quality of the water
Initial soil moisture content
Spacing, slope, shape and size of the furrows
Surface roughness.

The length of the furrows were:

Treatment 1 $L = 62.5$ m
Treatment 2 $L = 125.0$ m
Treatment 3 $L = 175.0$ m

The average inflow $Q = 0.62$ liter $\sec^{-1}$ (37.2 liter $\min^{-1}$), with a range between 0.59 liter $\sec^{-1}$ and 0.64 liter $\sec^{-1}$.

This series of experiments was included in order to investigate the variability in average depth of water infiltrated during the furrow wetting period.

4.2. EXPERIMENTAL ARRANGEMENTS AND DESIGN

The trials were conducted in Plot 2 B-39 (photograph Fig. 4) which functions as the Experimental Station of the Cojedes-Sarare Irrigation Project. The area used was a rectangle of approximately 70 m by 200 m located in the North Eastern section of the field.

Fig. 4. Photograph of the Experimental Station of the Cojedes-Sarare Irrigation Project.

Since the slope was assumed to be one of the constants, some levelling work had to be done on the land, to get a uniform topography. Excessive earth movement was avoided because the experiments were to be run on a field that is representative for the type of land condition prevailing in the Project. Furthermore, intensive and refined land levelling would have affected the uniformity of the soil, which was supposed to be held constant in the trials.

The furrows were layed out from the North West towards the South East with a length of 200 m and a spacing of 0.70 m, depending on the general slope and the location of the irrigation and the drainage ditches. In order to reproduce field conditions, with several adjacent furrows being operated simultaneously under identical conditions, a buffer furrow was installed on each side of the test furrows. All the measurements as inflow and outflow, stream flow section, soil water content, advance of the water front during the wetting period, were carried out in the central furrows, but with approximately the same flow supplied to the relevant buffers.

The experimental lay out contained five blocks, each block composed of 12 furrows, plus a waste furrow for surplus discharge. For the necessary measurements footpaths were provided for along each 6th furrow (Fig. 5). At the center line of each block, stakes were placed in the ridges of the furrows. So, the transversal alignments determined by five stakes in a row marked the spots for taking measurements of flow advance and wetted cross section at longitudinal intervals of 12.5 m.

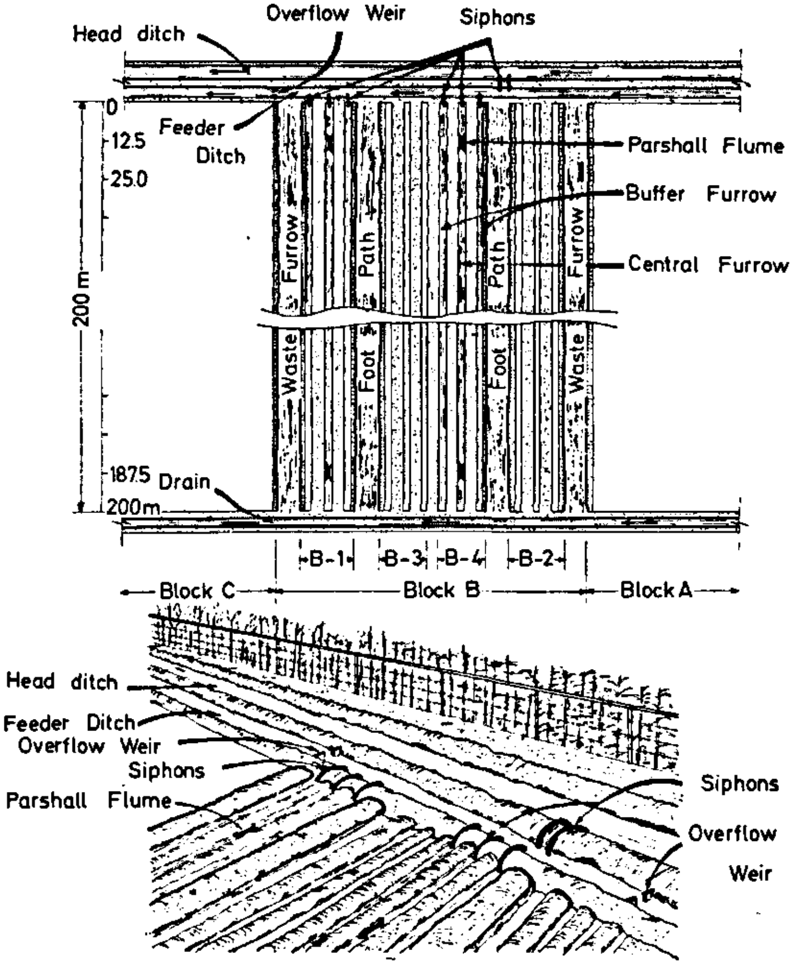

FIG. 5. Experimental field lay-out. Diversion structures and diversion devices.

The supply for the experiments was obtained from a secondary canal. The required constant water level in the head ditch was maintained by a check structure. From the head ditch, a flow slightly larger than the one required was diverted to the feeder ditches located at the upper end of each block (Fig. 5) parallel to the head ditch. Timber checks with rectangular overflow weirs were arranged to secure a constant head for each block of the trials.

The diversion into the furrows was done with siphons with submerged outlet. Parshall flumes were used to measure the furrow inflow and the outflow (photograph Fig. 6). The furrow meters with throat width of 2 inches (5.08 cm) and 1 inch (2.54 cm) were located as shown in Fig. 5. In this way an effective furrow length of 175 m remained available between the flumes.

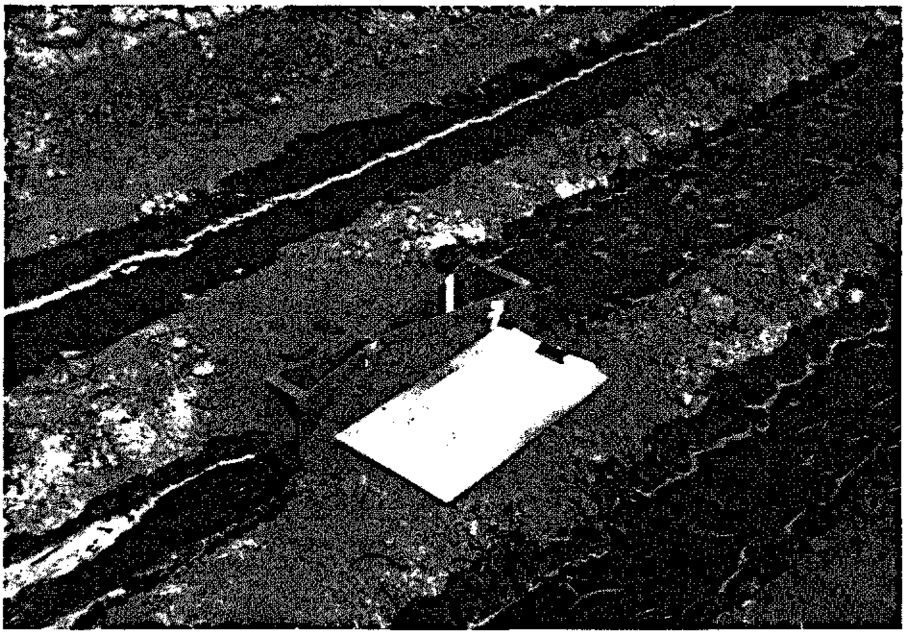

FIG. 6. Photograph of the Parshall measuring flume used for the trials.

4.2.1. *First series of experiments*

For statistical reasons and in view of the required soil uniformity of the selected soil series, a number of five replicates was thought acceptable. As already indicated, the field was subdivided into five blocks with four test furrows each. In each block a random distribution of the treatments was adopted as follows:

Block	A	B	C	D	E
Treatment	3 2 4 1	2 4 3 1	2 4 1 3	1 4 2 3	2 4 1 3

In order to use the constant supply efficiently, and to complete the trials during the dry season, two treatments were combined in the first series of experiments and simultaneously carried out. Therefore, treatments 1 and 4, respectively 2 and 3, could be completed in one day. The work usually consisted of 4 hours of effective control on the irrigation of 6 furrows, representing two treatments in one block with a flow of 7.5 liter sec^{-1}.

The irrigations were scheduled in sequence because they could not all be handled at the same time. The requirement that the initial soil moisture content be constant was satisfied in this schedule. The times of plowing and furrowing the land in each of the blocks were adjusted to the irrigation schedule.

4.2.2. *Second series of experiments*

The same furrows were used, but the experimental design was different from that of the first series. The replicates of one treatment were now in the same block; there were four replicates of treatments 1 and 2 and two of Treatment 3, comprising a total of ten furrows. The differences in initial soil moisture content were obtained by staggering the irrigations of each block after an intense rainfall which made the soil moisture content uniform in the field.

This approach which undoubtedly reduces the statistical reliability of the experiments was adopted because of the practical impossibility to obtain the same moisture content in the field in randomized replicates of the same treatment.

4.2.3. *Third series of experiments*

The furrows were arranged in the same way as in the first series with five replicates but with only three different treatments (9 furrows) in each block. For the variation in furrow length, the furrow outflow meter was set up at the points: 75.0 m, 137.5 m and 187.5 m in order to obtain the proposed effective distance between in- and outflow meters (Treatment 1: 62.5 m, Treatment 2: 125.0 m, Treatment 3: 175.0 m).

4.3. EXECUTION OF THE EXPERIMENTS

The trials and field determinations were made in the period from January to March 1970. During this time, furrow trials were performed with the variables that were previously mentioned. Also, some determinations were done of the physical characteristics of the soil and particularly of the soil-water relationships. These will be discussed in Chapter 5.

4.3.1 *First series of experiments*

The measurements in the furrows were taken during the first or advance period (x: increasing) and during the second irrigation stage (x: constant).

1. *Advance of the water front.* The time of arrival of the water front at each point in the central furrow was recorded on a form that was especially designed for this purpose. Of the buffer furrows only the time of intake and the time of arrival at the far end were recorded. The relevant data were processed for roughness conditions, which are listed in tables 1, 2 and 3.
2. *Stream flow section.* During the advance stage measurements regarding all the upstream cross-section at 12.5 m interval were carried out, every time the water front covered 50%, 78.5% and 100% of the effective furrow length. To this effect readings of the depth h and the top width T were taken (photograph Fig. 7). Simultaneously, water inflow size was measured at the intake Parshall flume.

The values of h and T were recorded on a especial form, on which also some calculations for the water balance were performed, i.e. inflow volume $V_i = Q\,t$,

TABLE 1. Water front advance time t in min for equal length increments x in m. Furrow condition: new, loose. First irrigation.

x m	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0	112.5	125.0	137.5	150.0	162.5	175.0	Block
Treatment 1	7	16	24	33	41	54	67	81	144						A
	14	23	33	46	60	73	91	107	128	143	164	184			B
	13	26	42	66	94	113	129	145[1]	177[1]	199	219				C
	6	15	20	26	37	49	59	70	80	93	102	113	122	133	D
	4	8	12	17	21	25	29	33	38	43	49	54	61	71	E
Total	44	88	131	188	253	314	375	436	568	534	534				
Average	9.9	17.6	26.2	37.6	50.6	62.8	75.0	87.2	113.6	119.5	134.0				
Treatment 2	5	11	16	24	33	41	51	63	73	84	95	114	126	139	A
	4	13	25	35	50	65	81	95	109	125	138	156	168	182	B
	7	12	17	25	36	46	54	61	70	80	90	108	117	131	C
	3	6	18	12	15	20	23	29	34	38	41	46	50	56	D
	3	5	8	10	13	15	18	22	24	27	31	35	39	43	E
Total	22	47	84	106	147	187	227	270	310	354	395	459	500	551	
Average	4.5	9.4	16.8	21.2	29.4	37.4	45.4	54.0	62.0	70.8	79.0	91.8	100.0	110.2	
Treatment 3	5	9	14	21	28	34	42	51	57	64	72	85	96	106	A
	9	11	16	19	22	27	32	39	42	49	57	65	71	77	B
	5	12	17	22	29	38	46	56	70	73	91	100	107	116	C
	3	6	8	10	13	15	18	21	24	28	31	36	39	43	D
	4	6	8	9	11	13	15	17	19	22	24	26	30	33	E
Total	26	44	63	81	103	127	153	184	212	236	275	312	343	375	
Average	5.2	8.8	12.6	16.2	20.6	25.4	30.6	36.8	42.4	47.2	55.0	62.0	68.6	75.0	
Treatment 4	3	5	7	10	14	17	21	25	28	32	37	44	49	56	A
															B[2]
	3	6	9	13	18	26	34	42	52	65	74	83	85	99	C
	3	5	7	9	12	15	18	20	23	26	30	33	36	38	D
	2	3	5	6	8	10	11	14	16	17	19	21	23	27	E
Total	11	19	28	38	52	68	84	101	119	140	160	181	193	220	
Average	2.7	4.7	7.0	9.5	13.0	17.0	21.0	25.2	29.7	35.0	40.0	45.2	48.2	55.0	

[1] By interpolation.
[2] No data available.

TABLE 2. Water front advance time *t* in min for equal length increments *x* in m. Furrow condition: re-used. Third irrigation.

x m	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0	112.5	125.0	137.5	150.0	162.0	175.0	Block
Treatment 1	7	15	21	29	37	43	50	56	60	66	78	90	97	112	A
	5	12	19	26	36	43	49	56	63	71	76	81	86	96	B
	5	9	13	16	22	29	33	40	46	50	68	74	79	83	C
	5	9	12	15	21	26	32	37	41	47	52	57	62	68	D
	4	9	12	19	25	30	34	36	40	44	49	55	62	76	E
Total	26	54	77	105	141	171	198	225	250	278	323	357	386	435	
Average	5.20	10.8	15.4	21.0	28.2	34.2	39.6	45.0	50.0	55.6	64.6	71.4	77.2	87.0	
Treatment 2	7	10	12	17	22	24	27	31	35	40	44	49	54	62	A
	6	10	14	18	24	29	35	41	47	52	59	68	77	84	B
	5	10	13	16	20	26	31	36	41	47	51	55	59	64	C
	2	4	6	9	13	17	20	23	27	30	33	36	40	47	D
	3	6	8	10	12	14	16	18	20	23	26	29	33	36	E
Total	23	40	53	70	91	110	129	149	170	192	213	237	263	293	
Average	4.6	8.0	10.6	14.0	18.2	22.0	25.8	29.8	34.0	38.4	42.6	47.4	52.6	58.6	
Treatment 3	5	8	11	17	22	27	32	35	38	43	48	56	61	70	A
	1	4	8	13	17	21	24	27	31	33	38	42	45	47	B
	4	7	10	13	17	23	29	33	39	45	50	55	58	63	C
	2	4	6	9	12	15	17	21	24	27	29	33	36	42	D
	2	5	6	8	11	14	16	19	21	24	27	31	35	42	E
Total	14	28	41	60	79	100	118	135	153	172	192	217	235	264	
Average	2.8	5.6	8.2	12.0	15.8	20.0	23.6	27.0	30.6	34.4	38.4	43.4	47.0	52.8	
Treatment 4	1	3	5	6	8	14	18	22	24	29	38	43	46	51	A
	2	5	9	13	17	21	25	27	29	32	37	40	43	46	B
	1	5	7	9	15	21	26	34	40	49	53	56	60	65	C
	3	4	7	9	14	18	21	24	28	32	36	38	42	56	D
	1	3	4	6	8	10	11	13	14	16	19	21	25	30	E
Total	8	20	32	43	62	84	101	120	135	158	183	198	216	248	
Average	1.6	4.0	6.4	8.6	12.4	16.8	20.2	24.0	27.0	31.6	36.6	39.6	43.2	49.6	

TABLE 3. Water front advance time *t* in min for equal length increments *x* in m. Furrow condition: re-used. Fourth irrigation.

x m	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0	112.5	125.0	137.5	150.0	162.5	175.0	Block
Treatment 1	10	16	20	27	32	40	46	50	54	60	70	78	84	90	A
	8	13	18	22	29	35	40	46	54	63	69	74	79	88	B
	4	8	13	17	21	25	29	33	45	47	57	66	70	74	C
	5	10	14	18	22	28	34	40	45	51	56	60	64	71	D
	5	10	15	21	29	35	40	45	50	57	63	72	83	95	E
Total	32	57	80	105	133	163	189	214	248	278	315	350	380	418	
Average	6.4	11.4	16.0	21.0	26.6	32.6	37.8	42.8	49.6	55.6	63.0	70.0	76.0	83.7	
Treatment 2	3	6	9	12	14	19	23	27	29	33	37	42	46	53	A
	5	8	12	16	20	25	30	34	39	44	50	54	57	62	B
	4	7	10	12	16	21	24	28	32	37	41	44	47	53	C
	4	6	9	12	16	21	25	30	33	38	41	46	50	58	D
	5	7	9	12	15	19	22	24	28	32	36	40	46	51	E
Total	21	34	49	64	81	105	124	143	161	184	205	226	246	277	
Average	4.2	6.8	9.8	12.8	16.2	21.0	24.8	28.6	32.3	36.8	41.0	45.1	49.2	55.4	
Treatment 3	2	5	8	13	17	20	24	27	30	34	38	44	48	60	A
	3	7	11	13	15	18	21	24	28	32	36	39	42	45	B
	3	6	8	11	14	18	22	28	32	37	40	43	45	53	C
	3	5	8	11	14	17	20	23	26	29	32	37	39	45	D
	3	5	7	9	13	16	19	22	25	28	32	35	39	43	E
Total	14	28	42	57	73	89	106	124	141	160	178	198	213	246	
Average	2.8	5.6	8.4	11.4	14.6	17.8	21.2	24.8	28.2	32.0	35.6	39.6	42.6	49.2	
Treatment 4	4	7	9	12	15	18	22	24	27	31	35	39	44	48	A
	3	6	8	10	13	16	19	21	23	26	30	32	35	37	B
	2	3	5	7	11	15	18	23	27	35	37	41	45	51	C
	2	4	7	10	14	18	21	24	28	31	35	38	48	54	D
	2	4	6	9	11	14	16	18	20	23	26	30	34	50	E
Total	13	24	35	48	64	81	96	110	125	146	163	180	206	240	
Average	2.6	4.8	7.0	9.6	12.8	16.2	19.2	22.0	25.0	29.2	32.6	36.0	41.2	48.0	

FIG. 7. Depth of water h and the width T taken with a tape measure.

surface volume V_s and resulting infiltration volume V_i. The average values of h and T for the third and fourth irrigations, are included in tables 4 and 5 respectively. The data obtained from the first irrigation were omitted because lack of consistency between replicates. The conditions under which the water front advanced during the first irrigation, caused a large and irregular variation of water volume in the furrow channel, making the measurements unreliable.

3. *Measurements during the second stage.* Simultaneous readings of inflow and outflow of the furrows once the water front reached the end of the furrow, were taken for the third irrigation for times of 15 min, 30 min, 60 min, 90 min, 120 min and 150 min after reaching the end of the furrows. Furthermore, h and T of the stream flow sections were measured during the third irrigation at 60 min and 120 min, and during the fourth irrigation at 60 min. The data were collected and calculations were done on a special form. The relevant data for third and fourth irrigations were processed and these are presented in tables 6 and 7.

4. *Additional measurements for the reduced inflow.* For the fourth irrigation reduction of inflow was applied at the times and according to the rates described in Section 4.1.1. As from the time of inflow reduction, readings were taken of the upstream furrowmeter at short time intervals, in order to record the decreasing inflow up to the moment that a constant value could be assumed. This variable inflow was a result of the decrease of water depth at the entrance section of the furrow, upstream of the meter. After recording inflow and out-

TABLE 4. Streamflow cross-section parameters h and T in cm, net infiltration areas A_{in} in m² and the terms of the balance equation in m³, for three water front advance stages. Third irrigation.

		$x = 87.5$ m						$x = 137.5$ m						$x = 175$ m					
		h	T	A_{in}	V_{in}	V_s	V_i	h	T	A_{in}	V_{in}	V_s	V_i	h	T	A_{in}	V_{in}	V_s	V_i
		cm	cm	m²	m³	m³	m³	cm	cm	m²	m³	m³	m³	cm	cm	m²	m³	m³	m³
Treatment 1	A	5.5	24.2	20.4	1.860	0.664	1.196	5.3	23.3	32.7	2.902	1.027	1.875	5.5	25.2	45.7	4.166	1.500	2.666
	B	6.8	26.0	22.7	1.823	0.883	0.940	5.6	24.6	34.6	2.827	1.147	1.680	5.1	24.2	43.6	3.571	1.335	2.236
	C	6.2	29.5	24.4	1.267	0.913	0.354	6.6	31.8	43.9	2.611	1.748	0.863	6.3	29.8	53.5	3.205	2.032	1.173
	D	5.5	24.0	20.3	1.190	0.659	0.531	5.6	23.2	33.0	2.006	1.081	0.925	5.8	24.2	44.8	2.659	1.519	1.140
	E	5.2	24.5	20.4	1.265	0.636	0.629	4.6	24.3	33.1	1.823	0.930	0.893	5.5	23.9	43.8	2.827	1.423	1.404
	Total	29.2	128.4	108.2	7.405	3.755	3.650	27.7	127.2	177.3	12.169	5.933	6.236	28.2	127.3	231.4	16.428	7.809	8.619
	Average	5.8	25.6	21.6	1.481	0.751	0.739	5.5	25.4	35.5	2.433	1.186	1.247	5.6	24.4	46.3	3.286	1.562	1.724
Treatment 2	A	5.3	24.7	20.6	1.460	0.654	0.806	5.3	23.7	33.1	2.480	1.045	1.435	5.2	23.8	42.9	3.452	1.332	2.120
	B	6.3	29.7	24.7	2.163	0.933	1.230	5.8	28.0	38.6	3.617	1.352	2.265	6.1	31.5	55.8	5.132	2.081	3.051
	C	5.7	28.4	23.3	1.841	0.808	1.033	5.7	28.5	39.0	3.029	1.352	1.677	5.7	27.6	49.5	3.910	1.703	2.207
	D	5.8	27.7	23.0	1.212	0.802	0.410	6.3	26.6	37.7	2.015	1.394	0.621	6.1	27.0	49.2	2.880	1.783	1.097
	E	4.3	25.0	20.2	0.960	0.537	0.423	4.7	24.9	33.8	1.560	0.974	0.586	5.8	25.6	46.8	2.160	1.607	0.553
	Total	27.4	135.5	111.8	7.636	3.734	3.902	27.8	131.7	182.2	12.701	6.117	6.584	28.9	135.5	244.2	17.534	8.506	9.028
	Average	5.5	27.1	22.4	1.527	0.747	0.780	5.6	26.3	36.4	2.540	1.223	1.317	5.8	27.1	48.8	3.507	1.701	1.806
Treatment 3	A	5.6	28.0	22.4	2.880	0.761	2.119	6.2	28.1	39.0	4.320	1.449	2.871	6.1	29.5	53.0	6.300	1.946	4.354
	B	6.0	28.2	23.4	2.160	0.845	1.315	6.5	30.9	42.8	3.420	1.672	1.748	6.3	29.3	53.0	4.230	1.997	2.233
	C	6.7	32.7	26.9	2.697	1.094	1.603	7.5	33.5	47.0	4.650	2.091	2.559	7.5	33.0	60.2	5.989	2.677	3.221
	D	5.5	26.9	22.2	1.377	0.738	0.639	6.0	26.8	37.5	2.524	1.339	1.185	6.6	27.0	50.0	3.772	1.928	1.844
	E	5.8	26.4	22.1	1.488	0.765	0.723	6.0	25.8	36.4	2.511	1.289	1.222	7.2	26.4	50.3	3.906	2.057	1.849
	Total	29.6	142.2	117.0	10.602	4.203	6.399	32.2	145.1	202.7	17.425	7.840	9.585	33.7	145.2	266.5	24.106	10.605	13.501
	Average	5.9	28.4	23.4	2.120	0.841	1.280	6.4	29.0	40.5	3.485	1.568	1.917	6.7	29.0	53.3	4.821	2.121	2.700
Treatment 4	A	6.3	28.3	23.8	2.160	0.890	1.270	7.0	28.6	40.8	4.560	1.666	2.894	6.8	30.6	55.6	6.159	2.252	3.907
	B	7.7	34.3	28.9	3.000	1.319	1.681	7.9	31.7	45.5	4.476	2.084	2.392	7.5	31.6	58.3	5.583	2.564	3.019
	C	6.5	31.7	26.2	3.120	1.029	2.091	7.0	33.9	46.7	6.360	1.974	4.386	7.3	33.3	60.3	7.800	2.630	5.170
	D	5.3	29.8	24.1	2.394	0.789	1.605	6.2	28.4	39.6	4.239	1.466	2.773	6.6	29.4	53.6	6.699	2.100	4.599
	E	5.5	29.8	24.2	1.320	0.819	0.501	6.6	29.4	41.3	2.280	1.615	0.665	7.0	30.9	56.5	3.600	2.341	1.259
	Total	31.3	153.9	127.2	11.994	4.846	7.148	34.7	152.0	213.9	21.915	8.805	13.110	35.2	155.8	284.3	29.841	11.887	17.954
	Average	6.3	30.8	25.4	2.399	0.969	1.430	6.9	30.4	42.8	4.383	1.761	2.622	7.0	31.2	56.9	5.968	2.377	3.591

TABLE 5 Streamflow cross-section parameters h and T in cm, net infiltration area A_{in} in m² and terms of the balance equation in m³, for three water front advance stages. Fourth irrigation.

		$x = 87.5$ m						$x = 137.5$ m						$x = 175$ m					
		h	T	A_{in}	V_{in}	V_s	V_t	h	T	A_{in}	V_{in}	V_s	V_t	h	T	A_{in}	V_{in}	V_s	V_t
		cm	cm	m²	m³	m³	m³	cm	cm	m²	m³	m³	m³	cm	cm	m²	m³	m³	m³
Treatment 1	A	7.2	22.7	20.8	1.765	0.816	0.950	6.2	23.0	33.6	2.688	1.187	1.501	6.5	24.4	46.3	3.456	1.716	1.740
	B	5.8	25.7	21.6	1.440	0.744	0.696	5.7	22.7	32.6	2.484	1.077	1.407	5.5	22.8	42.2	3.168	1.357	1.811
	C	4.8	26.5	21.5	1.044	0.635	0.409	5.2	26.3	36.0	2.086	1.138	0.948	5.1	25.6	45.6	2.718	1.413	1.305
	D	4.8	23.7	19.5	1.224	0.568	0.656	4.8	23.8	32.7	2.016	0.947	1.069	4.7	22.8	40.8	2.556	1.160	1.396
	E	5.5	25.0	20.9	1.440	0.687	0.753	4.9	24.4	33.5	2.268	0.995	1.273	5.2	23.4	42.5	3.420	1.317	2.103
Total		28.1	123.6	104.3	6.913	3.450	3.464	26.8	120.2	168.4	11.542	5.344	6.198	27.0	119.0	217.4	15.318	6.963	8.355
Average		5.6	24.7	20.9	1.383	0.690	0.693	5.4	24.0	33.7	2.308	1.069	1.240	5.4	23.8	43.5	3.064	1.393	1.671
Treatment 2	A	5.5	26.6	22.0	1.325	0.731	0.594	5.9	26.0	36.6	2.131	1.277	0.854	5.6	25.2	45.8	3.053	1.530	1.523
	B	4.8	27.3	22.0	1.692	0.654	1.038	4.8	26.8	26.2	3.150	1.071	2.079	5.5	27.3	48.8	3.906	1.625	2.281
	C	5.3	29.4	23.8	1.411	0.778	0.633	5.9	28.6	39.4	2.431	1.405	1.026	5.5	27.7	49.3	3.151	1.649	1.502
	D	5.8	28.5	23.5	1.410	0.826	0.584	5.6	27.3	37.6	2.293	1.273	1.020	5.8	26.9	48.6	3.231	1.688	1.543
	E	4.3	26.4	21.1	1.320	0.567	0.753	5.2	26.1	35.8	2.160	1.130	1.030	5.3	24.8	44.8	3.060	1.422	1.638
Total		25.7	138.2	112.4	7.158	3.556	3.602	27.4	134.8	185.6	12.165	6.156	6.009	27.7	131.9	237.3	16.401	7.914	8.487
Average		5.1	27.6	22.5	1.432	0.711	0.720	5.5	27.0	37.1	2.433	1.231	1.202	5.5	26.4	47.5	3.280	1.583	1.697
Treatment 3	A	6.5	29.9	25.0	2.232	0.971	1.261	7.0	30.2	42.6	3.534	1.760	1.774	4.8	26.5	46.5	4.502	1.377	3.125
	B	6.0	29.8	24.5	1.827	0.893	0.934	5.4	29.1	39.4	3.177	1.308	1.869	4.1	26.3	45.3	3.712	1.167	2.545
	C	6.2	34.2	27.7	2.046	1.059	0.987	7.0	34.5	47.4	3.720	2.010	1.710	6.1	29.2	52.4	4.549	1.928	2.621
	D	5.7	29.4	24.1	1.860	0.837	1.023	5.5	27.9	38.2	2.976	1.277	1.699	4.9	24.7	44.0	3.546	1.310	2.236
	E	6.2	29.7	24.6	1.710	0.920	0.790	6.2	29.3	40.6	2.880	1.512	1.368	4.8	27.2	47.7	3.483	1.413	1.870
Total		30.6	153.0	125.9	9.675	4.680	4.995	31.1	151.0	208.2	16.287	7.867	8.420	24.7	133.9	235.9	19.792	7.195	12.397
Average		6.1	30.6	25.2	1.935	0.936	0.999	6.2	30.2	41.6	3.257	1.573	1.684	4.9	26.8	47.2	3.958	1.439	2.479
Treatment 4	A	7.8	30.9	26.6	2.640	1.204	1.436	6.8	30.4	42.6	4.200	1.721	2.479	5.5	28.0	49.8	5.028	1.667	3.361
	B	7.3	31.8	26.9	2.280	1.159	1.121	7.4	30.8	43.9	3.600	1.897	1.703	5.9	26.4	48.0	3.982	1.686	2.296
	C	6.0	32.0	26.1	2.160	0.959	1.201	6.3	32.7	44.6	4.440	1.715	2.725	4.7	28.2	49.0	5.240	1.434	3.806
	D	5.8	33.0	26.6	2.520	0.956	1.564	5.8	31.5	42.7	4.200	1.521	2.679	4.3	26.9	46.5	5.196	1.252	3.944
	E	5.8	33.2	26.8	1.920	0.962	0.958	5.8	31.8	43.0	3.120	1.535	1.585	4.8	29.5	51.1	4.272	1.533	2.739
Total		32.7	160.9	133.0	11.520	5.240	6.280	32.1	157.2	216.8	19.560	8.389	11.171	25.2	139.0	244.4	23.718	7.572	16.146
Average		6.5	32.2	26.6	2.304	1.048	1.256	6.4	31.4	43.4	3.912	1.678	2.234	5.0	27.8	48.9	4.744	1.514	3.229

TABLE 6. Streamflow cross-section a_f in cm², net infiltration area A_{in} in m², and water volume in the furrow V_s in m³, at times t_1 = 60 min and t_2 = 120 min of the second stage. Third irrigation.

		Time																	
		60 min						120 min						Average					
		h	T	a_f	P	A_{in}	V_s	h	T	a_f	P	A_{in}	V_s	h	T	a_f	P	A_{in}	V_s
		cm	cm	cm²	cm	m²	m³	cm	cm	cm²	cm	m²	m³	cm	cm	cm²	cm	m²	m³
Treatment 1	A	5.5	24.7	90.5	27.6	48.3	1.583	5.4	25.2	90.6	28.0	49.0	1.585	5.4	25.0	89.9	27.8	48.6	1.573
	B	4.9	24.0	78.3	26.5	46.4	1.370	5.0	25.8	86.0	28.2	49.3	1.505	4.9	24.9	81.2	27.3	47.8	1.421
	C	6.1	30.2	122.7	33.2	58.1	2.147	6.4	29.8	127.0	33.1	57.9	2.222	6.3	30.0	125.9	33.2	58.1	2.203
	D	5.8	23.6	91.2	26.9	47.1	1.596	5.9	24.8	97.4	28.2	49.3	1.704	5.8	24.2	93.5	27.6	48.3	1.636
	E	6.5	26.0	112.5	29.8	52.1	1.968	5.2	26.1	90.4	28.6	50.0	1.582	5.9	26.0	102.2	29.2	51.1	1.788
Total		28.8	128.5	495.2	144.0	252.0	8.664	27.9	131.7	491.4	146.1	255.5	8.598	28.3	130.1	492.7	145.1	253.9	8.621
Average		5.8	25.7	99.0	28.8	50.4	1.733	5.6	26.3	98.3	29.2	51.1	1.720	5.7	26.0	98.5	29.0	50.8	1.724
Treatment 2	A	5.9	28.0	110.0	31.0	54.2	1.925	6.0	27.7	110.7	30.9	54.1	1.937	6.0	27.9	111.5	31.0	54.2	1.951
	B	6.0	31.1	124.3	33.9	59.3	2.175	6.1	30.0	121.9	33.0	57.7	2.133	6.0	30.6	122.2	33.5	58.6	2.138
	C	6.3	29.2	122.5	32.5	56.9	2.144	6.7	30.2	134.7	33.8	59.1	2.357	6.5	29.7	128.6	33.1	57.9	2.250
	D	6.9	27.4	125.9	31.5	55.1	2.203	7.2	28.2	135.2	32.5	56.9	2.366	7.1	27.8	131.4	32.1	56.2	2.299
	E	6.6	27.5	120.9	31.3	54.8	2.116	6.7	27.7	123.6	31.6	55.3	2.163	6.6	27.6	121.3	31.5	55.1	2.123
Total		31.7	143.2	603.6	160.2	280.3	10.563	32.7	143.8	626.1	161.8	283.1	10.956	32.2	143.6	615.0	161.2	282.0	10.761
Average		6.3	28.6	120.7	32.0	56.1	2.113	6.5	28.8	125.2	32.4	56.6	2.191	6.4	28.7	123.0	32.2	56.4	2.152
Treatment 3	A	6.4	29.6	126.1	33.0	57.7	2.156	5.9	29.3	115.1	32.7	57.2	2.003	6.1	29.5	119.8	32.6	57.0	2.096
	B	6.5	30.0	129.9	33.4	58.4	2.273	6.2	31.6	130.5	34.5	60.4	2.284	6.4	30.8	131.3	34.0	59.5	2.298
	C	7.5	33.7	168.3	37.7	66.0	2.945	7.5	33.6	167.8	37.6	65.8	2.936	7.5	33.6	167.8	37.6	65.8	2.936
	D	7.2	28.2	135.2	32.5	56.9	2.366	7.3	28.6	139.0	33.0	57.7	2.432	7.3	28.4	138.1	32.9	57.6	2.417
	E	8.2	29.2	159.4	34.5	60.4	2.789	8.2	29.1	158.9	34.4	60.2	2.780	8.2	29.2	159.4	34.5	60.4	2.789
Total		35.8	150.7	718.8	171.1	299.4	12.529	35.1	152.2	711.3	172.2	301.3	12.435	35.5	151.5	716.4	171.6	300.3	12.536
Average		7.2	30.1	143.8	34.2	59.9	2.506	7.0	30.4	142.3	34.4	60.3	2.487	7.1	30.3	143.3	34.3	60.1	2.507
Treatment 4	A	7.2	32.4	155.4	36.2	63.3	2.719	6.9	32.2	148.0	35.8	62.6	2.590	7.1	32.3	152.7	36.0	63.0	2.672
	B	6.5	32.0	138.5	35.2	61.6	2.423	6.5	31.7	137.2	34.9	61.1	2.401	6.5	31.9	138.1	35.1	61.4	2.417
	C	7.5	33.3	166.3	37.3	65.3	2.910	7.4	34.2	168.5	38.0	66.5	2.949	7.5	33.8	168.8	37.8	66.0	2.954
	D	6.8	31.1	140.8	34.7	60.7	2.464	6.9	31.7	145.7	35.3	61.8	2.550	6.9	31.4	144.3	35.0	61.2	2.525
	E	8.0	32.9	175.3	37.5	65.6	3.068	8.5	34.1	193.0	38.8	68.0	3.377	8.2	33.5	182.9	38.4	67.2	3.201
Total		36.0	161.7	776.3	180.9	316.5	13.584	36.2	163.9	792.4	182.8	320.0	13.867	36.2	163.9	786.8	182.3	318.8	13.769
Average		7.2	32.3	155.3	36.2	63.3	2.717	7.2	32.8	158.5	36.6	64.0	2.773	7.2	32.8	157.4	36.5	63.8	2.745

TABLE 7. Streamflow cross-section a_f in cm^2, net infiltration area A_{in} in m^2, and water volume in the furrow V_s in m^3, at time t_2 = 60 min of the second stage. Fourth irrigation ..

	h	T	a_f	P	A_{in}	V_s
	cm	cm	cm^2	cm	m^2	m^3
Treatment 1						
A	4.7	19.1	59.8	21.8	38.1	1.046
B	2.7	16.4	29.5	17.5	30.6	0.516
C	3.4	20.9	47.3	22.3	39.0	0.828
D	3.2	16.8	35.8	18.3	32.0	0.626
E	3.8	20.1	50.9	21.9	38.2	0.891
Total	17.8	93.3	223.3	119.3	177.9	3.907
Average	3.6	18.7	44.7	23.9	35.6	0.781
Treatment 2						
A	3.3	20.9	46.1	22.2	38.8	0.807
B	4.1	22.1	60.3	24.0	42.0	1.055
C	3.8	21.5	54.4	23.2	40.6	0.952
D	4.3	23.1	66.1	25.0	43.7	1.157
E	4.1	22.3	60.9	24.1	42.2	1.066
Total	19.6	109.9	287.8	118.5	207.3	5.037
Average	3.9	22.0	57.6	23.7	41.5	1.007
Treatment 3						
A	4.8	28.0	89.5	30.0	52.5	1.566
B	4.1	25.4	69.3	27.0	47.2	1.213
C[1]	6.0	29.2	116.7	32.2	56.3	2.042
D	5.0	25.2	83.9	27.6	48.3	1.468
E	5.2	28.6	99.0	30.9	54.1	1.732
Total	25.1	136.4	458.4	147.7	258.4	8.021
Average	5.0	27.3	91.7	29.5	51.7	1.604
Treatment 4						
A	5.8	28.4	109.7	31.3	54.8	1.920
B	5.6	26.7	99.6	29.5	51.6	1.743
C	4.8	27.8	88.9	29.8	52.1	1.556
D	5.1	27.5	93.4	29.8	52.1	1.634
E	5.3	32.2	113.6	34.4	60.2	1.988
Total	26.6	142.6	505.2	154.8	270.8	8.841
Qverage	5.3	28.5	101.0	31.0	54.2	1.768

[1] At 90 min instead of 60 min.

TABLE 8. Furrow inflow and outflow rates in liter sec^{-1} and furrow inflow and outflow volumes in m^3, as a function of the time t_2 of the second stage. Treatment 1, fourth irrigation.

Block		Time of the reduced inflow													Time of the cutt off flow						Over
	t min	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	flow time
A	Q	0.654	0.440	0.300	0.220	0.175	0.155	0.138	0.138	0.138	0.138	0.138	0.138	0.138							
	Q_{out}	0	0.323	0.366	0.352	0.267	0.170	0.148	0.118	0.074	0.066	0.058	0.058	0.058	0.066	0.066	0.066	0.038	0.026	0.012	
	V_{in}				0.353			0.505			0.630			0.754							
	V_{out}				0.259			0.465			0.555			0.610			0.665			0.696	
	V_s	1.716												1.046							
B	Q	0.617	0.330	0.230	0.181	0.155	0.145	0.138	0.138	0.138	0.138	0.138	0.138	0.138							
	Q_{out}	0	0.323	0.352	0.366	0.267	0.170	0.128	0.099	0.082	0.066	0.051	0.038	0.038	0.038	0.038	0.038	0.032	0.032	0.021	
	V_{in}				0.287			0.425			0.549			0.673							
	V_{out}				0.257			0.462			0.545			0.587			0.621			0.649	0.652
	V_s	1.357												0.516							
C	Q	0.635	0.380	0.250	0.193	0.159	0.159	0.159	0.159	0.159	0.159	0.159	0.159	0.159							
	Q_{out}	0	0.295	0.382	0.352	0.281	0.204	0.148	0.108	0.090	0.074	0.066	0.058	0.058	0.066	0.066	0.066	0.058	0.032	0.026	
	V_{in}				0.313			0.461			0.604			0.747							
	V_{out}				0.256			0.476			0.568			0.625			0.684			0.724	0.732
	V_s	1.413												0.828							
D	Q	0.167	0.305	0.210	0.175	0.159	0.159	0.159	0.159	0.159	0.159	0.159	0.159	0.153							
	Q_{out}	0	0.267	0.323	0.308	0.242	0.159	0.118	0.099	0.074	0.058	0.058	0.051	0.051	0.058	0.058	0.058	0.051	0.032	0.026	
	V_{in}				0.273			0.418			0.562			0.704							
	V_{out}				0.223			0.407			0.485			0.534			0.585			0.622	0.630
	V_s	1.160												0.626							
E	Q	0.617	0.170	0.163	0.156	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148							
	Q_{out}	0	0.204	0.242	0.254	0.229	0.170	0.090	0.074	0.082	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.051	0.038	
	V_{in}				0.215			0.350			0.483			0.616							
	V_{out}				0.172			0.343			0.414			0.481			0.547			0.601	0.610
	V_s	1.317												0.891							

flow during one hour the supply siphon was taken out, thereafter, the recorded outflow of the remaining surface water storage.

A special form was also used to record the effects of the reduced inflow. The relevant data were processed and summarized in tables 8, 9, 10 and 11, one for each treatment divided in two time periods: reduced inflow and cut-off flow.

4.3.2. *Second series of experiments*

Only the inflow and the outflow were measured after the end of the run had been reached. These simultaneous measurements were taken at first at intervals of 5 min and finally of 30 min during a total period of 150 min. A special form to record only the inflow and outflow data measured at the corresponding furrow meters was not used. The values of the recorded infiltrated flow are summarized in Table 12.

4.3.3. *Third series of experiments*

As in the second series of experiments, simultaneous readings of inflow and outflow were taken after the end of the run had been reached, at time intervals of 5 min to 30 min during a total period of 120 min. The infiltrated flow data are presented in Table 13.

Table 9. Furrow inflow and outflow rate in liter sec^{-1} and furrow inflow and outflow volumes in m^3, as a function of the time t_2 of the second stage. Treatment 2, fourth irrigation.

	Time of the reduced inflow									
Block	t min	0	5	10	15	20	25	30	35	40
A	Q	0.980	0.575	0.390	0.310	0.281	0.281	0.281	0.281	0.281
	Q_{out}	0	0.444	0.545	0.528	0.444	0.352	0.281	0.229	0.217
	V_{in}				0.483			0.740		
	V_{out}				0.376			0.736		
	V_s	1.530								
B	Q	1.047	0.525	0.370	0.300	0.275	0.270	0.267	0.267	0.267
	Q_{out}	0	0.337	0.477	0.460	0.366	0.281	0.217	0.159	0.138
	V_{in}				0.257			0.505		
	V_{out}				0.313			0.608		
	V_s	1.625								
C	Q	1.024	0.425	0.315	0.290	0.285	0.281	0.281	0.281	0.281
	Q_{out}	0	0.323	0.477	0.477	0.382	0.308	0.242	0.193	0.170
	V_{in}				0.419			0.674		
	V_{out}				0.311			0.626		
	V_s	1.649								
D	Q	0.937	0.410	0.315	0.295	0.295	0.295	0.295	0.295	0.295
	Q_{out}	0	0.413	0.494	0.397	0.323	0.254	0.204	0.159	0.148
	V_{in}				0.402			0.667		
	V_{out}				0.331			0.594		
	V_s	1.688								
E	Q	1.024	0.510	0.370	0.295	0.295	0.295	0.295	0.295	0.295
	Q_{out}	0	0.308	0.428	0.428	0.323	0.295	0.242	0.229	0.204
	V_{in}				0.462			0.727		
	V_{out}				0.285			0.571		
	V_s	1.422								

						Time of the cut off flow				Over flow time
45	50	55	60	65	70	75	80	85	90	
0.281	0.281	0.281	0.281							
0.204	0.204	0.204	0.204	0.204	0.193	0.193	0.148	0.099	0.066	
0.993			1.245							
0.942			1.126			1.304			1.417	1.450
			0.807							
0.267	0.267	0.267	0.260							
0.138	0.138	0.138	0.148	0.138	0.128	0.108	0.082	0.044	0.026	
0.745			0.984							
0.751			0.876			0.994			1.052	1.058
			1.055							
0.281	0.281	0.281	0.281							
0.170	0.159	0.159	0.159	0.159	0.159	0.148	0.108	0.074	0.038	
0.927			1.264							
0.796			0.941			1.082			1.165	1.174
			0.952							
0.295	0.295	0.295	0.288							
0.148	0.148	0.148	0.148	0.170	0.159	0.148	0.099	0.082	0.032	
0.933			1.197							
0.739			0.872			1.015			1.096	1.099
			1.157							
0.295	0.295	0.295	0.295							
0.204	0.204	0.204	0.229	0.229	0.229	0.204	0.138	0.074	0.044	
0.993			1.258							
0.767			0.954			1.156			1.272	1.294
			1.066							

TABLE 10. Furrow inflow and outflow rate in liter sec^{-1} and furrow inflow and outflow volumes in m^3, as a function of the time t_2 of the second stage. Treatment 3, fourth irrigation.

Block		Time of the reduced inflow										
	t min	0	5	10	15	20	25	30	35	40	45	50
A	Q	0.591	0.591	0.591	0.591	0.591	0.591	0.591	0.591	0.591	0.591	0.591
	Q_{out}	0	0.108	0.148	0.181	0.267	0.366	0.444	0.477	0.477	0.511	0.528
	V_{in}				0.532			1.064			1.596	
	V_{out}				0.104			0.387			0.817	
	V_s	1.377										
B	Q	0.564	0.564	0.564	0.564	0.564	0.564	0.564	0.564	0.564	0.564	0.564
	Q_{out}	0	0.337	0.494	0.444	0.366	0.337	0.323	0.323	0.337	0.337	0.352
	V_{in}				0.508			1.015			1.523	
	V_{out}				0.316			0.641			0.938	
	V_s	1.167										
C	Q_{in}	0.591	0.591	0.591	0.591	0.591	0.591	0.591	0.591	0.591	0.591	0.591
	Q_{out}	0	0.323	0.413	0.460	0.460	0.444	0.460[1]	0.511[1]	0.511[1]	0.511[1]	0.511[1]
	V_{in}				0.532			1.064			1.596	
	V_{out}				0.289			0.699			1.151	
	V_s	1.928										
D	Q	0.591	0.591	0.591	0.591	0.591	0.591	0.591	0.591	0.591	0.591	0.591
	Q_{out}	0	0.281	0.337	0.382	0.428	0.428	0.444	0.477	0.494	0.511	0.511
	V_{in}				0.539			1.064			1.596	
	V_{out}				0.242			0.623			1.057	
	V_s	1.310										
E	Q	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620
	Q_{out}	0	0.170	0.267	0.295	0.308	0.337	0.366	0.413	0.428	0.444	0.477
	V_{in}				0.558			1.116			1.674	
	V_{out}				0.175			0.467			0.841	
	V_s	1.413										

[1] By interpolation or extrapolation.

Time of the cut off flow											Over flow time
55	60	65	70	75	80	85	90	95	100	105	
0.591	0.591										
0.528	0.528	0.528	0.528	0.444	0.308	0.204	0.118	0.074	0.058	0.032	
	2.128										
	1.289			1.752			1.990			2.052	2.071
	1.566										
0.564	0.564										
0.366	0.382	0.397	0.397	0.413	0.352	0.229	0.128	0.074	0.058	0.026	
	2.030										
	1.261			1.618			1.873			1.936	1.942
	1.213										
0.591	0.591										
0.511[1]	0.511[1]	0.528	0.511	0.397	0.254	0.138	0.074	0.058	0.045[1]	0.035[1]	
	2.128										
	1.611			2.058			2.246			2.293	2.310
	2.042										
0.591	0.591										
0.528	0.528	0.528	0.528	0.366	0.217	0.118	0.058	0.038	0.032	0.026	
	2.128										
	1.524			1.975			2.139			2.173	2.181
	1.468										
0.620	0.620										
0.494	0.511	0.528	0.528	0.477	0.352	0.229	0.159	0.090	0.051	0.038	
	2.232										
	1.275			1.740			2.009			2.080	2.104
	1.732										

TABLE 11. Furrow inflow and outflow rates in liter sec^{-1} and furrow inflow and outflow volumes in m^3, as a function of the time t_2 of the second stage. Treatment 4, fourth irrigation.

Block	Time of the reduced inflow											
	t min	0	5	10	15	20	25	30	35	40	45	50
A	Q	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675
	Q_{out}	0	0.382	0.337	0.337	0.337	0.352	0.366	0.413	0.428	0.428	0.444
	V_{in}				0.607			1.215			1.822	
	V_{out}				0.266			0.578			0.949	
	V_s	1.667										
B	Q	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675	0.675
	Q_{out}	0	0.673	0.673	0.610	0.570	0.550	0.545	0.562	0.580	0.580	0.580
	V_{in}				0.607			1.215			1.822	
	V_{out}				0.495			0.998			1.510	
	V_s	1.686										
C	Q	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620
	Q_{out}	0	0.352	0.413	0.444	0.460	0.477	0.494	0.528	0.528	0.528	0.545
	V_{in}				0.558			1.116			1.674	
	V_{out}				0.296			0.717			1.187	
	V_s	1.434										
D	Q	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620
	Q_{out}	0	0.229	0.281	0.323	0.366	0.382	0.397	0.413	0.413	0.428	0.444
	V_{in}				0.558			1.116			1.674	
	V_{out}				0.201			0.553			0.905	
	V_s	1.252										
E	Q	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620	0.620
	Q_{out}	0	0.217	0.281	0.337	0.397	0.444	0.477	0.494	0.528	0.528	0.545
	V_{in}				0.558			1.116			1.674	
	V_{out}				0.200			0.574			1.031	
	V_s	1.533										

[1] By extrapolation.

		Time of the cut off flow									Over flow time
55	60	65	70	75	80	85	90	95	100	105	
0.675	0.675										
0.444	0.477	0.477	0.444	0.295	0.204	0.074	0.030[1]	0.015[1]			
	2.430										
	1.351			1.743			1.875			1.882	1.882
	1.920										
0.675	0.675										
0.580	0.580	0.580	0.562	0.444	0.281	0.159	0.099	0.058	0.032	0.026	
	2.430										
	2.032			2.528			2.741			2.787	2.793
	1.743										
0.620	0.620										
0.562	0.562	0.562	0.460	0.366	0.217	0.118	0.058	0.038	0.026	0.021	
	2.232										
	1.683			2.128			2.292			2.323	2.328
	1.556										
0.620	0.620										
0.444	0.444	0.460	0.444	0.366	0.229	0.138	0.074	0.032	0.012		
	2.232										
	1.302			1.695			1.870			1.892	1.892
	1.634										
0.620	0.620										
0.545	0.562	0.580	0.580	0.477	0.413	0.295	0.204	0.159	0.118	0.082	
	2.232										
	1.521			2.025			2.339			2.465	2.521
	1.988										

TABLE 12. Furrow infiltration rate Q_i in liter sec^{-1} as a function of time of the second stage t_2 in min, for different initial soil moisture contents. Furrow condition: re-used. Second irrigation.

		Time t min												
	Replicate	5	10	15	20	25	30	45	60	75	90	120	150	Wetting time T_1 min
Treatment 1	1	0.380	0.340	0.300	0.270	0.252	0.240	0.214	0.202	0.200	0.198	0.194	0.190	85
	2	0.370	0.330	0.300	0.260	0.224	0.200	0.148	0.128	0.120	0.116	0.110	0.102	153
	3	0.380	0.340	0.300	0.270	0.246	0.224	0.180	0.154	0.142	0.136	0.130	0.122	155
	4	0.480[1]	0.444[1]	0.410	0.380	0.340	0.302	0.244	0.218	0.204	0.200	0.200	0.200	133
	Total	1.610	1.454	1.310	1.180	1.062	0.966	0.786	0.702	0.666	0.650	0.634	0.614	526
	Average	0.402	0.363	0.327	0.295	0.265	0.241	0.196	0.175	0.166	0.162	0.158	0.153	131
	$\bar{I}$ mm hr^{-1}	11.81	10.67	9.61	8.67	7.79	7.08	5.76	5.14	4.88	4.76	4.64	4.50	
Treatment 2	1	0.300	0.264	0.240	0.222	0.208	0.196	0.176	0.164	0.158	0.152	0.150	0.150	125
	2	0.302	0.284	0.266	0.250	0.232	0.214	0.166	0.140	0.124	0.120	0.120	0.120	130
	3	0.270	0.240	0.210	0.182	0.150	0.120	0.082	0.070	0.070	0.070	0.070	0.070	114
	4	0.328	0.300	0.278	0.256	0.234	0.220	0.180	0.154	0.134	0.122	0.112	0.100	103
	Total	1.200	1.088	0.994	0.910	0.824	0.750	0.604	0.528	0.486	0.464	0.452	0.440	472
	Average	0.300	0.272	0.248	0.227	0.206	0.187	0.151	0.132	0.122	0.116	0.113	0.110	118
	$\bar{I}$ mm hr^{-1}	8.82	7.99	7.29	6.67	6.05	5.49	4.44	3.88	3.58	3.41	3.32	3.23	
Treatment 3	1	0.240	0.220	0.200	0.180	0.160	0.142	0.104	0.088	0.080	0.080	0.076	0.074	57
	2	0.230	0.216	0.200	0.188	0.174	0.162	0.136	0.118	0.106	0.100	0.100	0.100	49
	Total	0.470	0.436	0.400	0.368	0.334	0.304	0.240	0.206	0.186	0.180	0.176	0.174	106
	Average	0.235	0.218	0.200	0.184	0.167	0.152	0.120	0.103	0.093	0.090	0.088	0.087	53
	$\bar{I}$ mm hr^{-1}	6.91	6.41	5.88	5.41	4.91	4.47	3.53	3.03	2.73	2.64	2.59	2.56	

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[1] By extrapolation.

TABLE 13. Furrow infiltration rate Q_i in liter sec^{-1} as a function of time of the second stage t_2 in min, for different furrow lengths. Furrow condition: re-used. Fifth irrigation.

	Block	Time t min											Wetting time T^1 min
		5	10	15	20	25	30	45	60	75	90	120	
Treatment 1	A	0.486	0.381	0.303	0.229	0.177	0.146	0.093	0.071	0.072	0.041	0.041	31
$L = 62.5$ m	B	0.464	0.333	0.218	0.166	0.113	0.082	0.019	0.019	0.009	0.009	0.009	30
	C	0.476	0.371	0.271	0.230	0.156	0.156	0.124	0.103	0.093	0.093	0.093	30
	D	0.465	0.329	0.240	0.177	0.146	0.114	0.072	0.057	0.041	0.041	0.041	24
	E	0.411	0.319	0.217	0.165	0.154	0.123	0.083	0.062	0.052	0.052	0.052	30
	Total	2.302	1.733	1.249	0.967	0.746	0.621	0.391	0.313	0.267	0.236	0.236	145
	Average	0.460	0.346	0.249	0.193	0.149	0.124	0.078	0.062	0.053	0.047	0.047	29
	$\bar{I}$ mm hr^{-1}	37.8	28.5	20.5	15.9	12.3	10.2	6.4	5.1	4.4	3.9	3.9	
Treatment 2	A	0.455	0.300	0.210	0.160	0.150	0.115	0.080	0.060	0.050	0.050	0.030	59
$L = 125{,}0$	B	0.475	0.375	0.310	0.240	0.200	0.160	0.130	0.100	0.080	0.080	0.080	64
	C	0.502	0.445	0.375	0.340	0.310[1]	0.270[1]	0.180	0.120	0.100	0.100	0.100	59
	D	0.425	0.330	0.275	0.230	0.190	0.170	0.140	0.120	0.090	0.090	0.090	51
	E	0.310[1]	0.270	0.230	0.180	0.160	0.150	0.100	0.080	0.080	0.080	0.070	50
	Total	2.167	1.720	1.400	1.150	1.010	0.865	0.630	0.480	0.400	0.400	0.370	283
	Average	0.433	0.344	0.280	0.230	0.202	0.173	0.126	0.096	0.080	0.080	0.074	56
	$\bar{I}$ mm hr^{-1}	17.8	14.2	11.5	9.5	8.3	7.1	5.2	3.9	3.3	3.3	3.0	
Treatment 3	A	0.380	0.275	0.230	0.190	0.150	0.140	0.115	0.090	0.070	0.060	0.040	108
$L = 175{,}0$ m	B	0.365	0.255	0.210	0.160	0.160	0.150	0.100	0.100	0.080	0.070	0.070	75
	C	0.300	0.230	0.180	0.160	0.130	0.120	0.100	0.100	0.080	0.080	0.080	93
	D	0.340	0.255	0.180	0.160	0.150	0.130	0.120	0.100	0.080	0.080	0.080	74
	E	0.475	0.375	0.325	0.270	0.240	0.210	0.160	0.150	0.130	0.100	0.100	78
	Total	1.860	1.390	1.125	0.940	0.830	0.750	0.595	0.540	0.440	0.390	0.370	428
	Average	0.372	0.278	0.225	0.188	0.166	0.150	0.119	0.108	0.088	0.078	0.074	85
	$\bar{I}$ mm hr^{-1}	10.9	8.2	6.6	5.5	4.9	4.4	3.5	3.2	2.6	2.3	2.2	

[1] By interpolation or extrapolation.

5. ASSOCIATED STUDIES

This section includes a discussion of the determinations which were necessary to evaluate soil and water properties affecting infiltration. It also covers a description of the calibration of the furrow meter used during the experiments.

5.1. SOIL DESCRIPTION

The soils of the Cojedes-Sarare Irrigation Project were developed from parent material that had been moved and redeposited by water as a consequence of the activity of the Cojedes and Sarare rivers. Geomorphological and vegetative characteristics as factors affecting soil formation have been the cause of some general differentiation in soil profiles. The resulting soils can be distinguished as follows: (i) soils formed under forest vegetation (Algodonal series, Ague Blanca series and Vegas series); (ii) soils formed under savanna vegetation (Gomeras series, Gil series, and San Rafael series).

The climate of the area, Tropical Savanna (*Aw*) according to the Köppen-classification, is characterized by a wet season with water surplus from June to October and a dry season with water deficit from January to April. The average yearly precipitation for Morena station, Cojedes State (Fig. 8), is 1,542 mm and the yearly potential evapotranspiration, estimated as 80% of class A standard US Weather Bureau pan evaporation 1,498 mm. For this station the water balance of the soil as determined by the climate showed a water deficit of 504 mm from January to April (GRASSI, 1968).

A detailed soil survey was made by the Western Soil Bureau of the Venezuelan Ministry of Public Works (1969) on an area of 12,588 hectares of the Project. According to this study, the Algodonal series and the Agua Blanca series form the typical agricultural soils which may be used for a great variety of orchard and field crops. Their classification is Vertic Hapludent in the US Department of Agriculture 7th Approximation (1960).

The chemical characteristics of the Algodonal series can be summarized as follows: high organic matter content; mildly alkaline reaction; medium exchange capacity; high base saturation. There is no accumulation of soluble salts nor of sodium.

A special soil survey of the experimental field conducted by ARISMENDI (1967) was also available which helped to locate and design the experiments. This study was based on a network of 100 m by 100 m profile descriptions of open pits and intermediate observations with a Hoffel tube. In addition, once the field experimental area was established, two pits were made at the places shown in Fig. 9 and a soil profile description was made by a pedologist of the Western Soil Bureau-Venezuelan Ministry of Public Works. Soil horizons were distinguished as shown in the photograph (Fig. 10) taken of Pit 2. Morphological

FIG. 8. Monthly mean rainfall and potential evapotranspiration (80% of pan evaporation), information from the Morena station, Venezuela.

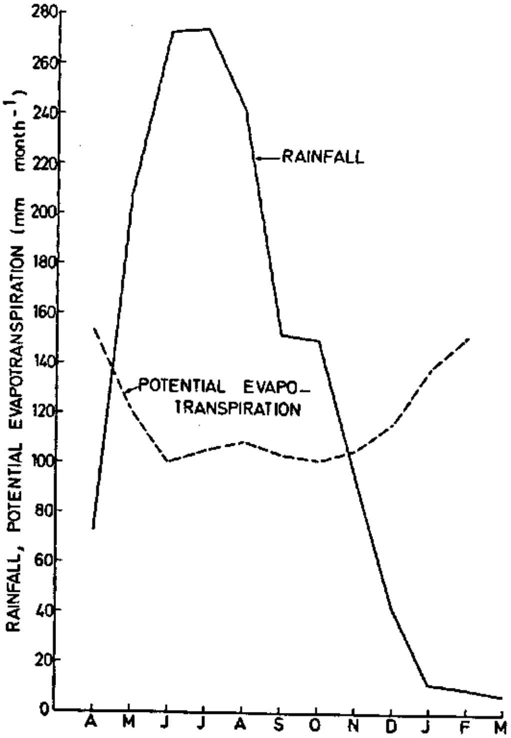
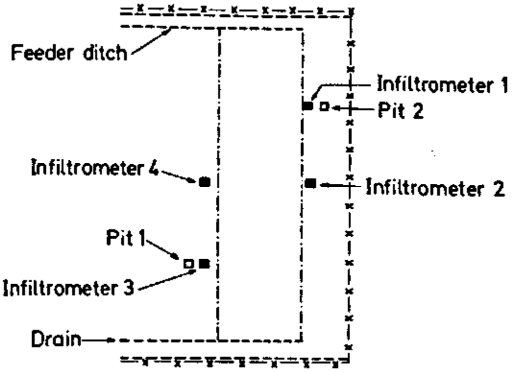


FIG. 9. Sketch of the location of pits and infiltrometers.



descriptions of soil profiles in both pits can be found in Appendix *B*.

Both profiles show small stratification and horizon differentiations, even though this characteristic is more marked in Pit 2. The texture of the soil indicates that the upper two horizons are clay and the lower ones are silty clay or silty clay loam, with moderately slow permeability. The results of the mechanical analysis made by the Western Soil Bureau-Venezuelan Ministry of Public Works according to the US Soil Survey Manual (1951) are included in Table 14.

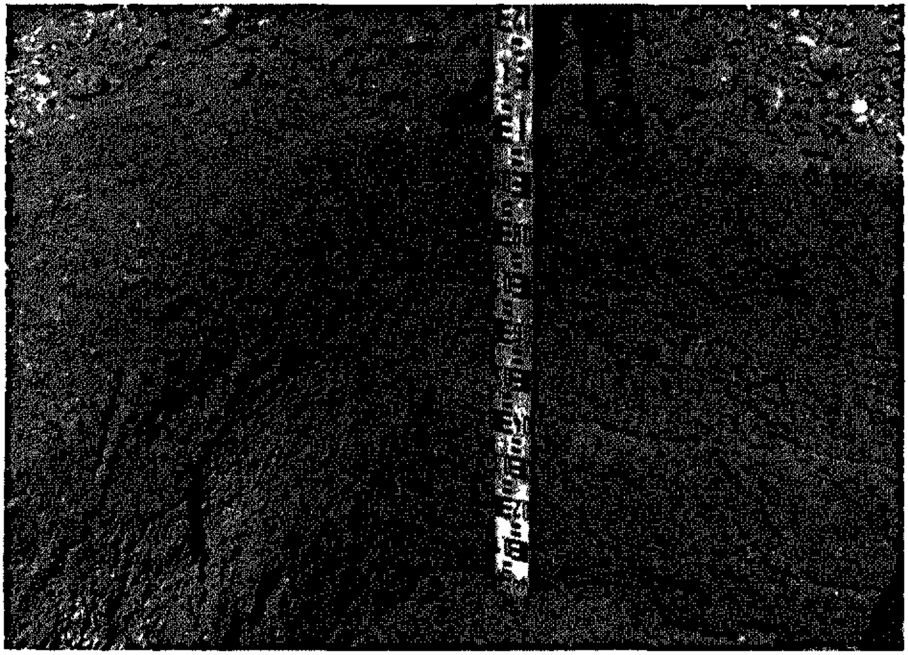


FIG. 10. Photograph of the soil profile in Pit 2.

TABLE 14. Mechanical analysis in Pit 1 and 2.

Pit 1					Pit 2				
Depth cm	Sand > 50 μ %	Clay < 2 μ %	Silt 2–50 μ %	Texture	Depth cm	Sand > 50 μ %	Clay < 2 μ %	Silt 2–50 μ %	Texture
0–20	10.28	52.60	37.12	C	0–15	14.28	48.76	36.96	C
20–32	6.04	55.32	38.64	C	15–32	17.96	45.48	36.56	C
32–42	7.96	45.48	46.56	SC	32–55	20.20	38.60	41.20	SCL
42–75	14.52	37.08	48.40	SCL	55–83	18.96	33.76	47.28	SCL

In the first two soil horizons there is some accumulation of organic matter, producing darker colors and a less sticky consistency under wet conditions. For Pit 1 biological activity (root development) was assessed; it was found to be abundant in the upper horizons and present to some degree in the entire profile. Lime accumulation down to the third horizon and mottles, reported in the last horizon, indicate the presence of a fluctuating watertable, which in the field experiments is not deeper than 2.0 m at the end of the dry season and could rise up to nearly 0.50 m from the land surface during the wet season. The few fine mica inclusions observed along the profile also show a recent formation and little weathered type of soil.

5.2. INFILTRATION RATE

Infiltration tests were conducted in specially designed wooden frame infiltrometers of 1.50 m by 1.50 m. These were assembled from four 20 cm wide timber boards simply joined together and kept in vertical position by an exterior earth embankment as shown in the photograph (Fig. 11).

A tank set up on a tire wheel system with a hose and control valve to deliver water, was used, because of the amount of water required to fill and refill the infiltrometer. To fill this basin infiltrometer, water was delivered at the maximum possible flow to cover the land as soon as possible with a water depth of approximately 10 cm. To prevent the jet of water from disturbing the uppermost soil layer and producing a surface seal, a plastic sheet covered the land while the water was applied.

Gauge readings of the water level during the time of infiltration were made on a plastic scale stuck in the soil in a vertical position. Each time the water level dropped about 5 cm, the infiltrometer was refilled. Readings were taken initially at time intervals of 2 min, then of 5 min and finally at time intervals of 15 min up to a total period of 165 min (Table 15).

The basin infiltrometer tests were replicated four times in the locations shown in Fig. 9, when the surface soil layer was loose and dry. Fig. 12 depicts the depth of water infiltration in mm against the time in min, computed from data of Table 15. Parameters of the Kostiakov and Philip equations are included in Table 16.

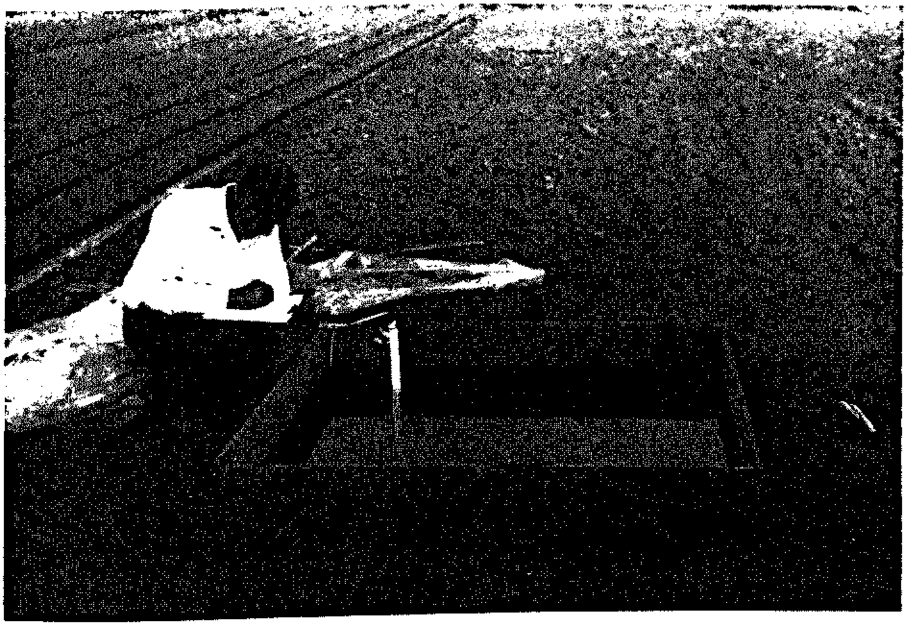


FIG. 11. Photograph of the wooden frame basin infiltrometer.

TABLE 15. Accumulated soil water infiltration I_{cum} in mm, as a function of time t in min. Procedure: small basin infiltrometer.

			Infiltrometertest				
	1		2		3		4
Time t min	Accumulated intake I_{cum} mm	Time t min	Accumulated intake I_{cum} mm	Time t min	Accumulated intake I_{cum} mm	Time t min	Accumulated intake I_{cum} mm
2	5	2	3	2	2	2	3
4	7	4	7	4	4	4	4
6	9	6	9	6	5	6	5
8	10	8	11	8	6	8	7
10	12	10	14	10	9	10	9
15	15	15	17	5	10	15	13
20	18	20	20	20	12	20	14
25	21	25	23	25	14	25	16
30	22	30	25	30	15	30	18
35	24	35	27	35	16	35	20
40	25	40	30	40	17	40	22
45	27	45	33	45	18	45	24
50	28	50	35	50	19	50	25
55	29	55	36	55	20	55	27
60	29	60	38	60	21	60	28
75	31	75	44	75	23	75	33
90	31	90	49	90	24	90	35
105	35	105	53	105	25	105	38
120	37	120	57	120	27	120	40
135	38	135	61	135	28	135	42
150	39	150	66	150	29	150	44
165	40	165	69	165	30	165	46

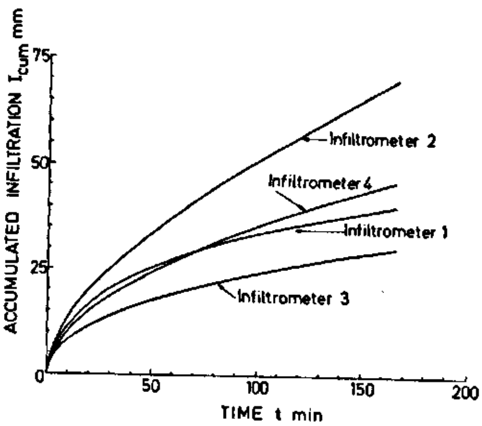
TABLE 16 Infiltration equations[1]. Procedure: small basin infiltrometers.

Infiltrometer test	Kostiakov $I_{cum} = A\,t^{B}$		Philip $I_{cum} = S\,t^{1/2} + C\,t$	
	A	B	S	C
1	3.987	0.476	4.170	−0.080
2	2.694	0.648	3.910	0.120
3	1.907	0.572	2.670	−0.023
4	1.893	0.649	3.240	0.030

[1] For I_{cum} in mm and t in min.

PHILIP (1957) pointed out that the use of the gravity term is definitely required beyond $t = 10{,}000$ sec. He stated that between $t = 1{,}000$ sec and $t = 10{,}000$ sec the effect of the term may be negligible. In our case $t = 165$ min (which equals 9,900 sec), which is close to the limit of necessary use of

FIG. 12. Accumulated infiltration I_{cum} as a function of time t for basin infiltrometers. The best fit curves according to Philip's equation.



the parameter C. The plot made for each test shows, in general, that the Philip equation fits the data better than the Kostiakov equation.

The infiltration curve (Fig. 12) obtained with Infiltrometer 2 differed markedly from those of the other three trials. Omitting the data from Infiltrometer 2, a general analysis was made by averaging the intercepts and the slopes (Eq. 2.6) which resulted in the following equation:

$$I_{cum} = 2.596\, t^{0.566*}$$

Likewise, single cylinder infiltrometers were set up near Pit 2 in order to obtain the rate of infiltration of an apparently compact horizon, which starts at a depth of 55 cm. For each trial, sets of four cylinder infiltrometers were used, located at the four vertexes of a square with sides of 5 m. The first trial was on the surface with the same conditions as for the basin infiltrometers. For the second trial, for each cylinder, a hole with 60 cm diameter was excavated until the apparently restricting soil stratum was reached.

In both infiltrometer experiments the readings started at time intervals of 5 min followed by 15 min intervals up to an accumulated time of 180 min. The data from the four replicates (Table 17) are very similar, except in the case of Infiltrometer 3 over the compact soil stratum. Because of the high values in this last case, possibly due to a local effect, these values were considered erratic and were omitted. Thus, the infiltration values for each replicate and accumulated time were averaged and the following equations obtained:

On the soil surface: $I_{cum} = 6.135\, t^{0.408*}$

On the top of the compact stratum: $I_{cum} = 0.992\, t^{0.616*}$

The infiltration data show that for the duration of the test, $t = 180$ min, the depth of water absorbed by the second stratum has been 55% of the depth of water that infiltrated through the surface.

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* For I_{cum} in mm and t in min.

TABLE 17. Accumulated soil water infiltration I_{cum} in mm, as a function of time t in min. Procedure: cylinder infiltrometer.

Infiltrometers on the land surface						Infiltrometers on the top of the compact stratum					
	Infiltrometer test						Infiltrometer test				
Time t	1	2	3	4	Average	Time t	1	2	3	4	Average
min	Acumulated depth I_{cum} mm					min	Acumulated depth I_{cum} mm				
5	10	10	10	10	10.0	5	4	3	9	2	3.0
10	16	18	15	16	16.2	10	6	4	11	3	4.3
15	20	21	18	20	19.8	15	7	5	14	4	5.3
20	23	24	21	23	22.7	30	9	6	21	6	7.0
25	25	25	23	24	24.2	45	11	8	29	8	9.0
40	31	29	28	28	29.0	60	14	9	34	12	11.7
55	35	32	31	30	32.0	75	15	10	41	15	13.3
70	38	34	35	32	34.7	90	17	11	45	17	15.0
85	41	36	36	34	36.8	105	19	13	53	21	17.7
100	44	39	40	35	39.5	120	20	14	57	23	19.0
115	48	41	41	36	41.5	135	22	15	63	26	21.0
130	50	43	44	39	44.0	150	24	17	69	28	23.0
145	52	45	46	40	45.8	165	25	19	75	31	25.0
150	54	46	48	40	47.0	180	28	20	80	33	27.0
165	55	48	49	41	48.3						
180	58	50	51	42	50.3						

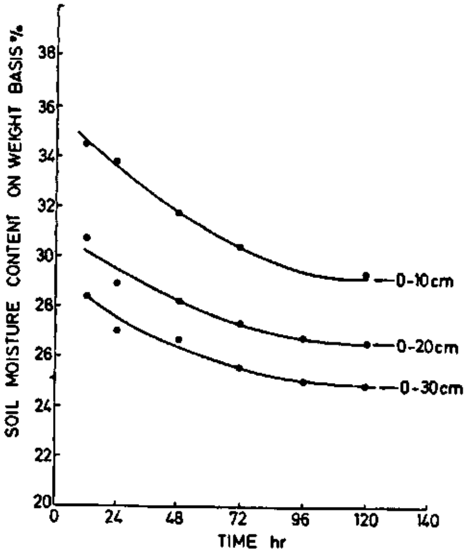
5.3. SOIL MOISTURE CHARACTERISTICS

The parcels of soil wetted during the basin infiltrometer trials, were later used to get values of water content at field capacity. After the water from the infiltrometer had penetrated the soil, the ground surface was covered with a plastic sheet. Thereafter, for 5 days soil sampling was carried out with a time interval of 24 hours. Soil samples were taken of soil layers from 10 cm down to 40 cm from the ground surface.

In Fig. 13 the average water contents as functions of time are plotted for the soil layers 0–10 cm, 0–20 cm and 0–30 cm. The layer of 30–40 was not included because it was found that little water penetrated to that depth. The reduction in soil moisture content with time, after infiltration of about 100 mm, is rather gradual in the three curves and these do not depict any inflection to be recognized as the equilibrium point indicating field capacity. However, the reduction of soil moisture content proceeds slowly after 96 hours. This time period can be accepted as referring to a practical acceptable equilibrium point corresponding with field capacity.

With samples taken from the same infiltrometer areas at intervals of 10 cm down to a depth of 40 cm, laboratory determinations were made of soil moisture

FIG. 13. Soil water content on weight basis as a function of time.



content as a function of the matric suction at 0.33 bar, 1.0 bar, 2.5 bar, 5.0 bar, 7.5 bar, 10.0 bar, and 15.0 bar. Average data for four replicates, from the stratum 0–20 cm, are plotted in Fig. 14 as the soil moisture content on a weight basis.

From a comparison of the curves in Fig. 13 and Fig. 14 it can be seen that for the stratum 0–20 cm, the assumed equilibrium in the field as reached after 96 hours occurred at approximately 0.33 bar matric suction. For the stratum 0–30 cm this equilibrium point was reached at approximately 0.58 bar matric suction. The gradual release of water upon increasing the suction may be interpreted according to BOLT (1970) as due to the arrangement of particles with large inter-aggregate pores and many smaller intra-aggregate pores.

The water content of the lowest soil stratum sampled shows that possibly deep percolation through the soil profile was not sufficient for the deeper layers. This is contrary to what is required according to the concept of field capacity. The earth enbankment on the outside of the infiltrometers showed a high soil moisture content. Excavation of the profile after finishing the soil sampling also showed an appreciable lateral movement of soil water and little deep percolation below a depth of 40 cm.

For the soil stratum 0–20 cm the value of the moisture content at field capacity is 26.8 % on the weight basis and the water content at 0.33 bar on the same basis is of 27.3 %. This value implies that field capacity corresponds to a moisture content slightly lower than at 0.33 bar matric suction, which is the one often use as an approximation for field capacity in deeply drained soils (BOLT 1970). For the permanent wilting point the water content at 15 bar matric suction was 12.5 % for the same stratum, so the available soil moisture is 14.3 % 26.8 %–12.5 %) on weight basis.

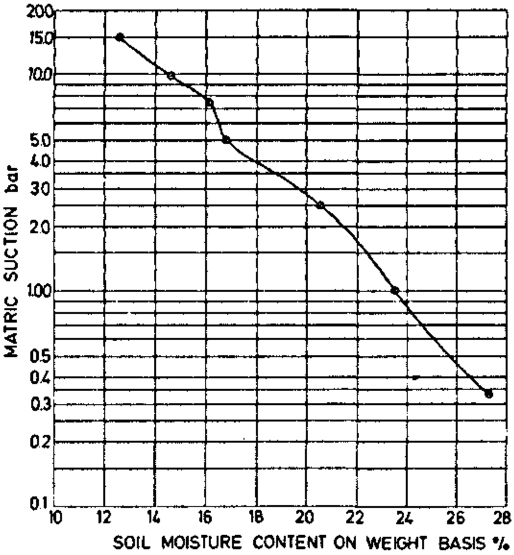


FIG. 14. Soil matric suction as a function of the soil moisture content on weight basis.

5.4. DRY BULK DENSITY

The dry bulk densities were determined for the differentiated horizons identified by the morphological description of the profiles by using the Uhland sampler. Two replicate samples were taken from each horizon. The values (Table 18) are thus the average of two replicates.

These data clearly show a dense soil horizon characterized by lime concretions starting at a depth between 55–75 cm. Under such conditions the rooting system is limited in depth. In a study on Algodonal series made by ABREU (1966) the crop roots were no deeper than 70 cm for maize and about 50 cm for beans.

TABLE 18. Dry bulk density in pits 1 and 2.

Pit 1		Pit 2	
Depth cm	Dry bulk density g cm^{-3}	Depth cm	Dry bulk density g cm^{-3}
0–20	1.49 ± 0.67%	0–15	1.48 ± 1.68%
20–42	1.52 ± 1.97%	15–32	1.55 ± 0.32%
42–75	1.66 ± 0.30%	32–55	1.56 ± 1.92%
		55–83	1.72 ± 0.29%

5.5. CHANGE OF SOIL MOISTURE CONTENT

Periodic soil moisture determinations were made by using a soil sampler tube of 85.0 cm length and a diameter of 2.0 cm. Replicated samples were taken twice a week at three depth with 15 cm increments, at three locations along the furrow (or five locations in the case of the second series of experiments). Samples were taken in the average position of the intersection of the free water surface and the wetted perimeter.

In order to keep the number of samples within manageable, soil moisture samples in each block were taken for the furrows under Treatment 2 and 3 (Table 19)

TABLE 19. Initial soil moisture content on weight basis (%) at the time of irrigation. First series of experiments – Variables: stream flow size and surface roughness

	Block and treatment	Date of Irrigation	Soil moisture content % of dry weight[1]				
			Soil layers cm				Sampling date
			0–15	15–30	30–45	0–45	
Furrow condition:	A1, A4	1–27–70					
loose	A2, A3	1–28	20.6	20.0	18.0	19.6	1–27–70
(first irrigation)	B1, B4	1–28					
	B2, B3	1–29					
	C1, C4	1–30					
	C2, C3	1–30					
	D1, D4	2–3					
	D2, D3	2–2					
	E1, E4	2–5					
	E2, E3	2–4	14.8	18.8	13.9	15.8	2–3
Furrow condition:	A1 A4	2–25					
re-used	A2, A3	2–26	12.5	21.3	17.8	17.2	2–23
(third irrigation)	B1, B4	2–27					
	B2, B3	2–28	12.6	19.6	18.8	17.0	2–27
	C1, C4	3–2					
	C2, C3	3–3	13.3	20.8	18.3	17.4	2–27
	D1, D4	3–4					
	D2, D3	3–5	10.8	18.6	15.7	15.0	3–3
	E1 E4	3–6					
	E2, E3	3–7	14.2	19.2	15.1	16.2	3–6
Furrow condition:	A1, A4	3–9					
re-used	A2, A3	3–10	13.2	20.0	16.6	16.6	3–6
(fourth irrigation)	B1, B4	3–11					
	B2, B3	3–12	13.0	19.5	13.0	15.2	3–11
	C1, C4	3–13					
	C2, C3	3–14	15.5	19.6	17.6	17.6	3–13
	D1, D4	3–16					
	D2, D3	3–17	13.6	18.1	15.7	15.8	3–13
	E1, E4	3–18					
	E2, E3	3–18	14.7	18.1	15.8	16.2	3–17

Second series of experiments. Variable: initial soil moisture content (second irrigation)

Treatment	Block	Date of Irrigation	Soil moisture content – % of dry weight[2]				
			Soil layers cm				Sampling date
			0–15	15–30	30–45	0–45	
2	B	2–16/17	14.4	20.7	22.5	19.3	2–16–70
3	B	2–17		nearly saturated			
1	D	2–23	12.3	19.0	17.5	16.3	2–23

Third series of experiments. Variable: furrow length (fifth irrigation)

Treatment			Date of Irrigation	Soil moisture content % of dry weight[1]				
1 62.5 m	2 125 m	3 175 m		Soil layers cm				Sampling date
				0–15	15–30	30–45	0–45	
A	A	A	3–19–70	15.3	18.0	15.9	16.4	3–17–70
B	B	B	3–20	11.7	16.6	18.2	15.5	3–20
C	C	C	3–21	11.9	21.6	17.5	17.0	3–20
D	D	D	3–23	15.8	20.1	15.5	17.1	3–23
E	E	E	3–24	17.8	21.4	18.0	19.1	3–23

[1] Average of three profiles along the furrow length.

[2] Average of five profiles along the furrow length.

of the first series of experiments. For the second and third series the same furrows were sampled. These show, that soil moisture contents in the strata 0–45 cm were rather constant during all experiments considering the date of irrigation, with the obvious exception during the second series of experiments, when the initial soil moisture content was introduced as a variable.

5.6. WATER QUALITY AND TEMPERATURE

The irrigation water of the Cojedes-Sarare Irrigation Project, the supply of which is regulated by 'Las Majaguas' reservoir is practically free of sediment. Periodic sampling during the experiments showed clear water free of sediment. The suspended material seen in some of the trials could be attributed to normal erosion in the upper section which was deposited in the lower section of the furrow (MECH and SMITH, 1967).

With regard to the salt content of the water, determinations conducted by the Western Soil Bureau-Venezuelan Ministry of Public Works, showed a medium salinity (EC = 333 μmhos cm^{-1}) and a low sodium hazard (SAR < 1.0).

In some of the trials, water temperature was recorded in the furrows. It was measured at different sites during the advance period of the wetting front as well as during the second irrigation stage (Table 20).

These temperature data, which were simultaneously recorded at the listed distances, indicate that there is a gradual increase in water temperature, from the intake up to the water front. The differences between the intake and the water front become greater when the front advances in the furrow bed, because of a longer run in contact with a soil at a higher temperature. The differences in water temperature between the furrow inflow and outflow remain nearly constant, even after 70 min of the second irrigation stage.

TABLE 20. Water temperature in °C[1].

	First stage Water front at:			Second stage	Related meteorological data[2]
	87.5 m	137.5 m	175.0 m		Air temperature:
Hour	9.10 AM	9.30 AM	9.50 AM	11.00 A.M.	8.00 AM 25.9°C
Time	39 min	59 min	79 min	149 min	2.00 PM 35.7°C
Distance m					
0	27.1	27.4	27.8	29.1	Soil temperature:
37.5	28.0	28.5	29.0	30.3	5 cm: 33.9°C
87.5	29.4	29.4	30.2	31.5	10 cm: 33.2°C
137.5		30.4	30.8	32.2	
175.0			31.5	32.4	

[1] Treatment 3, Block D, third series of experiments. Date: March 23 1970.

[2] At the Meteorological Station, 5 Km from the Experimental Station.

5.7. TOPOGRAPHIC SURVEY

After the fourth irrigation the stable furrow bed was surveyed. Levelling rod readings were taken for the marked sites at distance intervals of 12.5 m, in the twenty test furrows.

The slope of the best fit line, of each of the twenty test furrows, obtained by regression analysis per 25.0 m of furrow section, are presented in Table 21. The averages of the furrow slope by blocks and by treatments according to the first series of experiments, and the standard deviation SD are also included in Table 21.

Likewise, Table 22 presents the deviation with respect to the regression line and the *SD* for a furrow in the centre of each block. (Fig. 15). Comparison of the values for different blocks indicates a satisfactory uniformity of the furrow slope

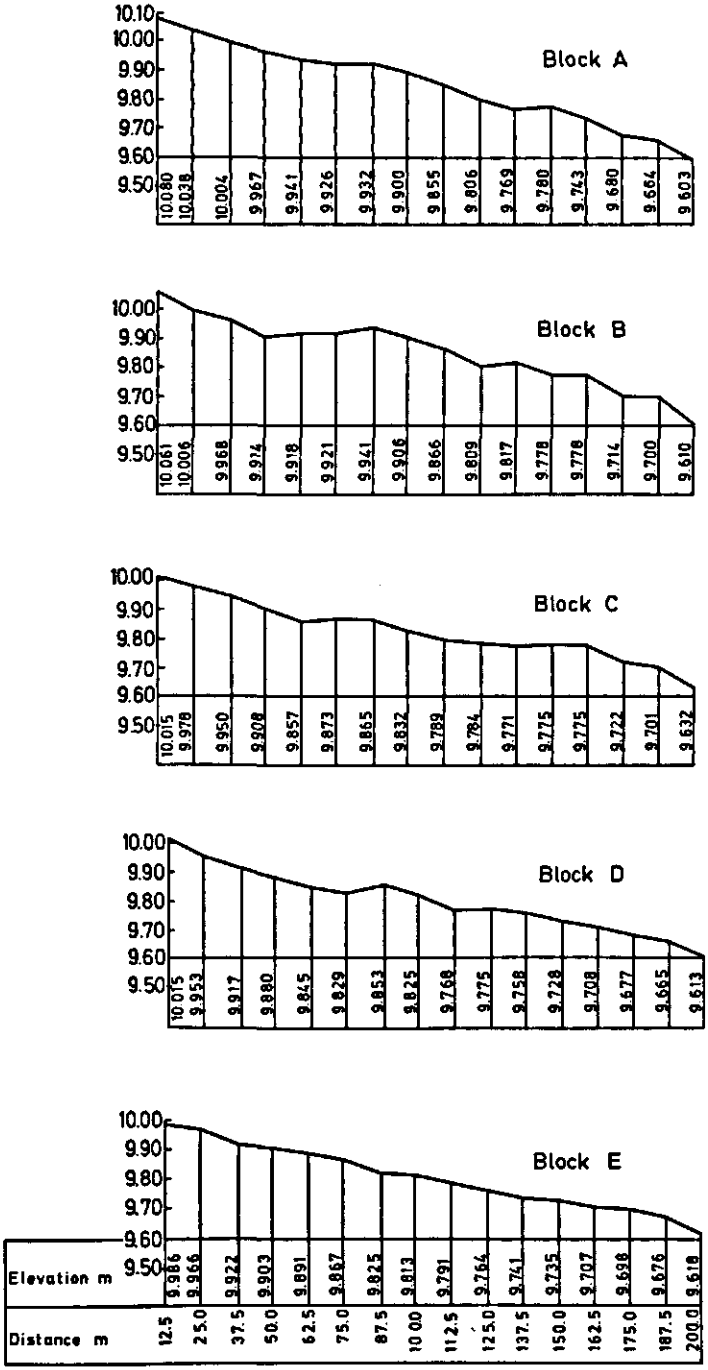


FIG. 15. Profiles of the furrow bed elevation. Treatment 2 first series of experiments.

TABLE 21. Topographic survey. Slope S_0 % of the best fit line.

Block	A				B				C				D				E			
Treat.	3	2	4	1	2	4	3	1	2	4	1	3	1	4	2	3	2	4	1	3
S_0 %	0.200	0.224	0.213	0.224	0.180	0.178	0.148	0.156	0.160	0.168	0.173	0.187	0.213	0.186	0.169	0.211	0.178	0.197	0.173	0.187
SD	0.011				0.016				0.011				0.021				0.011			
S_0 % (avg)	0.215				0.165				0.172				0.195				0.184			

Treat.	1	2	3	4
S_0 % (avg)	0.188	0.182	0.187	0.188
SD	0.029	0.025	0.024	0.017

and only slight deviation from the regression line along the same furrow. This is noteworthy considering that the trials were conducted under actual field conditions.

TABLE 22. Topographic survey. Furrow bed elevations and deviations from the best fit line.

Distance	Block and treatment														
	A 2			B 4			C 4			D 4			E 4		
m	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
12.5	10.080	10.067	+0.013	10.033	10.026	+0.007	9.987	9.974	+0.013	10.058	9.995	+0.063	9.989	9.980	+0.009
25.0	10.038	10.039	−0.001	9.984	10.004	−0.020	9.965	9.953	+0.012	9.992	9.972	+0.020	9.958	9.955	+0.003
37.5	10.004	10.011	−0.007	9.996	9.982	+0.014	9.945	9.932	+0.013	9.970	9.949	+0.021	9.936	9.930	+0.006
50.0	9.967	9.983	−0.016	9.966	9.960	+0.006	9.928	9.911	+0.017	9.943	9.926	+0.017	9.897	9.905	−0.008
62.5	9.941	9.955	−0.014	9.906	9.938	−0.032	9.879	9.890	−0.011	9.886	9.903	−0.017	9.882	9.880	+0.002
75.0	9.926	9.927	−0.001	9.928	9.916	+0.012	9.850	9.869	−0.019	9.841	9.880	−0.039	9.855	9.855	0.000
87.5	9.932	9.899	+0.033	9.905	9.894	+0.011	9.855	9.848	+0.007	9.845	9.857	−0.012	9.817	9.830	−0.013
100.0	9.900	9.871	+0.029	9.896	9.872	+0.024	9.815	9.827	−0.012	9.823	9.834	−0.011	9.813	9.805	+0.008
112.5	9.855	9.843	+0.012	9.846	9.850	−0.004	9.767	9.806	−0.039	9.807	9.811	−0.004	9.793	9.780	+0.013
125.0	9.806	9.815	−0.009	9.813	9.828	−0.015	9.753	9.785	−0.032	9.783	9.788	−0.005	9.755	9.755	0.000
137.5	9.769	9.787	−0.018	9.778	9.806	−0.028	9.745	9.764	−0.019	9.764	9.765	−0.001	9.729	9.730	−0.001
150.0	9.780	9.759	+0.021	9.792	9.784	+0.008	9.773	9.743	+0.030	9.747	9.742	+0.005	9.688	9.705	−0.007
162.5	9.743	9.731	+0.012	9.780	9.762	+0.018	9.727	9.722	+0.005	9.722	9.719	+0.003	9.672	9.680	−0.008
175.0	9.680	9.703	−0.023	9.724	9.740	−0.016	9.708	9.701	+0.007	9.708	9.696	+0.012	9.671	9.655	−0.016
187.5	9.664	9.675	−0.011	9.686	9.718	−0.032	9.681	9.680	+0.001	9.695	9.673	+0.022	9.655	9.630	+0.025
SD			0.018			0.020			0.020			0.025			0.011

(1) Furrow bed elevation m.
(2) Best fit line elevation m.
(3) Deviation from the best fit line elevation m.

The Parshall flumes of 1 inch (2.54 cm) and 2 inches (5.08 cm) throat width were calibrated in the field. In order to secure a free flow, the flume was placed in a raised position. The calibration was done by volumetric measurement, to that effect a bucket was placed in a hole excavated under the furrow bed level. It was possible to have an ample range of flow sizes, by controlling of the water head by means of an overflow weir located downstream in the feeder ditch and by changing or combining siphons with different diameters.

Field calibration from both furrow meters tested, fall onto a smooth curve when plotted on double logarithmic paper (Fig. 16). From these plots the relation between Q and h_a was expressed in the equations that follow:

1 - inch Parshall flume $Q = 0.0380h_a^{1.635*}$
2 - inch Parshall flume $Q = 0.0774h_a^{1.655*}$

Standard calibration of the Parshall flume made by SKOGERBOE *et al.* (1967), gave the following equations for free flow, if they are converted to the same units (Q in liter sec^{-1} and h_a in cm):

1 - inch Parshall flume $Q = 0.0477\ h_a^{1.55}$
2 - inch Parshall flume $Q = 0.0954\ h_a^{1.55}$

Field calibration checks well with the standard calibration made by SKOGER-

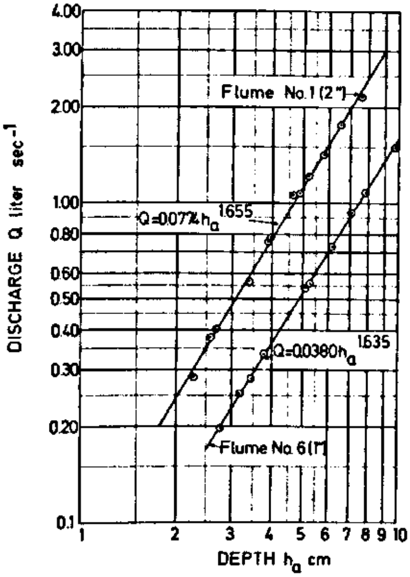


FIG. 16. Free flow calibration for 1 inch (2.54 cm) and 2 inch (5.08 cm) throat width Parshall flume.

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* For h_a expressed in cm and Q in liter sec^{-1}.

BOE *et al.* (1967) in the case of the meter of 2 inches (5.08 cm) throat width. The calibration data differ slightly for the same head in the case of 1 inch (2.54 cm) throat width, giving a lower discharge in the field. However, these differences are particularly small for the flow range within which the meter was used. From the equations obtained by means of the field calibration, Table 23 for free flow discharge, was computed.

TABLE 23 Free flow calibration for the Parshall flume.

Head	Discharge	Head	Discharge	Head	Discharge
h_a cm	Q liter sec^{-1}	h_a cm	Q liter sec^{-1}	h_a cm	Q liter sec^{-1}
	$W = 1''$ (2,54 cm)		$Q = 0.038\ h_a{}^{1.635}$		
0.5	0.012	2.4	0.159	4.3	0.413
0.6	0.016	2.5	0.170	4.4	0.428
0.7	0.021	2.6	0.181	4.5	0.444
0.8	0.026	2.7	0.193	4.6	0.460
0.9	0.032	2.8	0.204	4.7	0.477
1.0	0.038	2.9	0.217	4.8	0.494
1.1	0.044	3.0	0.229	4.9	0.511
1.2	0.051	3.1	0.242	5.0	0.528
1.3	0.058	3.2	0.254	5.1	0.545
1.4	0.066	3.3	0.267	5.2	0.562
1.5	0.074	3.4	0.281	5.3	0.580
1.6	0.082	3.5	0.295	5.4	0.599
1.7	0.090	3.6	0.308	5.5	0.617
1.8	0.099	3.7	0.323	5.6	0.635
1.9	0.108	3.8	0.337	5.7	0.654
2.0	0.118	3.9	0.352	5.8	0.673
2.1	0.128	4.0	0.366	5.9	0.692
2.2	0.138	4.1	0.382	6.0	0.711
2.3	0.148	4.2	0.397		
	$W = 2''$ (5.08 cm)		$Q = 0.077\ h_a{}^{1.655}$		
2.2	0.274	3.9	0.736	5.6	1.339
2.3	0.295	4.0	0.768	5.7	1.379
2.4	0.317	4.1	0.799	5.8	1.419
2.5	0.339	4.2	0.832	5.9	1.460
2.6	0.361	4.3	0.865	6.0	1.501
2.7	0.385	4.4	0.898	6.1	1.543
2.8	0.409	4.5	0.933	6.2	1.585
2.9	0.433	4.6	0.967	6.3	1.627
3.0	0.458	4.7	1.002	6.4	1.671
3.1	0.484	4.8	1.038	6.5	1.714
3.2	0.510	4.9	1.074	6.6	1.758
3.3	0.536	5.0	1.110	6.7	1.802
3.4	0.564	5.1	1.148	6.8	1.847
3.5	0.591	5.2	1.185	6.9	1.892
3.6	0.620	5.3	1.223	7.0	1.938
3.7	0.675	5.4	1.261	7.1	1.984
3.8	0.678	5.5	1.300	7.2	2.020

6. DATA ANALYSIS

A detailed analysis of the data from the first series of experiments was made, because more variables are involved in the first series of experiments than in the others. The third irrigation of the first series was taken as the basic pattern, and the relevant data were thouroughly analysed because: (i) the surface roughness of the furrow was the one factor it had in common with field practice; (ii) the differences in advance rate with the fourth irrigation were small; (iii) the constant inflow permitted a better check of the theory, than in the case of the fourth irrigation with reduced inflow.

Two types of equations are used to express the correspondence between two sets of observations for each of the variables being studied. Some data were related by a linear equation:

$$y = a_0 + a_1 x \tag{6.1}$$

Others e.g. the intake and advance data required an exponential function:

$$y = a x^b \tag{6.2}$$

Then

$$\log y = \log a + b \log x$$

where

x is the independent variable
y is the dependent variable
a_0 is the y-intercept of the linear function
a_1 is the slope of the line of the linear function
a is the y-intercept of the curve of the exponential function
b is the exponent of the exponential function.

The constants a and b of Eq. 6.2., for a set of values of x and y can be obtained by plotting the data on double logarithmic paper, but in this thesis all relationships were obtained by regression analysis using the least squares method. In this method the exponent b (Eq. 6.2) becomes

$$b = \frac{\Sigma (\log x_i \log y_i) - \dfrac{\Sigma \log x_i \, \Sigma \log y_i}{N}}{\Sigma (\log x_i^2) - \dfrac{(\Sigma \log x_i)^2}{N}} \tag{6.3}$$

for (x_i, y_i) $i = 1, 2 \ldots\ldots, N$.

Then:

$$\log a = \frac{\Sigma \log y_i}{N} - \frac{b\, \Sigma \log x_i}{N} \tag{6.4}$$

Equations were obtained for each one of the single furrow experiments. Then, to get a more generalized type of equation for each treatment the intercepts and the exponents of the replicates (Eq. 6.2) were averaged. When the number of data was not sufficient to get single furrow section parameters, an over-all regression analysis was made with the available data for each treatment.

6.1. ADVANCE CURVE AND ADVANCE FUNCTION

The advance function (Eq. 3.1) was studied with respect to the variable inflow Q and surface roughness. The accumulated times of arrival of the water front at each station were averaged for the five replicates and plotted as t against x in figures 17, 18 and 19.

For the third and fourth irrigations making use of the same furrows, the data for replicates of the same treatment were rather consistent. However, the data varied greatly for the first irrigation when the furrow had just been made and the soil was loose (Table 1). The advance rate of the water front was rather small in blocks A, B and C, first irrigation. Due to differences in soil preparation, the furrows remained more cloddy and rougher with respect to water flow in blocks A, B and C than in blocks D and E.

Fig. 17 shows a clear separation between the curves for the first irrigation in response to the supplied flow. Differences in advance time are smaller in third

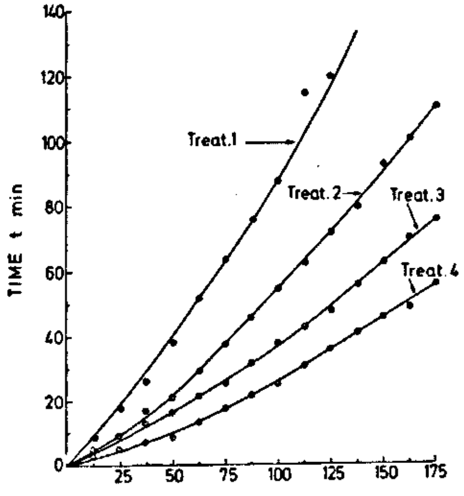

FIG. 17. Furrow water front advance time t as a function of equal length increments x for different inflow sizes. Furrow condition: new loose, first irrigation.

and fourth irrigations (figures 18 and 19) with a smooth surface, than in the first irrigation, even when curves for extreme flow treatments are compared.

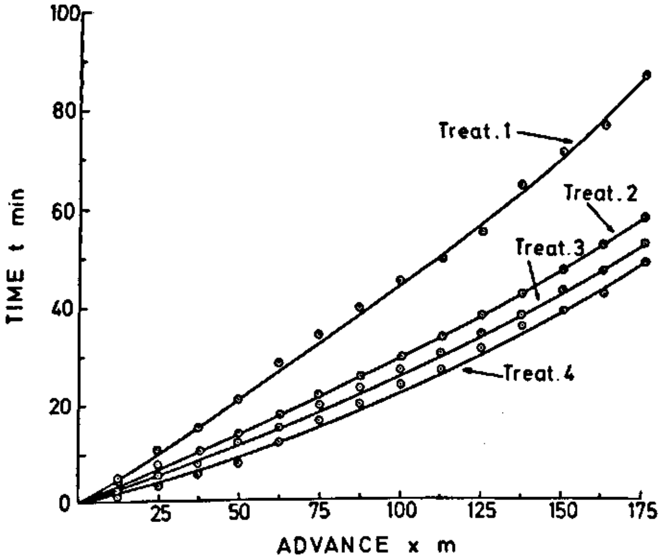

FIG. 18. Furrow water front advance time t as a function of equal length increments x for different inflow sizes. Furrow condition: re-used, third irrigation.

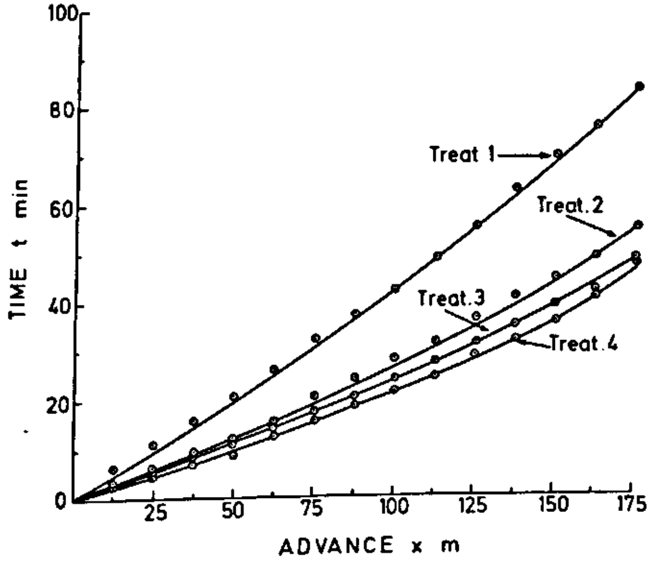

FIG. 19. Furrow water front advance time t as a function of equal length increments x for different inflow sizes. Furrow condition: re-used, fourth irrigation.

With regard to the effect of roughness, advance curves for the four flow treatments of the first and third irrigations are compared in figures 20 and 21. The differences are greater for the smaller flow, but decline gradually as the flow increases.

By regression analysis (equations 6.3 and 6.4) parameters of the advance function (Eq. 3.1) were obtained as $t = f(x)$ for each of the 40 single furrow trials (4 treatments with 5 replicates of 2 roughness conditions).* Single furrow equations were obtained for $t = f(x)$, by adjusting the time t for fixed advance x, for 12.5 m distance increments. The equations were then converted in the computer to the form of the advance equation $x = f(t)$. The parameters of these single experiment equations and the multiple correlation coefficient, R^2, are included in Table 24. Hence, the general equations were obtained for each treatment by taking the averages of the coefficients and the exponents of the replicates (Table 25). A similar analysis for the first irrigation was not made because the scattering of points prevented a reliable good fit.

In figures 22 and 23 the equations of Table 25 are shown. Although the third irrigation shows a greater coefficient p in every case, except Treatment 2, the fourth irrigation shows a greater exponent r, which leads to approximately the same average advance rate for a furrow length L = 175.0 m. Even when the

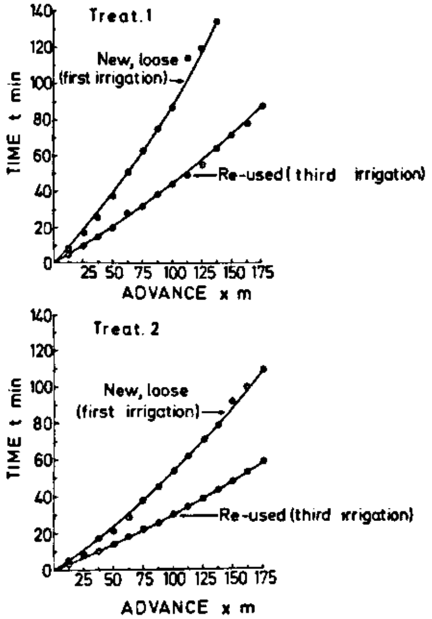

FIG. 20. Furrow water front advance time t as a function of equal length increments x for different furrow conditions. Treatments 1 and 2.

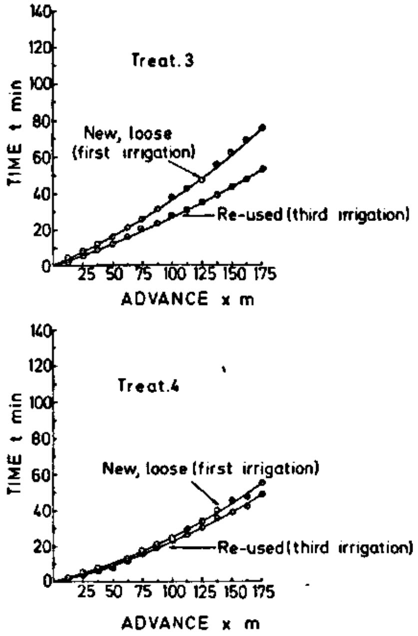

FIG. 21. Furrow water front advance time t as a function of equal length increments x, for different furrow conditions. Treatments 3 and 4.

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* This analysis was made in the CDC 3200 computer of the Department of Mathematics.

TABLE 24. Single furrow trial advance equation, $x = p\,t^r$, and multiple correlation coefficient R^2.

Treat.	Block	S_0%	Third irrigation			Fourth irrigation		
			p	r	R^2	p	r	R^2
1	A	0.224	1.796	0.991	0.996	0.982	1.172	0.989
	B	0.156	2.637	0.908	0.995	1.621	1.063	0.989
	C	0.173	3.528	0.897	0.984	3.902	0.893	0.992
	D	0.213	3.002	0.976	0.991	2.716	0.983	0.997
	E	0.173	3.261	0.945	0.993	3.030	0.911	0.997
2	A	0.224	1.613	1.181	0.976	4.838	0.925	0.996
	B	0.180	2.642	0.972	0.987	2.930	0.998	0.993
	C	0.160	2.620	1.017	0.993	3.635	0.991	0.991
	D	0.169	7.724	0.821	0.996	4.253	0.938	0.986
	E	0.178	3.829	1.102	0.991	2.902	1.087	0.973
3	A	0.200	3.055	0.977	0.990	6.766	0.813	0.996
	B	0.148	9.435	0.722	0.973	3.810	1.010	0.994
	C	0.187	4.267	0.902	0.988	5.253	0.897	0.991
	D	0.211	7.394	0.861	0.998	4.906	0.958	0.996
	E	0.187	6.841	0.905	0.991	5.265	0.951	0.989
4	A	0.213	9.897	0.755	0.945	3.367	1.050	0.989
	B	0.178	5.479	0.888	0.990	4.115	1.044	0.997
	C	0.168	8.729	0.707	0.966	9.793	0.745	0.979
	D	0.186	6.517	0.856	0.984	7.673	0.803	0.996
	E	0.197	9.574	0.903	0.976	7.347	0.882	0.986

TABLE 25 General advance equations, $x = p\,t^r$. Third and fourth irrigations.

Treat.		Inflow Q liter sec^{-1}		Inflow Q liter min^{-1}	$x = p\,t^r$ m
		Average	Range		
Third irrigation	1	0.63	0.62–0.68	37.77	$x = 2.790\,t^{0.942}$
	2	0.99	0.90–1.13	59.44	$x = 3.369\,t^{1.003}$
	3	1.52	1.50–1.60	90.96	$x = 5.943\,t^{0.864}$
	4	1.99	1.95–2.00	119.36	$x = 7.923\,t^{0.815}$
Fourth irrigation	1	0.61	0.60–0.64	36.47	$x = 2.296\,t^{0.995}$
	2	0.99	0.92–1.05	59.63	$x = 3.674\,t^{0.985}$
	3	1.51[1]	1.50–1.55	80.77[2] 90.47[1]	$x = 5.184\,t^{0.921}$
	4	1.98[1]	1.95–2.00	98.83[2] 118.54[1]	$x = 6.310\,t^{0.888}$

[1] Average inflow V_{in}/t for $x = 137.5$ m
[2] Average inflow V_{in}/t for $L = 175.0$ m

inflow was reduced at a water front advance of $x = 137.5$ m, as in treatments 3 and 4 of the fourth irrigation, the average advance rate for $L = 175.0$ m was about the same.

The analysis of variance[*] shows that the differences in the coefficients p between third and fourth irrigations are significant, but those of the exponent r are not. In both irrigations Treatment 1 was very significantly different (probability < 0.01) from the other three. Treatment 2 did not show a significant difference with 3, neither Treatment 3 with 4; but Treatment 2 was significantly different (probability < 0.05) from Treatment 4. The coefficient of variation CV of p and r were as follows:

	p	r
Third irrigation	18.68%	28.38%
Fourth irrigation	10.44%	25.71%

A plot of p from the general equations (Table 25) against Q on double logarithmic paper (Fig. 24) for both irrigations, shows an exponential relationship, with a coefficient of correlation $R = 0.983$, and the regression equation is:

$$p = 0.0645\, Q^{1.00} \tag{6.5}$$

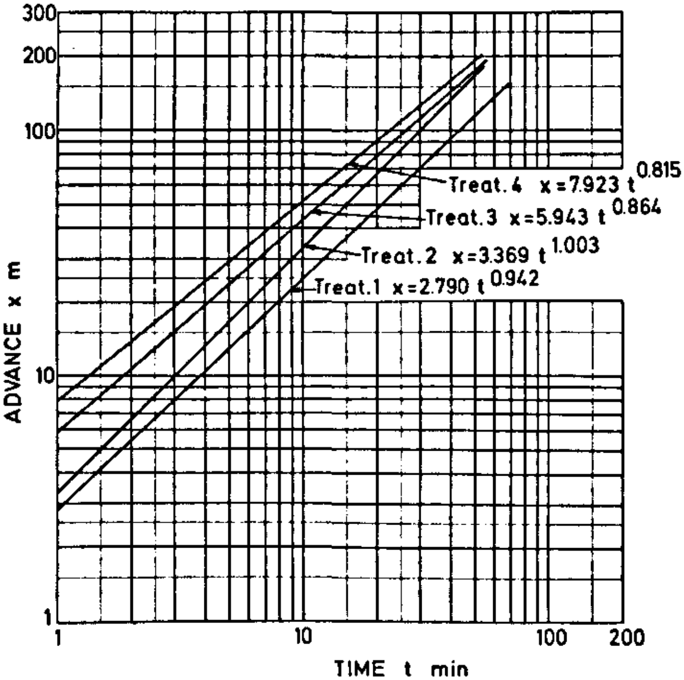

FIG. 22. Advance equations, $x = p\,t^r$, for four different treatments of inflow sizes. Third irrigation.

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[*] Student's-Neuman-Keuls test.

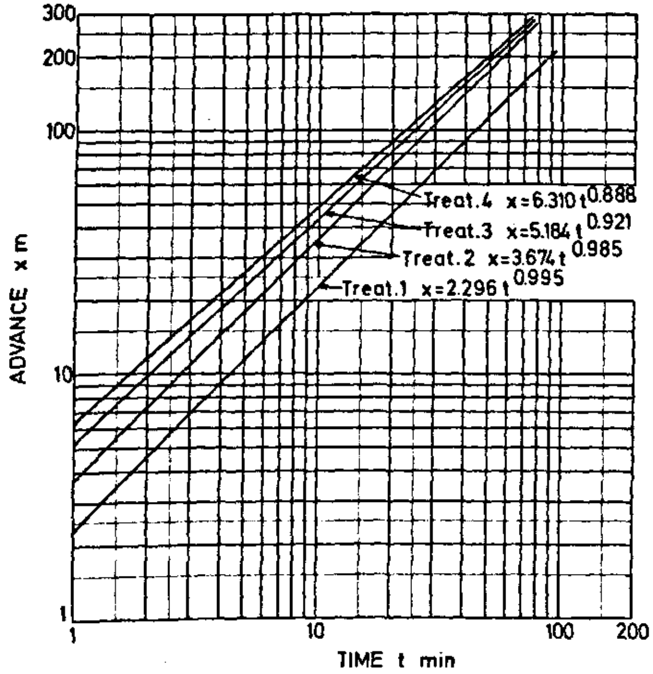

FIG. 23. Advance equations, $x = p\, t^r$, for four different treatments of inflow sizes. Four irrigation.

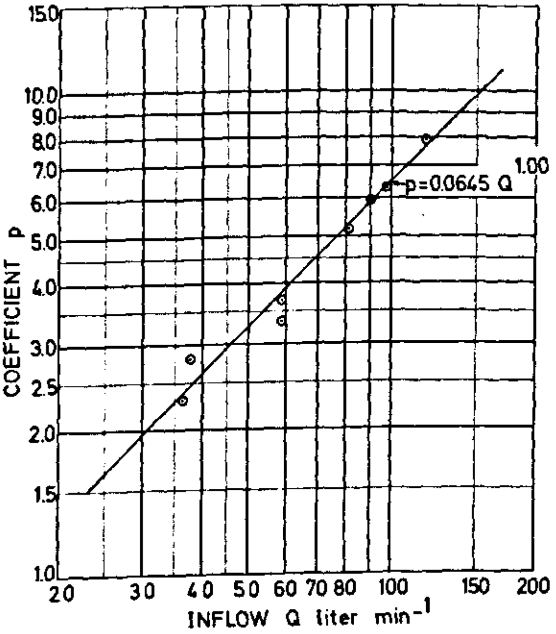

FIG. 24. Relationship between the coefficient p of the advance equation and the furrow inflow size Q. Third and fourth irrigations.

Then if $p = u\,Q^s$ (Eq. 3.4) we may conclude that the roughness conditions represented by $u = 0.0645$ have been the same during the third and fourth irrigations.

The range over which these equations have been obtained is 12.5 m $< x <$ 175.0 m. The functions derived from these equations that will be discussed later are therefore also valid within this range.

6.2 INFILTRATION DURING THE ADVANCE PERIOD: FIRST IRRIGATION STAGE

The average wetted perimeter P and section a_f were obtained from data of depth h and top width T of the flow section taken when the advance front was at $x = 87.5$ m, $x = 137.5$ m and $x = 175.0$ m. For that purpose, a furrow with a parabolic shape was assumed, which was later checked by direct measurement of 100 furrow sections (five in each test furrow). A simple device was designed, in order to measure the ordinates (photograph Fig. 25) at intervals of 2.0 cm, with a vertical ruler on a horizontal axis over the land surface.

As can be seen in Fig. 26, the points representing the average ordinate of 20 sections in each block, show a good fit with the parabolic arc. Then, a_f becomes

$$a_f = 2/3\,h\,T \tag{6.6}$$

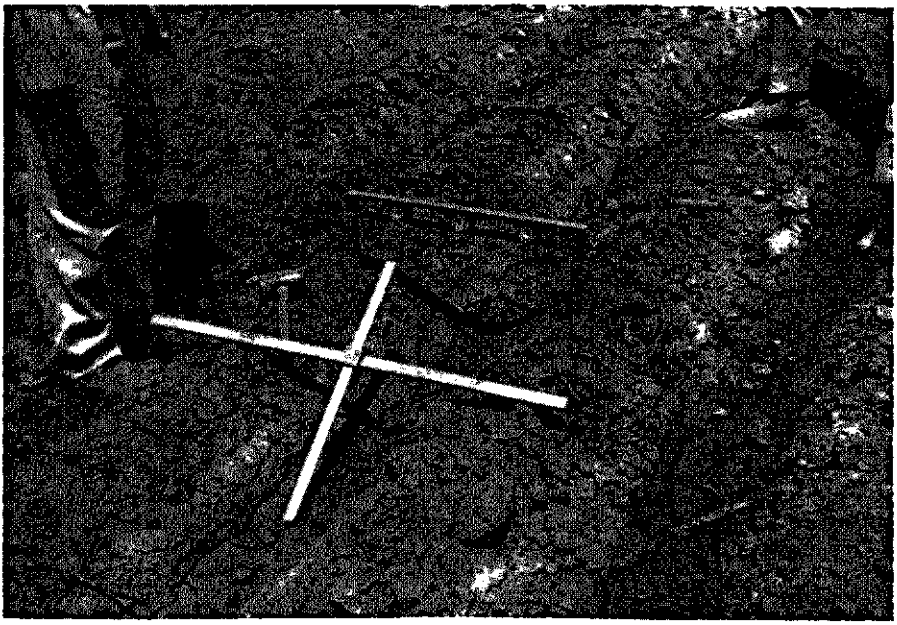

FIG. 25. Photograph showing the procedure for furrow cross section survey.

And:

$$P = (T/2)\,[\sqrt{1 + c_1^2} + 1/c_1 \ln (c_1 + \sqrt{1 + c_1^2})] = (T/2)\,X \qquad (6.7)$$

for $c_1 = 4\,h/T$

The values of the factor X (the terms within the square brackets) as a function of c_1, are given in Table 26.

Because in the last 12.5 m furrow section, a decline occurs in the water surface profile toward the water front, an adjustment was made in the values of a_f and P, computed from the averages values of h and T (equations 6.6 and 6.7). The adjustment was made by assuming a zero value for a_f and P at the water front. The values of the flow section a_f and the wetted perimeter P are averages of the measurements taken upstream of the site reached by the water front. Those values were adjusted by multiplying them by the ratio $N/(N + 1)$, where N is the number of points on the basis of which the averages were obtained.

6.2.1. *Area of infiltration*

The data of the wetted perimeter P (Table 27) show an increase with x and with Q. The scarce number of values of P, only three for each single experiment

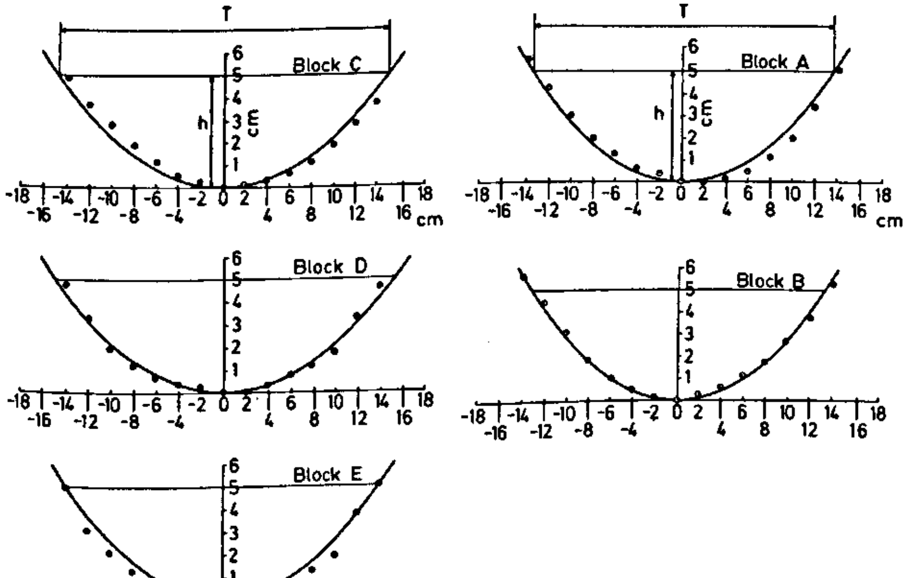

FIG. 26. Average furrow cross section for each block. The curve represents the calculated parabolic arc.

TABLE 26. Parabola coefficients to compute the furrow wetted perimeter.

$$P = (T/2)\,[\sqrt{1 + c_1^2} + 1/c_1 \ln (c_1 + \sqrt{1 + c_1^2})] = (T/2) \,.\, X$$

$c_1 = 4h/T$	X	$c_1 = 4h/T$	X
0.60	2.113	0.96	2.280
0.62	2.122	0.98	2.284
0.64	2.128	1.00	2.295
0.66	2.136	1.02	2.308
0.68	2.144	1.04	2.317
0.70	2.153	1.06	2.331
0.72	2.161	1.08	2.340
0.74	2.169	1.10	2.355
0.76	2.179	1.12	2.363
0.78	2.187	1.14	2.372
0.80	2.195	1.16	2.384
0.82	2.205	1.18	2.397
0.84	2.214	1.20	2.408
0.86	2.225	1.22	2.422
0.88	2.232	1.24	2.432
0.90	2.234	1.26	2.445
0.92	2.256	1.28	2.457
0.94	2.264	1.30	2.469

($x = 87.5$ m, $x = 137.5$ and $x = 175.0$ m) did not allow for a more reliable function for P to be calculated. Therefore, it was only possible to get a linear function of the type of Eq. 6.1 between P and x by regression analysis. If x is substituted from Eq. 3.1, equations for $P = f(t)$ are obtained (Table 28). Then the net infiltration area A_{i_n} and the gross infiltration area A_{i_g} become

$$A_{i_n} = P\,x = P\,p\,t^r \tag{6.8}$$

$$A_{i_g} = w\,x = w\,p\,t^r \tag{6.9}$$

However, equations for A_{i_n} were obtained in exponential form, by analysing the extreme values of each function, viz for $t = 1.0$ and $t = T_1$ (Table 29), where $t = T_1$ is the time to reach the end of the run $L = 175.0$ m.

6.2.2. *Infiltration function*

Since the inflow volume $V_{in} = Q\,t$ is known, the infiltrated volume V_i becomes

$$V_i = Q\,t - V_s \tag{6.10}$$

Since:

TABLE 27. Furrow wetted perimeter P in cm, for three water front advance stages. Third and fourth irrigations.

	Treatment 1			Treatment 2			Treatment 3			Treatment 4		
	Water front at m:			Water front at m:			Water front at m:			Water front at m:		
	87.5	137.5	175	87.5	137.5	175	87.5	137.5	175	87.5	137.5	175
Third irrigation												
A	23.3	23.8	26.1	23.6	24.1	24.5	25.6	28.4	30.3	27.2	29.7	31.8
B	25.9	25.2	24.9	28.2	28.1	31.9	26.8	31.1	30.3	33.0	33.1	33.3
C	27.9	31.9	30.6	26.7	28.4	28.3	30.8	34.2	34.4	29.9	34.0	34.5
D	23.2	24.0	25.6	26.3	27.4	28.1	25.4	27.3	28.6	27.7	29.0	31.0
E	23.5	24.2	25.5	23.2	24.8	26.7	25.3	26.5	28.8	27.8	30.0	32.6
Average	24.8	25.8	26.5	25.6	26.6	27.9	26.8	29.5	30.5	29.1	31.2	32.6
Fourth irrigation									(1)			(1)
A	23.8	24.4	26.4	25.1	26.6	26.2	28.5	31.0	26.6	30.4	31.0	28.2
B	24.7	23.7	24.1	25.1	26.3	27.9	28.0	28.6	25.9	30.7	31.9	27.4
C	24.6	26.2	26.0	27.2	28.6	28.2	31.6	34.5	29.9	29.8	32.4	28.0
D	22.3	23.8	23.3	26.8	27.3	27.8	27.5	27.8	25.1	30.4	31.0	26.6
E	23.9	24.4	24.3	24.1	26.0	25.6	28.1	29.5	27.2	30.6	31.3	29.2
Average	23.9	24.5	24.8	25.7	27.0	27.1	28.7	30.3	26.9	30.4	31.5	27.9

[1] Reduced inflow

TABLE 28. Furrow wetted perimeter P in cm, as a function of the advance distance x in m and as a function of the advance time t in min.

	Treat.	$P = f(x)$	$P = f(t)$
Third irrigation	1	$P = 22.99 + 0.0204\,x$	$P = 22.99 + 0.0569\,t^{0.942}$
	2	$P = 23.23 + 0.0259\,x$	$P = 23.23 + 0.0872\,t^{1.003}$
	3	$P = 23.19 + 0.0429\,x$	$P = 23.19 + 0.2549\,t^{0.864}$
	4	$P = 25.60 + 0.0403\,x$	$P = 25.60 + 0.3193\,t^{0.815}$
Fourth irrigation	1	$P = 22.91 + 0.0111\,x$	$P = 22.91 + 0.0255\,t^{0.995}$
	2	$P = 24.27 + 0.0174\,x$	$P = 24.27 + 0.0639\,t^{0.985}$
	3	$P = 25.90 + 0.0320\,x^{*}$	$P = 25.90 + 0.1659\,t^{0.921*}$
	4	$P = 28.50 + 0.0220\,x^{*}$	$P = 28.50 + 0.1388\,t^{0.888*}$

* Obtained from the average of the five replicates at $x = 87.5$ m and $x = 137.5$ m.

TABLE 29. Net infiltration areas A_{in} in m², as a function of the advance time t in min.

Treat.	Third irrigation	Fourth irrigation
1	$A_{in} = 0.643\,t^{0.973}$	$A_{in} = 0.526\,t^{1.014}$
2	$A_{in} = 0.786\,t^{1.048}$	$A_{in} = 0.894\,t^{1.001}$
3	$A_{in} = 1.393\,t^{0.933}$	$A_{in} = 1.350\,t^{0.970*}$
4	$A_{in} = 2.054\,t^{0.876}$	$A_{in} = 1.807\,t^{0.920*}$

* Valid up to $x = 137.5$ m.

$$V_s = a_f\, x = a_f\, p\, t^r \tag{6.11}$$

then

$$V_i = Q\, t \left(1 - \frac{a_f\, p\, t^{r-1}}{Q}\right) \tag{6.12}$$

The values of V_i (tables 4 and 5) for each single experiment and advance stage ($x = 87.5$ m, $x = 137.5$ m and $x = 175.0$ m) were plotted as a function of the advance time, for the third and fourth irrigations (figures 27, 28, 29 and 30). A few erratic values were omitted and by regression analysis (Eq. 6.2) the equations for $V_i = f(t)$ and the coefficient of variation CV (%) were obtained (Table 30).

The average infiltration along the furrow $\bar{I}_{cum}$ for the net area A_{in} becomes then:

$$\bar{I}_{cum} = \frac{V_i}{A_{in}} = \frac{Q\, t - a_f\, x}{P\, x} \tag{6.13}$$

or

$$\bar{I}_{cum} = \frac{Q\, t^{1-r}}{P\, p} - \frac{a_f}{P} \tag{6.14}$$

If in Eq. 6.14, P is substituted as given in Eq. 6.7 and a_f as in Eq. 6.6, then:

$$\bar{I}_{cum} = \frac{2\, Q\, t^{1-r}}{T X\, p} - \frac{4\, h}{3\, X} \tag{6.15}$$

For the gross area A_{ig}

$$\bar{I}_{cum} = \frac{Q\, t - a_f\, x}{w\, x} \tag{6.16}$$

and

$$\bar{I}_{cum} = \frac{Q\, t^{1-r}}{w\, p} - \frac{a_f}{w} \tag{6.17}$$

With the equations for $V_i = f(t)$ and $A_i = f(t)$ (Table 30), equations for $\bar{I}_{cum} = V_i / A_i$ were obtained for the net and gross infiltration area (Table 30). By applying the r exponents from Table 25 and $(b + 1)$ being the exponent of the $\bar{I}_{cum}$ function in Table 30, with $(b + 1)$ known to be equal to the exponent of t in the I_{cum} function, and F being calculated (equation 3.17 or 3.18), a can be computed since $a\, F/(b + 1)\,(b + 2)$ equals the coefficient of the first function

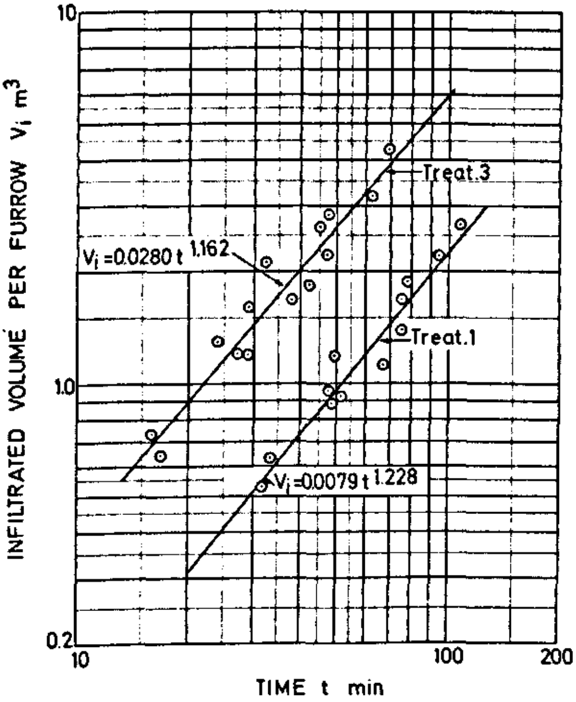

FIG. 27. Plot of V_i data as a function of the advance time t and representation of the regression line. Treatments 1 and 3 third irrigation.

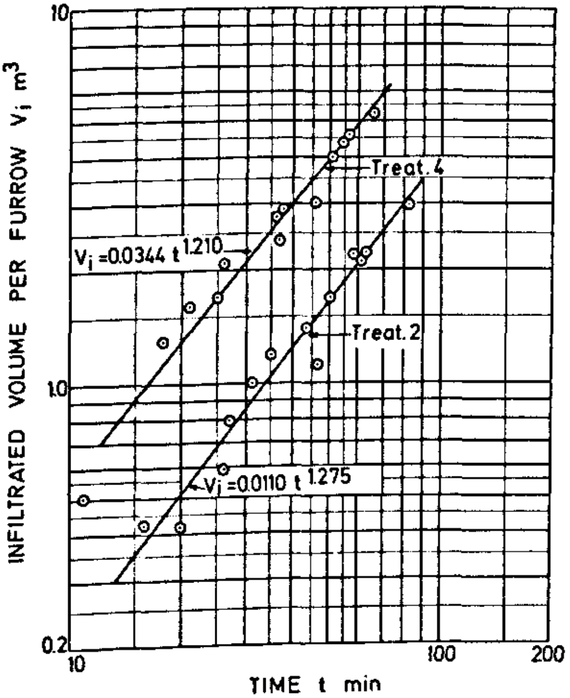

FIG. 28. Plot of V_i data as a function of the advance time t and representation of the regression line. Treatments 2 and 4 third irrigation.

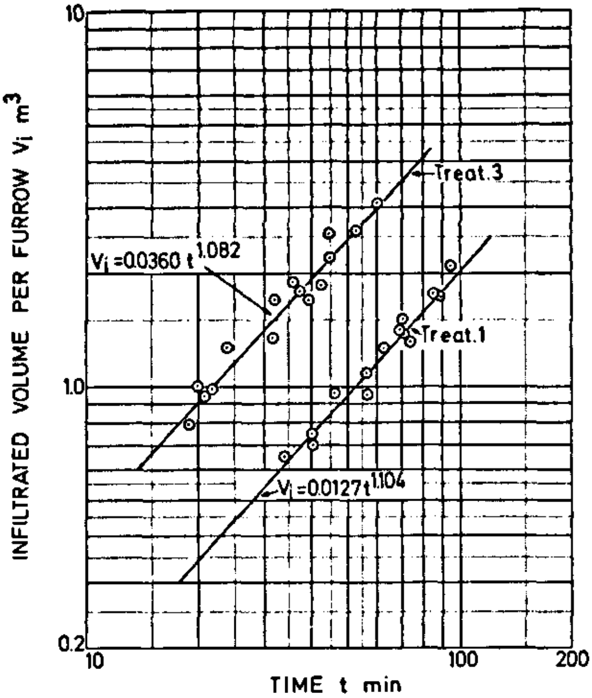

FIG. 29. Plot of V_i data as a function of the advance time t and representation of the regression line. Treatments 1 and 3 fourth irrigation.

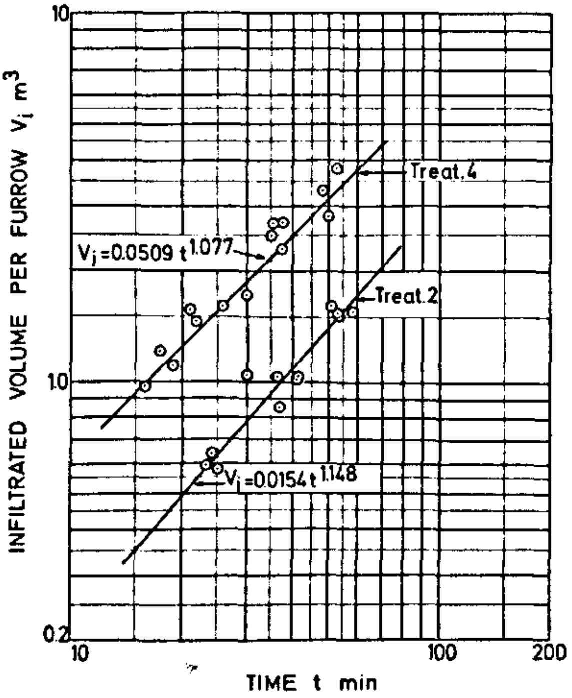

FIG. 30. Plot of V_i data as a function of the advance time t and representation of the regression line. Treatments 2 and 4 fourth irrigation.

TABLE 30. Equations for V_t, A_t, $\bar{I}_{cum}$ and Q_t, as functions af the advance time t in min. Third and fourth irrigations.

	Treat.	V_t m³	CV %	A_t m²		$\bar{I}_{cum}$ mm		Q_t liter min⁻¹
				Net	Gross	Net	Gross	
Third irrigation	1	$0.0079\,t^{1.228}$	12.21	$0.643\,t^{0.973}$	$w\,2.790\,t^{0.942}$	$12.222\,t^{0.255}$	$\frac{2.817}{w}\,t^{0.286}$	$9.655\,t^{0.228}$
	2	$0.0110\,t^{1.275}$	15.52	$0.786\,t^{1.048}$	$w\,3.369\,t^{1.003}$	$14.015\,t^{0.227}$	$\frac{3.268}{w}\,t^{0.272}$	$14.041\,t^{0.275}$
	3	$0.0280\,t^{1.162}$	12.88	$1.393\,t^{0.933}$	$w\,5.943\,t^{0.864}$	$20.079\,t^{0.229}$	$\frac{4.706}{w}\,t^{0.298}$	$32.490\,t^{0.162}$
	4	$0.0344\,t^{1.210}$	11.68	$2.054\,t^{0.876}$	$w\,7.923\,t^{0.815}$	$16.736\,t^{0.334}$	$\frac{4.338}{w}\,t^{0.395}$	$41.605\,t^{0.210}$
Fourth irrigation	1	$0.0127\,t^{1.104}$	7.59	$0.526\,t^{1.014}$	$w\,2.296\,t^{0.995}$	$24.064\,t^{0.090}$	$\frac{5.518}{w}\,t^{0.109}$	$13.994\,t^{0.104}$
	2	$0.0154\,t^{1.148}$	8.05	$0.894\,t^{1.001}$	$w\,3.674\,t^{0.985}$	$17.284\,t^{0.147}$	$\frac{4.205}{w}\,t^{0.163}$	$17.738\,t^{0.148}$
	3	$0.0360\,t^{1.082}$	9.66	$1.350\,t^{0.970*}$	$w\,5.184\,t^{0.921}$	$26.652\,t^{0.112*}$	$\frac{6.940}{w}\,t^{0.161}$	$38.941\,t^{0.082}$
	4	$0.0509\,t^{1.077}$	10.58	$1.807\,t^{0.920*}$	$w\,6.310\,t^{0.888}$	$28.152\,t^{0.157*}$	$\frac{8.062}{w}\,t^{0.189}$	$54.777\,t^{0.077}$

* Valid up to 137.5 m

(Table 31).

Using the cumulative infiltration equation (2.6), I_{cum} was computed for time $(T_1 - t_x)$ that water has been in contact with each point for the gross area $w = 0.70$ m of the third irrigation. The plot of I_{cum} (Fig. 31) for different points along the furrow show a marked difference in infiltration pattern for the various treatments: when Q increases, infiltration also increases, although with larger flow the time of application is shorter. This important finding of the experiments will be discussed in Chapter 7.

6.2.3. *Unit inflow – infiltration function*

An equation for the infiltration flow $Q_i = f(t)$ is obtained when the equation for $V_i = f(t)$ is presented in differential form:

$$\frac{dV_i}{dt} = Q_i$$

Table 30 includes the equation for Q_i for each treatment of the third and fourth irrigations. Figures 32 and 33 show $Q_i = f(t)$ since the beginning of the flow for the first and second stages of treatments 1 and 3 during the third irrigation.

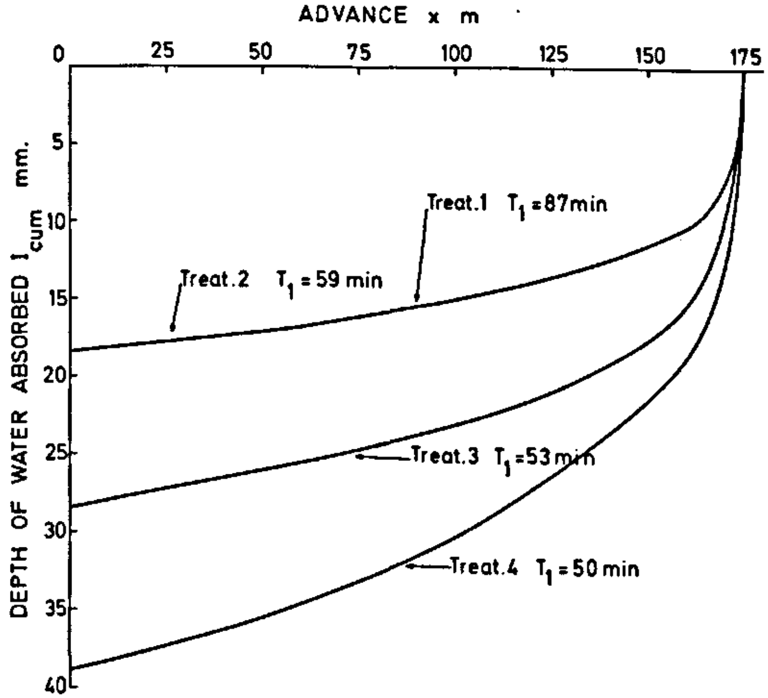

FIG. 31. Infiltration pattern along the furrow length during the first stage third irrigation.

TABLE 31. Parameters of the infiltration equation for the first irrigation stage. Third and fourth irrigations.

Treat.		Net area						Gross area				
		r	A	B	b	F	a	$A\ w$	B	b	F	$a\ w$
Third irrigation	1	0.942	15.216	0.255	−0.745	1.008	3.880	3.594	0.286	−0.714	1.008	1.028
	2	1.003	17.194	0.227	−0.773	1.000	3.903	4.167	0.272	−0.725	1.000	1.146
	3	0.864	24.262	0.229	−0.771	1.017	5.556	5.983	0.298	−0.702	1.021	1.783
	4	0.815	21.593	0.334	−0.666	1.034	7.212	5.818	0.395	−0.605	1.040	2.298
Fourth irrigation	1	0.995	26.233	0.090	−0.910	1.000	2.361	6.127	0.109	−0.890	1.000	0.674
	2	0.985	19.823	0.147	−0.853	1.001	2.914	4.650	0.163	−0.837	1.001	0.758
	3	0.921	29.491	0.112	−0.888	1.005	3.303	8.000	0.161	−0.839	1.007	1.288
	4	0.888	32.280	0.157	−0.843	1.009	5.068	9.481	0.189	−0.811	1.011	1.792

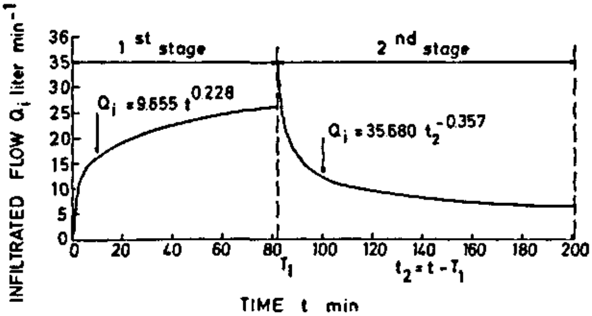

FIG. 32. Furrow infiltrated flow, Q_i as a function of time t first and second stages. Treatment 1 third irrigation.

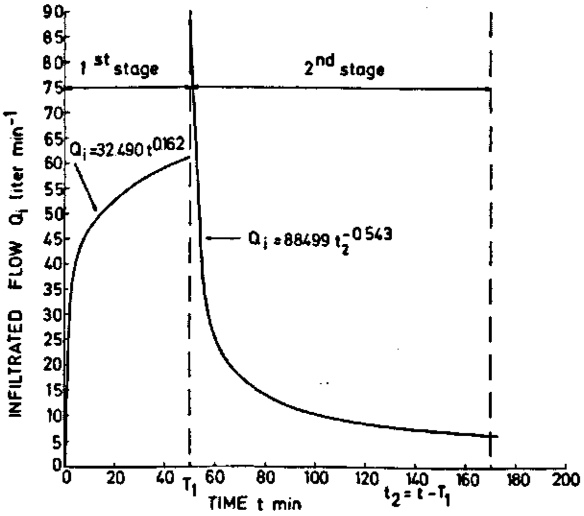

FIG. 33. Furrow infiltrated flow Q_i as a function of time t first and second stages. Treatment 3 third irrigation.

Also

$$Q_i = Q - \frac{dV_s}{dt} = Q - a_f \frac{dx}{dt}$$

Hence

$$Q_i = Q - a_f\, r\, p\, t^{r-1} \tag{6.18}$$

If $Q_i = f(t)$ is divided by the infiltration area A_i, the unit infiltration flow becomes

$$q_i = \frac{Q_i}{A_i} = \frac{1}{A_i} \frac{dV_i}{dt} = \frac{Q - a_f\, r\, p\, t^{r-1}}{A_i} \tag{6.19}$$

Then, for the net infiltration area A_{in}:

$$q_i = \frac{Q\,t^{-r}}{P\,p} - \frac{a_f\,r\,t^{-1}}{P} \qquad (6.20)$$

And for the gross infiltration area A_{ig}:

$$q_i = \frac{Q\,t^{-r}}{w\,p} - \frac{a_f\,r\,t^{-1}}{w} \qquad (6.21)$$

If the same procedure is used for the inflow into the furrow Q, the unit inflow q_0 for the net infiltration area A_{in} becomes:

$$q_o = \frac{Q}{A_{in}} = \frac{Q\,t^{-r}}{P\,p} \qquad (6.22)$$

And for the gross infiltration area A_{ig}

$$q_o = \frac{Q\,t^{-r}}{w\,p} \qquad (6.23)$$

Equations for $q_i = f(t)$ and $q_0 = f(t)$, for the first stage, related to net and gross infiltration areas are included in Table 32. Figures 34 and 35 show the curves derived from those equations for the gross area $w = 1.00$ m of the third irrigation. When $q_0 = f(t)$ and $q_i = f(t)$ are plotted for the same treatment the

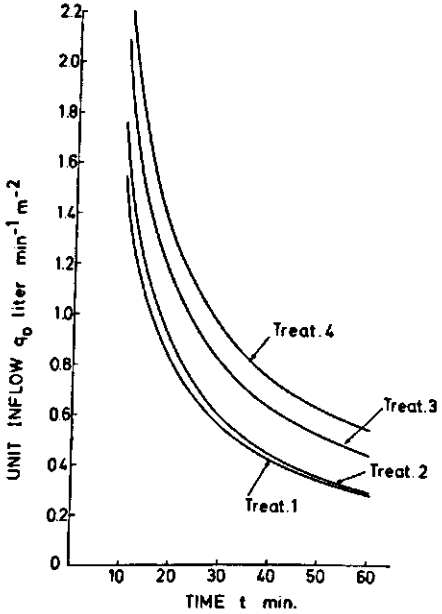

FIG. 34. Furrow inflow q_0 per unit of gross infiltration area $w = 1.00$ m as a function of the advance time t for different inflow sizes. Third irrigation.

curves show convergence for the advance time for which the unit inflow rates approach the infiltration unit flow (Fig. 36). For the largest t values involved, Eq. 6.21 gradually approaches Eq. 6.23.

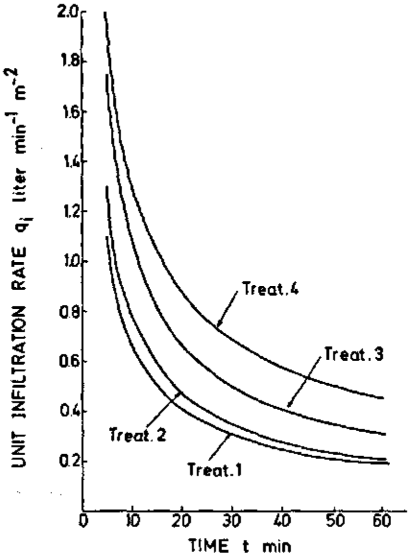

FIG. 35. Furrow infiltrated flow q_i per unit of gross infiltration area w = 1.00 m as a function of the advance time t for different inflow sizes. Third irrigation.

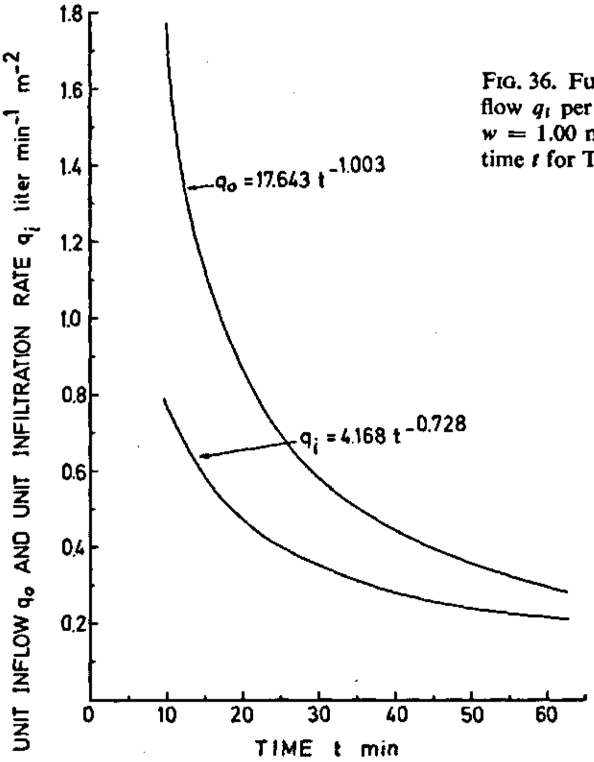

FIG. 36. Furrow inflow q_0 and infiltrated flow q_i per unit of gross infiltration area w = 1.00 m as a function of the advance time t for Treatment 2. Third irrigation.

TABLE 32. *Equations for the unit inflow q_o and unit infiltration rate q_i in liter $min^{-1}m^{-2}$. Third and fourth irrigations. First and second stages.*

			Net area		Gross area	
		Treatment	q_o liter min^{-1} m^{-2}	q_i liter min^{-1} m^{-2}	q_o liter min^{-1} m^{-2}	q_i liter min^{-1} m^{-2}
Third irrigation	1st stage	1	$58.731\, t^{-0.973}$	$15.013\, t^{-0.745}$	$\frac{13.538}{w} t^{-0.942}$	$\frac{3.460}{w} t^{-0.714}$
		2	$75.662\, t^{-1.048}$	$17.873\, t^{-0.773}$	$\frac{17.643}{w} t^{-1.003}$	$\frac{4.168}{w} t^{-0.728}$
		3	$65.297\, t^{-0.933}$	$23.324\, t^{-0.771}$	$\frac{15.305}{w} t^{-0.864}$	$\frac{5.467}{w} t^{-0.702}$
		4	$58.122\, t^{-0.876}$	$20.259\, t^{-0.666}$	$\frac{15.065}{w} t^{-0.815}$	$\frac{5.251}{w} t^{-0.605}$
	2nd stage	1	0.744	$0.703\, t^{-0.357}$	$\frac{37.77}{w\,L}$	$\frac{35.680}{w\,L} t^{-0.357}$
		2	1.055	$1.190\, t^{-0.542}$	$\frac{59.44}{w\,L}$	$\frac{67.045}{w\,L} t^{-0.542}$
		3	1.516	$1.472\, t^{-0.543}$	$\frac{90.96}{w\,L}$	$\frac{88.499}{w\,L} t^{-0.543}$
		4	1.875	$2.128\, t^{-0.605}$	$\frac{119.36}{w\,L}$	$\frac{135.463}{w\,L} t^{-0.605}$
Fourth irrigation	1st stage	1	$69.269\, t^{-1.014}$	$26.579\, t^{-0.910}$	$\frac{15.884}{w} t^{-0.995}$	$\frac{6.095}{w} t^{-0.891}$
		2	$66.708\, t^{-1.001}$	$19.843\, t^{-0.853}$	$\frac{16.230}{w} t^{-0.985}$	$\frac{4.828}{w} t^{-0.837}$
		3	$67.015\, t^{-0.970*}$	$28.845\, t^{-0.888*}$	$\frac{17.452}{w} t^{-0.921}$	$\frac{7.512}{w} t^{-0.839}$
		4	$65.000\, t^{-0.920*}$	$30.314\, t^{-0.843*}$	$\frac{18.786}{w} t^{-0.888}$	$\frac{8.681}{w} t^{-0.811}$

* Valid up to 137.5 m.

6.2.4. *Unit inflow q_0*

If Eq. 3.24 is equated to equations for $q_0 = f(t)$ related to gross area (Table 32), it can be seen that the coefficients have the same order of magnitude in both irrigations. This agrees with the assumption that u (Eq. 3.3) is governed mainly by the slope and that other factors are constant during the trials. When the coefficients and the exponents were averaged, the following general equation was obtained for third and fourth irrigations, relating to gross area:

$$q_0 = \frac{16.238}{w}\, t^{-0.927*} \tag{6.24}$$

The values for each treatment obtained from equations in Table 32, and Fig. 34 show a consistent influence of flow size. Then, ratios of q_0 calculated for each treatment, and q_0 values calculated with the general Eq. 6.24, were obtained for every 10 min from $t = 10$ min to $t = 60$ min. The average of the six ratios was taken as a coefficient C_3 for each treatment. Then:

$$q_0 = C_3\, \frac{16.238}{w}\, t^{-0.927} \tag{6.25}$$

But $q_0 = Q/A_{tg} = Q/w\,x$, and Eq. 6.25 becomes

$$\frac{Q}{w\,x} = \frac{C_3\, 16.238}{w}\, t^{-0.927} \tag{6.26}$$

Because C_3 varies with Q, a flow function: $\phi\,(Q) = Q/C_3\ 16.238$, was obtained (Fig. 37)

Then:

$$x = \phi\,(Q)\, t^{0.927} \tag{6.27}$$

This equation is similar to $x = f(t)$ formula of Table 25 but with average exponent and the consequent correction in the coefficient. If Eq. 6.27 is compared with the advance function (Eq. 3.1), then it appears that p is affected by Q, S_0, roughness and furrow hydraulic characteristics. The average exponent $r = 0.927$, depends on the soil infiltration rate, even though it does not act as an average value.

By substituting in Eq. 6.23, the general expression $p = u\,Q^s$ from Eq. 3.4:

$$q_0 = \frac{Q\,t^{-r}}{w\,u\,Q^s} = \left(\frac{1}{u}\,Q^{1-s}\right)_{av} \frac{t^{-r}}{w} \tag{6.28}$$

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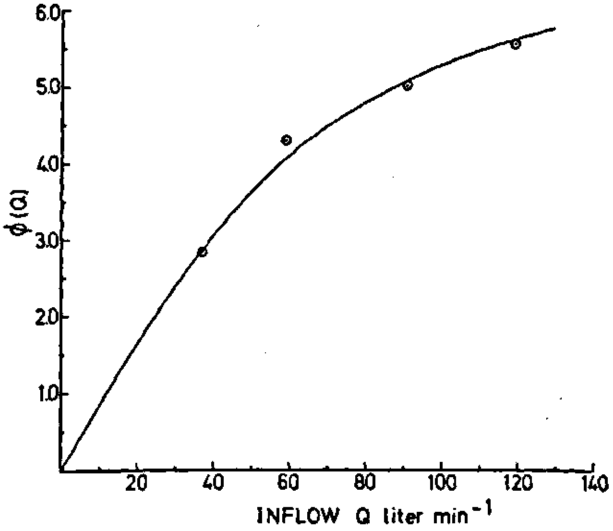
* q_0 in liter min^{-1} m^{-2} and t in min.

FIG. 37. Plot of flow function $\phi(Q)$ against the furrow inflow Q to be used in the advance equation (6.27) third and fourth irrigations.



From Eq. 6.5, $u = 0.0645$, then the average term within brackets, equals the coefficient 16.238 (Eq. 6.24), for an s value very close to 1.0. Eq. 6.26 becomes then:

$$q_0 = \frac{C_3\,Q^{1-s}}{u\,w}\,t^{-0.927} \tag{6.29}$$

The flow function was presented as $\phi(Q) = Q/C_3$ 16.238. If the coefficient 16.238 is substituted for the term within brackets (Eq. 6.28), then:

$$\phi(Q) = \frac{Q\,u}{C_3\,Q^{1-s}} = \frac{Q^s\,u}{C_3} \tag{6.30}$$

As according to Eq. 6.5, $p = u\,Q^s$, a modified formula of Eq. 6.27, for all treatments of the third and fourth irrigations will be:

$$x = \frac{p}{C_3}\,t^{0.927} \tag{6.31}$$

6.2.5. *Relationships between I_{cum} and q_i*

The relationships between I_{cum} and q_i is also analysed. By solving equations 6.13 and 6.19 for A_i, and equating these values we have:

$$A_i = \frac{V_i}{I_{cum}} = \frac{Q_i}{q_i} \tag{6.32}$$

Then, solving for q_l, Eq. 6.32 becomes

$$q_l = I_{cum} \frac{Q_l}{V_t} \tag{6.33}$$

By sustitution of $\bar{I}_{cum}$ from Eq. 3.16 in Eq. 6.33:

$$q_l = \frac{F\, a\, t^{b+1}\, Q_l}{(b+1)(b+2)\, V_t} \tag{6.34}$$

In order to present a simpler formula for q_l, $(a\, t^{b+1}/b + 1)$ in Eq. 6.34 can be replaced by I_{cum_0} (Eq. 2.5). A further simplification of Eq. 6.34 is obtained by substituting $F/(b + 2) = C_2$ (Eq. 3.19), and by combining C_2 with the ratios Q_l/V_t for the treatments of the third irrigation (Table 30) in a coefficient $C_4 = C_2\, Q_l\, t/V_t$ (Table 33).
We have then:

$$q_l = C_4 \frac{I_{cum_0}}{t} \tag{6.35}$$

From Eq. 2.9 follows:

$$q_l = C_4\, I_{av} \tag{6.36}$$

If the coefficient C_4 is unity, Eq. 6.36 is similar to Eq. 3.28 found by NUGTEREN (1969) for $q_0 = q_l$, for the assumption that the advance velocity of the water front is constant. C_4 therefore, can be considered a correction factor related to the F factor (Eq. 3.17).

TABLE 33. Values of Q_l/V_t and coefficients C_2 and C_4. Third irrigation.

Treat.	Q_l/V_t	C_2	C_4
1	$1.228\, t^{-1}$	0.784	0.963
2	$1.275\, t^{-1}$	0.784	1.000
3	$1.162\, t^{-1}$	0.786	0.913
4	$1.210\, t^{-1}$	0.745	0.901

6.2.6. *Dimensionless ratio $Q\, t/V_x$ and $\bar{I}_{cum}/\bar{D}$*

To find a means of checking Eq. 3.11 with the data in this thesis, the dimensionless ratio $Q\, t/\bar{D}\, w\, x$ against $\bar{I}_{cum}/\bar{D}$ was analysed per unit of furrow spacing. Since:

$$\frac{Q\,t}{\bar{D}\,x} = \frac{I_{cum} + \bar{D}}{\bar{D}}$$

Then:

$$\frac{Q\,t}{\bar{D}\,x} = 1.00 + \left(\frac{I_{cum}}{\bar{D}}\right) \tag{6.37}$$

If $C_2 = I_{cum}/I_{cum_0}$, is solved for I_{cum} and substituted in Eq. 6.37, this equation becomes

$$\frac{Q\,t}{\bar{D}\,x} = 1.00 + C_2\left(\frac{I_{cum_0}}{\bar{D}}\right) \tag{6.38}$$

Even though the value of the coefficient C_2 depends also on F, it appears that the coefficients to be used in Eq. 3.11, obtained from Eq. 3.19, are in the same order of magnitude as the ones obtained by WILKE and SMERDON (1965). With data from the experiments for Treatment 1 of the third irrigation (Table 31), $C_2 = 1.008/0.286 = 0.783$. Wilke and Smerdon give for $(b + 1) = 0.3$, a coefficient of 0.792.

6.2.7. *Water balance*

The balance equation at a given advance time expressed as a depth of water can be written:

$$D_{in} = \bar{D} + I_{cum} \tag{6.39}$$

Where

D_{in} is the average depth of water supplied.

The average depth of water $\bar{D}$ and $\bar{I}_{cum}$ in mm for the three water front advance stages ($x = 87.5$ m, $x = 137{,}5$ m and $x = 175.0$ m) are nearly the same for identical treatments (Table 34), excepting the last section of treatments 3 and 4, fourth irrigation, due to flow reduction at $x = 137.5$ m. In general, all values for the same treatment increase with the advance length, although very slightly; and for the same front advance they increase with Q. The differences between treatments 1 and 2 are practically nill, but the other differences between subsequent treatments are much more marked.

The average depth of water absorbed by the soil with respect to the average depth of water supplied to the furrows $(\bar{I}_{cum}/D_{in})$ 100 (Table 34) is practically the same for different advance lengths. But, some increase is shown with increase in Q. In general, these values go from 50% to 60% being greater in the last section of the fourth irrigation of treatments 3 and 4. Then between 30% to 40% remained on the surface. The depth of water on the surface in treatments 3 and 4, fourth irrigation, is lower than in third irrigation because of the flow reduction at $x = 137.5$ m, with no increase of the advance time.

The values of $\bar{D}$ have a small increase with x and with Q; about 35 mm is commonly found for the net infiltration area (Table 34).

TABLE 34. Terms of the balance equation expressed as water depth in mm, for three water front advance stages. Third and fourth irrigations.

		Water front at:											
	Treat.	87.5 m				137.5 m				175.0 m			
		D_{in}	$\overline{D}$	$\bar{I}_{cum}$	$(\bar{I}_{cum}/D_{in})100$	D_{in}	$\overline{D}$	$\bar{I}_{cum}$	$(\bar{I}_{cum}/D_{in})100$	D_{in}	$\overline{D}$	$\bar{I}_{cum}$	$\bar{I}_{cum}/D_{in})100$
Third irrigation	1	68.6	34.8	33.8	49.2	68.5	33.4	35.1	51.3	70.9	33.7	37.2	52.4
	2	68.1	33.3	34.8	51.0	69.8	33.6	36.2	51.7	71.8	34.8	37.0	51.5
	3	90.6	35.9	54.7	60.4	86.0	38.7	47.3	55.0	90.4	39.8	50.6	56.0
	4	94.4	38.1	56.3	59.7	102.4	41.1	61.3	59.8	104.8	41.8	63.1	60.2
Fourth irrigation	1	66.2	33.0	33.2	50.0	68.5	31.7	36.8	53.7	70.4	32.0	38.4	54.4
	2	63.6	31.6	32.0	50.1	65.6	33.2	32.4	49.3	69.0	33.3	35.7	51.6
	3	76.7	37.1	39.6	51.6	78.2	37.8	40.4	51.5	83.8[1]	30.4	52.5	62.5
	4	86.6	39.3	47.3	54.7	90.1	38.6	51.4	57.0	97.0[1]	30.9	66.1	68.3

[1] Reduced inflow.

6.3. INFILTRATION DURING THE SECOND IRRIGATION STAGE

A distinction has to be made between third irrigation with constant inflow Q and fourth irrigation with reduced inflow Q_r.

6 3.1. *Constant inflow: third irrigation*

The values of $Q_i = Q - Q_{out}$ for each trial were first plotted against time in the second stage $t_2 = t - T_1$ and the curve which fitted best, was drawn. By interpolation in these curves, Q_i were obtained (Table 35) for each time interval of 15 min; thus V_i was found for the average Q_i in each interval. With the accumulated V_i values, equations for $V_i = f(t)$ were drawn for each single trial using a computer program developed by the Department of Mathematics. The data of Block A were omitted because they were inconsistent. The analysis of variance* shows significant differences in the coefficients of the equations between treatments 1 and 2 (probability < 0.01) and between treatments 3 and 4, (probability < 0.01) but no differences between treatments 2 and 3. With regard to the exponents, this analysis shows a significant difference between Treatment 1 and the other three, (probability < 0.01) but no differences between treatments 2 and 3, or between treatments 3 and 4. The coefficient of variation CV was 15.4% for the exponents and 14.3% for the coefficients of the equations.

By averaging the coefficients and the exponents for single trial equations, the general function for each treatment was obtained (Table 36). From then on, equations for $Q_i = f(t)$ were obtained by differentiation of the equations $V_i = f(t)$ (Table 36). By making the same analysis as described in Section 6.2.3 we have:

$$Q_i = Q - Q_{out} - \frac{dV_s}{dt}$$

and

$$Q_i = Q - Q_{out} - L\frac{d\,(a_f)}{dt} \tag{6.40}$$

Between the values of V_s for $t_2 = t - T_1 = 0$ min (Table 4) and $t_2 = t - T_1 = 60$ min (Table 6) there is an appreciable increase in water storage. But from $t_2 = 60$ min to $t_2 = 120$ min, this storage remains nearly constant. The increase of the outflow with time is reflecting the changes in V_s, but it cannot clearly be shown because only two measurements of the flow sections were taken during the second stage.

The values of $Q_i = f(t)$, during the first and second irrigation stages, treatments 1 and 3, were plotted in figures 32 and 33. There is a discontinuity between the first and the second stage; during the first stage Q_i is increasing and

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* Student- t-test.

TABLE 35. Furrow inflow and outflow rates in liter sec^{-1} and furrow inflow and outflow volumes in m^3, as a function of the time t_2 of the second stage. Third irrigation.

	Block	Time min	0	15	30	45	60	75	90	105	120
Treatment 1	B	$Q - Q_{out}$	0.456	0.230	0.160	0.155	0.150	0.140	0.130	0.120	0.110
		$V_{in} - V_{out}$		0.309	0.484	0.626	0.763	0.893	1.014	1.126	1.229
	C	$Q - Q_{out}$	0.441	0.280	0.190	0.185	0.180	0.180	0.180	0.175	0.170
		$V_{in} - V_{out}$		0.324	0.535	0.704	0.868	1.030	1.192	1.352	1.507
	D	$Q - Q_{out}$	0.422	0.150	0.140	0.125	0.110	0.110	0.110	0.105	0.100
		$V_{in} - V_{out}$		0.257	0.387	0.506	0.612	0.711	0.810	0.907	0.999
	E	$Q - Q_{out}$	0.433	0.380	0.210	0.145	0.080	0.070	0.060	0.055	0.050
		$V_{in} - V_{out}$		0.366	0.631	0.791	0.892	0.959	1.017	1.069	1.116
Treatment 2	B	$Q - Q_{out}$	0.792	0.340	0.280	0.225	0.170	0.135	0.100	0.095	0.090
		$V_{in} - V_{out}$		0.509	0.788	1.015	1.193	1.330	1.436	1.524	1.607
	C	$Q - Q_{out}$	0.735	0.410	0.130	0.095	0.060	0.060	0.060	0.060	0.060
		$V_{in} - V_{out}$		0.515	0.758	0.859	0.929	0.983	1.037	1.091	1.145
	D	$Q - Q_{out}$	0.675	0.300	0.170	0.120	0.070	0.055	0.040	0.040	0.040
		$V_{in} - V_{out}$		0.439	0.650	0.780	0.865	0.921	0.964	1.000	1.036
	E	$Q - Q_{out}$	0.628	0.380	0.240	0.180	0.120	0.100	0.080	0.075	0.070
		$V_{in} - V_{out}$		0.453	0.680	0.869	1.004	1.103	1.184	1.254	1.319
Treatment 3	B	$Q - Q_{out}$	1.009	0.200	0.180	0.165	0.150	0.125	0.100	0.100	0.100
		$V_{in} - V_{out}$		0.544	0.715	0.870	1.012	1.136	1.237	1.327	1.417
	C	$Q - Q_{out}$	1.057	0.620	0.250	0.225	0.200	0.175	0.150	0.125	0.100
		$V_{in} - V_{out}$		0.754	1.145	1.359	1.550	1.719	1.865	1.989	2.090
	D	$Q - Q_{out}$	0.990	0.500	0.250	0.200	0.150	0.137	0.125	0.112	0.100
		$V_{in} - V_{out}$		0.670	1.007	1.209	1.366	1.495	1.613	1.720	1.815
	E	$Q - Q_{out}$	0.990	0.450	0.200	0.150	0.100	0.100	0.100	0.100	0.100
		$V_{in} - V_{out}$		0.648	0.940	1.097	1.209	1.299	1.389	1.479	1.569
Treatment 4	B	$Q - Q_{out}$	1.552	0.250	0.150	0.150	0.150	0.150	0.150	0.150	0.150
		$V_{in} - V_{out}$		0.811	0.991	1.126	1.261	1.396	1.531	1.666	1.801
	C	$Q - Q_{out}$	1.670	0.700	0.250	0.200	0.150	0.150	0.150	0.150	0.150
		$V_{in} - V_{out}$		1.066	1.493	1.695	1.852	1.987	2.122	2.257	2.392
	D	$Q - Q_{out}$	1.618	0.700	0.300	0.225	0.150	0.150	0.150	0.150	0.150
		$V_{in} - V_{out}$		1.043	1.493	1.729	1.898	2.033	2.168	2.303	2.438
	E	$Q - Q_{out}$	1.419	0.850	0.300	0.250	0.200	0.187	0.175	0.162	0.150
		$V_{in} - V_{out}$		1.021	1.538	1.785	1.987	2.161	2.324	2.476	2.616

during the second stage it is decreasing. The infiltration area A_t is constant for a gross area $A_{tg} = w\,L$, and should be variable for the net one $A_{tn} = P\,L$. But due to the lack of data, A_{tn} was taken as a constant for each treatment and the values used were averages for $t_2 = 60$ min and $t_2 = 120$ min.

The equations for the third irrigation show that intake rates for the first and second stages vary greatly, being much smaller during the second stage. The effect of the flow size on infiltration is clearly shown in Fig. 38, where I_{cum} was plotted against Q, for different infiltration times for the third irrigation with gross area $w = 0.70$ m. The relation is curvilinear for the first stage and linear for the second stage.

Table 36. Infiltration equations for the second irrigation stage. Third irrigation.

Treat.	V_t m³	Q_t liter min⁻¹	Net area		Gross area[1]	
			$\bar{I}_{cum}$ mm	$\bar{I}$ mm min⁻¹	$\bar{I}_{cum}$ mm	$\bar{I}$ mm min⁻¹
1	$0.0555\, t^{0.643}$	$35.680\, t^{-0.357}$	$1.093\, t^{0.643}$	$0.703\, t^{-0.357}$	$\frac{0.317}{w} t^{0.643}$	$\frac{0.204}{w} t^{-0.357}$
2	$0.1464\, t^{0.458}$	$67.045\, t^{-0.542}$	$2.599\, t^{0.458}$	$1.190\, t^{-0.542}$	$\frac{0.837}{w} t^{0.458}$	$\frac{0.383}{w} t^{-0.542}$
3	$0.1938\, t^{0.457}$	$88.499\, t^{-0.543}$	$3.224\, t^{0.457}$	$1.472\, t^{-0.543}$	$\frac{1.107}{w} t^{0.457}$	$\frac{0.506}{w} t^{-0.543}$
4	$0.3434\, t^{0.394}$	$135.463\, t^{-0.605}$	$5.395\, t^{0.394}$	$2.128\, t^{-0.606}$	$\frac{1.962}{w} t^{0.394}$	$\frac{0.774}{w} t^{-0.606}$

[1] For $L = 175.0$ m.

In Fig. 39 some of the hydraulic characteristics of the furrow taken from the average values in Table 6, were plotted as a function of Q for the third irrigation, second stage. It is evident that P, a_f and the hydraulic radius R_h increase along with Q. Values for other flow sizes can be obtained by interpolation in the curves for the same furrow size, shape, surface roughness and slope.

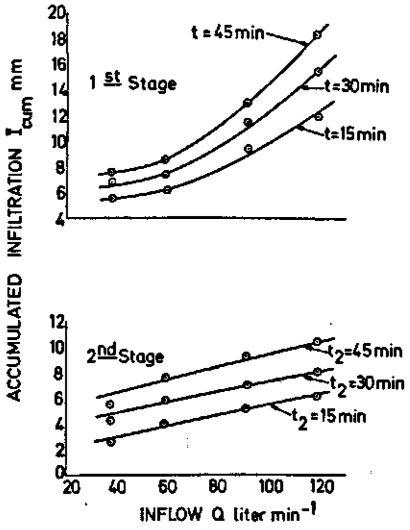


Fig. 38. Plot of the data of accumulated intake $\bar{I}_{cum}$ as a function of the inflow size Q obtained by means of equations for first and second stage, third irrigation.

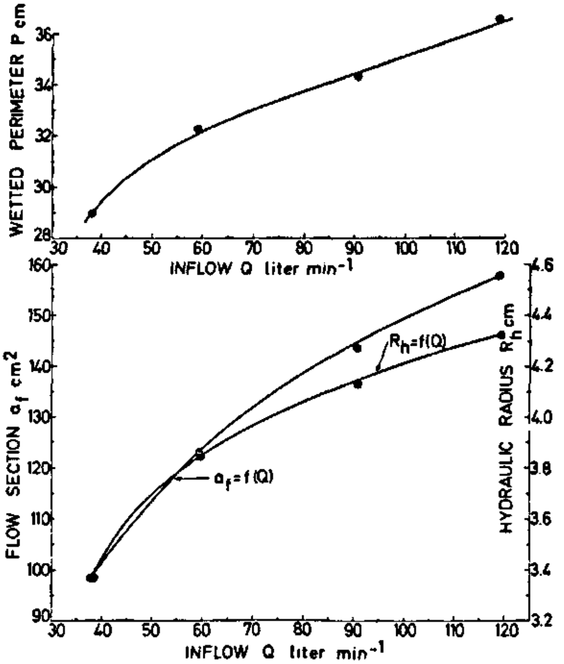


FIG. 39. Furrow hydraulic flow characteristics obtained for the second stage.

6.3.2. *Unit inflow q_0 and unit infiltration flow q_i*

For a constant furrow length L, $q_0 = Q/w\,L$ remained constant and q_i varied as a function of time. As $q_i = Q_i/w\,L$, one obtains by substitution of Q_i from Eq. 6.40:

$$q_i = \frac{(Q - Q_{out})}{w\,L} - \frac{1}{w}\,\frac{d\,(a_f)}{dt} \tag{6.41}$$

In Fig. 40 the curves for $q_i = f(t)$ were drawn for the third irrigation on the gross area. The values of $q_i/q_0 = f(t)$ for time intervals up to 120 min, were calculated by using the equations in Table 32. As during the first irrigation stage, the values for different treatments did not differ much. So, the general equations for Q_i and q_i are as follows:

$$Q_i = 1.077\,t_2^{-0.564}Q \tag{6.42}$$

$$q_i = 1.077\,t_2^{-0.564}q_0 \tag{6.43}$$

The values for each treatment obtained from equations in Table 32 and Fig. 40, show a consistent influence of the flow size. Then, ratios of q_i calculated for each treatment, and the values calculated with the general equation (6.43) were

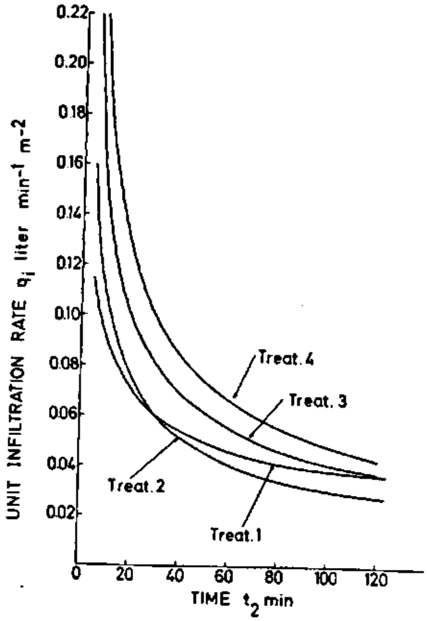


FIG. 40. Furrow infiltration flow q_i per unit of gross infiltration area $w = 1.00$ m as a function of the second time stage t_2 for different inflow sizes, third irrigation.

obtained for 30 min, 45 min, 60 min, 90 min and 120 min of the second stage. The averages of the five ratios was taken as a coefficient C_5 for each treatment, from the data of treatments 2, 3 and 4. The data of Treatment 1 were not used because the exponent was very different from the one of the other treatments. Then, as q_i in liter min^{-1} m^{-2} is equivalent to $\bar{I}$ in mm min^{-1}, Eq. 6.43 for the net infiltration area $A_{in} = P\,L$ becomes

$$\bar{I} = \frac{C_5\, Q\, 1.077}{P\, L}\, t_2^{\,-0.564} \qquad (6.44)$$

Because C_5 varies with Q, a flow function: $\omega(Q) = C_5\, Q\, 1.077$ was obtained (Fig. 41). Then

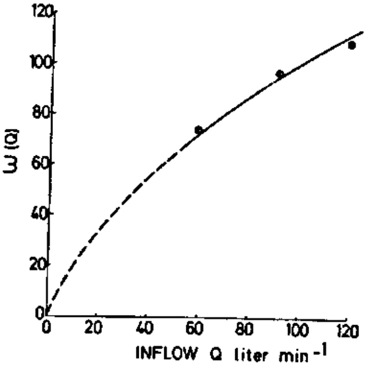


FIG. 41. Plot of flow function ω (Q) against furrow inflow Q to be used in the general equations 6.44 to 6.47, third irrigation.

$$I = \frac{\omega(Q)}{P\,L} t_2^{-0.564} \tag{6.45}$$

For the gross infiltration area $A_{ig} = w\,L$ we have:

$$I = \frac{\omega(Q)}{w\,L} t_2^{-0.564} \tag{6.46}$$

Integrating with respect to time, between 0 and t_2, i.e.:

$$I_{cum\,2} = \frac{\omega(Q)}{w\,L}\int_0^{t_2} t_2^{-0.564}\, dt_2$$

$$I_{cum\,2} = \frac{\omega(Q)\, t_2^{-0.564+1}}{(-0.564+1)\,w\,L}$$

$$I_{cum\,2} = \frac{\omega(Q)\, t_2^{0.436}}{0.436\,w\,L} \tag{6.47}$$

Then for any given Q value, the greater the value of L, the greater will be the average previous wetting during the first stage, and the lower the values of I (Eq. 6.46). Under the given conditions of the experiments this effect will be accounted for in the flow function $\omega(Q)$.

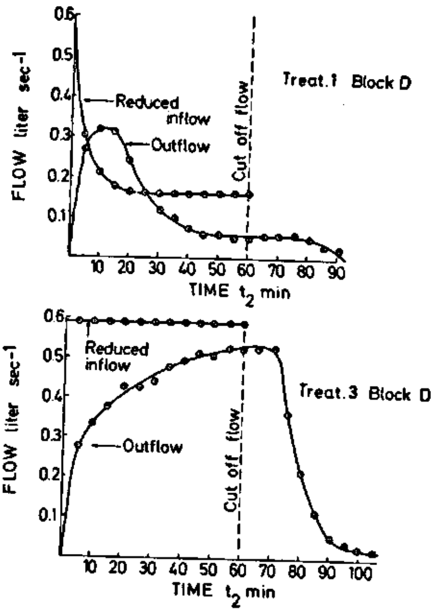
6.3.3. *Reduced inflow*

In the case of the fourth irrigation, instantaneous values of $Q - Q_{out}$ and the accumulated values of V_{in} and V_{out} for time intervals of 15 min are presented in tables 8, 9, 10 and 11. In investigating the effects of reduced flow, two periods were distinguished: (i) reduced inflow, with records of in- and outflow; (ii) cut-off inflow being the recession stage during which only the outflow was recorded.

Also in this case of inflow reduction, the second infiltration time stage begins with $t_2 = 0$ min when $x = L = 175.0$ m. The difference in the shape of the curves of Q (Fig. 42) for both treatments is due to the fact that the reduction inflow was executed upon arrival of the water front at the end of the furrows in treatments 1 and 2, whereas in treatments 3 and 4 the reduction was executed at 78.5% of the run.

Infiltration equations are not presented due to the variable inflow and the importance of change of storage under such conditions. The data can be used for single furrow analysis of second stage and recession stage and also by averaging the replicates of each treatment.

FIG. 42. Furrow flow hydrograms, inflow and outflow, for reduced inflow. Treatments 1 and 3, fourth irrigation.



6.4. INFLUENCE OF THE INITIAL SOIL WATER CONTENT

Table 12 includes the instantaneous values of infiltration flow, Q_i for the second stage, in furrows of a constant length $L = 175.0$ m. Flow measurements were not taken at constant intervals. Once the best fit curve for $Q_i = f(t)$ was drawn, values of Q_i were interpolated to extend the data.

Equations for single furrows were obtained as $Q_i = f(t)$ by using a computer program developed by the Department of Mathematics. Then by averages of the coefficients and the exponents of the equations for four replicates in treatments 1 and 2 and two replicates in Treatment 3, the general equations for each treatment were drawn. Such equations were converted to infiltration rate I in mm hr^{-1} for a gross infiltration area $A_{i_g} = 175.0 \times 0.70 = 122.5$ m^2, as follows:

Treat.	*Soil moisture content*	I mm hr^{-1}
1	Low (16.3%)	$I = 22.188\, t_2^{-0.340}$
2	Moderately moist (19.3%)	$I = 17.856\, t_2^{-0.363}$
3	Very high (Nearly saturated)	$I = 14.351\, t_2^{-0.361}$

These equations (Fig. 43) show only small variation in the exponent, but an apparent reduction in the coefficient with an increase of initial soil moisture content. The analysis of variance* show however, that these differences are not

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* Student t-test.

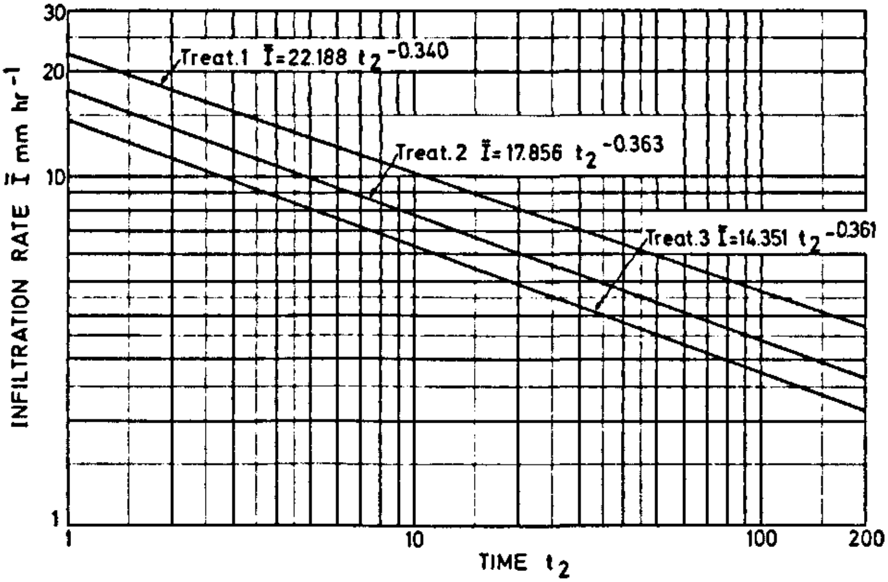

Fig. 43. Infiltration rate $\bar{I}$ as a function of time during the second stage t_2. Variable initial soil moisture content. Second irrigation.

significant. It is evident that the lay-out of this series of experiments has definite effects on the results as shown above, and the infiltration functions do not represent the entire experimental field.

6.5. INFLUENCE OF FURROW LENGTH

In these trials the flow measurements, inflow and outflow during the second stage, were taken at pre-established time intervals. The values of Q_t in liter sec^{-1} for each accumulated time are listed in Table 13. With these data, equations for $\bar{I} = f(t)$, related to gross infiltration area, were obtained (Fig. 44) by the same procedure as was explained in Section 6.4, in this case, however for five replicates of each treatment.

The curves (Fig. 44) show that with increasing L, or the degree of variation in wetting, the coefficients decrease and the exponent of t in the equations increases:

Treat.	*Furrow length m*	$\bar{I}$ mm hr^{-1}
1	62.5	$\bar{I} = 172.710\, t_2^{-0.830}$
2	125.0	$\bar{I} = 59.780\, t_2^{-0.652}$
3	175.0	$\bar{I} = 27.395\, t_2^{-0.544}$

The analysis of variance* show significant differences between the treatments

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* Student t-test.

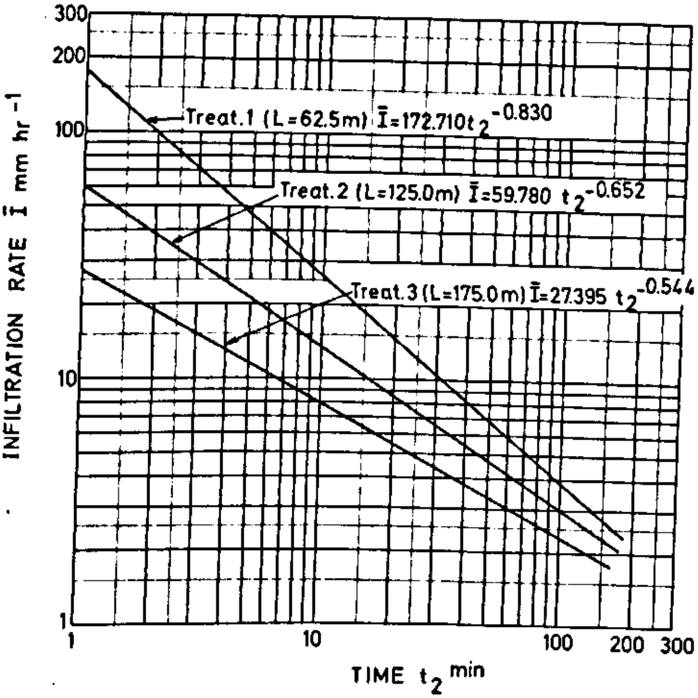

FIG. 44. Infiltration rate $\bar{I}$ as a function of time during the second stage t_2. Variable furrow length. Fifth irrigation.

to exist in the coefficients (probability < 0.05 between treatments 1 and 2 and probability < 0.01 between treatments 2 and 3), as well as in the exponents (probability < 0.01 between treatments 1 and 2 and probability < 0.05 between treatments 2 and 3). It is noted that the exponent and the coefficient of the equation for $L = 175.0$ m suit rather well the ones of Eq. 6.46.

The availability of Q_i and Q_{out} data for different furrow sections permitted the determination of $Q_i = f(t)$ values for three furrow sections, as if they were in the same furrow with flow meters between each section. Fig. 45 show the hydrographs with constant inflow at the furrow head, and the outflow at 62.5 m, 125.0 m and 175.0 m. Timing started with the application of water at the furrow head, so the beginning of run-off is delayed in each section by the advance time. Some small differences in the recorded inflow of each treatment made it necessary to adjust the outflow values.

Q_i was expressed as the difference between two successive curves for a time period which included the time during which the measurements for the four curves were made (Fig. 45). The curves of $Q_i = f(t)$ in the three furrow sections, for the time length of the selected period which covered 40 min after the 175.0 m was reached, are shown in Fig. 46. This result clearly shows the effect of furrow length and the amount of soil water that infiltrated into the soil during the wetting period, on the infiltration equation parameters, when the inflow-outflow method is used.

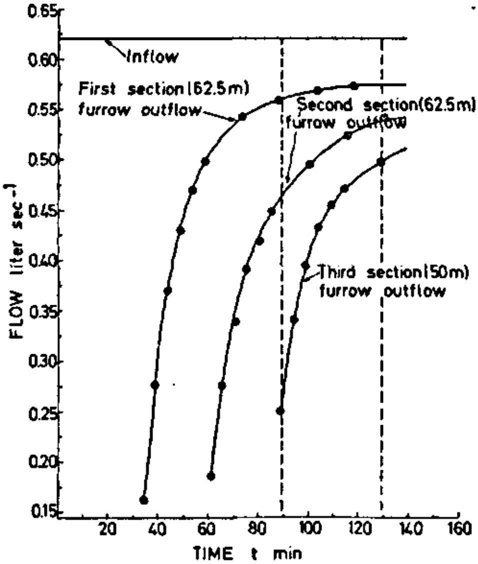

FIG. 45. Furrow flow hydrograph. Inflow to the furrow head and outflow from different furrow section along the furrows. Fifth irrigation.

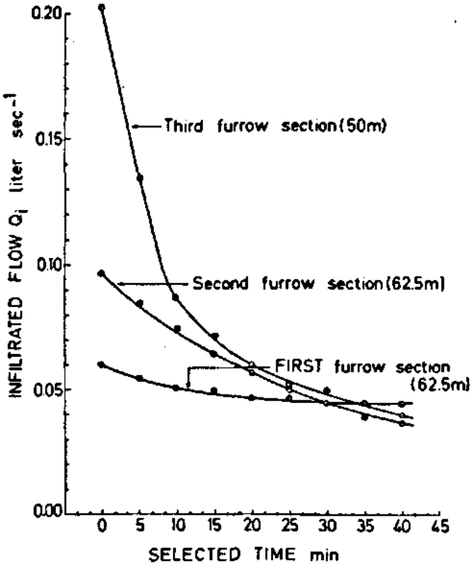

FIG. 46. Simultaneous infiltration rate Q_i as a function of the selected time in three furrow sections along the hypothetical furrow length. Fifth irrigation.

6.6. IRRIGATION EFFICIENCY

The direct measurements and the general equations obtained, enable us to account for deep percolation and run-off losses.

To determine deep percolation losses below a certain soil depth, the infiltration profile as a result of irrigation must be known. Fig. 47 shows the infiltration profiles, measured in the first series of experiments in each treatment of the third irrigation during the advance time and the second stage $t_2 = 120$ min, related to the gross width $w = 0.70$ m. If a net depth of water D_n has been applied at the end of the furrow and by taking D_{av} as the average of the I_{cum} values for the eight stations along the furrow (at 25.0 m distance), percentile ratios were obtained to account for water losses, in relation to the infiltrated flow and to the total depth of inflow D_{in} (Table 37).

The data show that percolation losses $D_p = D_{av} - D_n$, range between 5.6% and 8.2% of the average infiltrated depth. Such losses may be considered rather small, realizing that $t_2 = 120$ min is somewhat short for the depth of water usually to be restored to the soil by irrigation, and that deep percolation losses diminish as time increases. Contrary, irrigation efficiency $E_f = (D_n/D_{in})\,100$ is very low, ranging from 26.5% to 34.7%. Therefore, the greatest effort must be devoted to lessen run-off losses by reducing the inflow.

The fourth irrigation was then analysed in relation to the incidence of flow

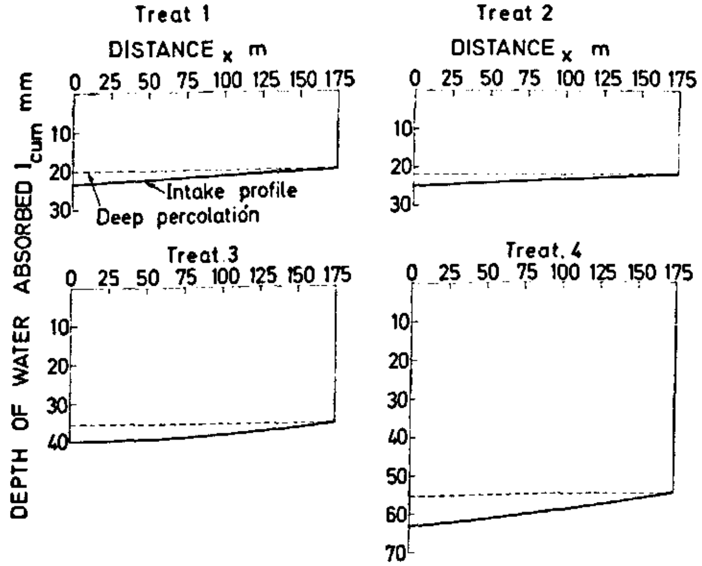

FIG. 47. Water intaken depth profiles along the furrow length for constant time of the second stage $t_2 = 120$ min. Third irrigation.

TABLE 37. Water losses and irrigation efficiency. Third irrigation, gross area $w = 0.70$ m.

Treat.	$(D_n/D_{av})\,100$	$(D_n/D_{in})\,100$	$(D_p/D_{in})\,100$
1	91.8	32.6	2.9
2	94.4	26.5	1.6
3	94.2	28.2	2.0
4	93.9	34.7	2.6

reduction. The averages of the measured volumes V_{in}, V_{out}, V_i and V_s for the five replicates were used (tables 5, 8, 9, 10 and 11). Change of storage V_s between $t_2 = 0$ min and $t_2 = 60$ min was taken into consideration in order to obtain the infiltrated volumes during the second and third stage (Table 38).

As deep percolation losses are not significant the value (V_i/V_{in}) 100 serves as an indication of efficiency. The values of (V_i/V_{in}) 100 (Table 38) clearly points out that flow reduction has lead to reasonably good values of the field application efficiency in every case. This in comparison with Table 37 shows an important effect as a consequence of reducing the flow. In principle a greater inflow (treatments 3 and 4), with flow reduction before the end of the run, has given rather good results. But Treatment 1 ($Q = 36.47$ liter min^{-1} and $Q_r = 9.0$ liter min^{-1}) was the most effective, followed by Treatment 2 ($Q = 59.63$ liter min^{-1} and $Q_r = 16.8$ liter min^{-1}), both having the flow reduction applied exactly when the end of the run is reached.

6.7. IRRIGATION DESIGN AND WATER MANAGEMENT

The management of flow sizes for different furrow length, spacing and net depth of water to be applied, is here being considered for the case of the third irrigation. Four different curves were plotted in figures 48 and 49 for respectively treatments 1 and 3 with gross infiltration area. The values for $q_0 = f(t)$ and $q_i = f(t)$ have to be divided by w if the spacing differs from unity.

For the furrow length L on the right vertical scale, the advance time can be read on the horizontal scale, and the corresponding values for q_0 and q_i for the first stage on the left vertical scale. For large length of run L, q_0 approaches q_i, which means that nearly all the inflow will infiltrate into the furrow.

Also, $q_i = f(t)$ for the second stage has been represented in the lower part of the figure for $L = 175.0$ m and $w = 1.00$ m. For other furrow length, as the intercept is inversely proportional with length, a different intercept will be found in accordance with the equations in Table 32, by multiplying the given coefficient by the ratio $175/L$. The slope of $q_i = f(t)$ is of the same magnitude during the first and second stages. The intercept of $q_i = f(t)$ for the second stage is very close to the q_i-value of first stage for the moment that the end of the run is reached. In fact this latter value equal the q_i-value for the second stage a few minutes after the beginning hereof. It has already noted in Section 6.3.1, that due to a discontinuity the two values do not exactly match at time T_1.

In view of the importance of applying reduced inflow, a flow must be selected for the second stage by using the q_i-function. Generally it can expected that q_i-values for $t_2 = 30-60$ min will be adequate, as sufficient stored volume is available to cover the flow required for infiltration in excess of the cut-back inflow. Even though q_i during the latter part of the first stage could be nearly as great as q_0, the water volume remaining in the furrow channel will give the extra flow required at the beginning of the second stage for an infiltration rate greater than the selected cut-back inflow.

TABLE 38. Water losses and irrigation efficiency. Fourth irrigation, gross area $w = 0.70$ m.

Treat.	Time min			V_{in} m³			V_l m³				$(V_l/V_{in})100$	D_{av} mm
	T_1	t_2	t_3	1st	2nd	T_1+t_2	1st	2nd	3 rd	$T_1+t_2+t_3$		
1	84	60	30	3.064	0.699	3.763	1.671	0.744	0.522	2.937	78.0	24.0
2	55	60	30	3.280	1.190	4.470	1.697	0.812	0.746	3.255	72.8	26.6
3	49	60	45	3.958	2.129	6.087	2.479	0.583	0.874	3.936	64.7	32.1
4	48	60	45	4.744	2.311	7.055	3.229	0.479	1.063	4.771	67.6	38.9

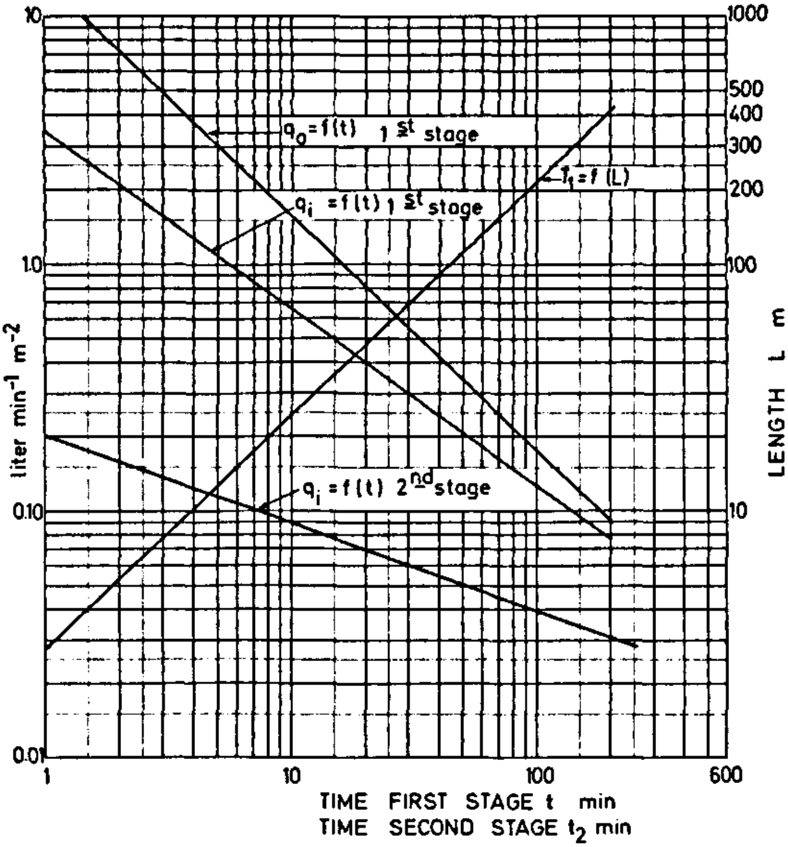

FIG. 48. Composite figure: L, q_0 and q_i as a function of t first stage ($w = 1.00$ m) and q_i as a function of t_2 second stage Treatment 1, third irrigation.

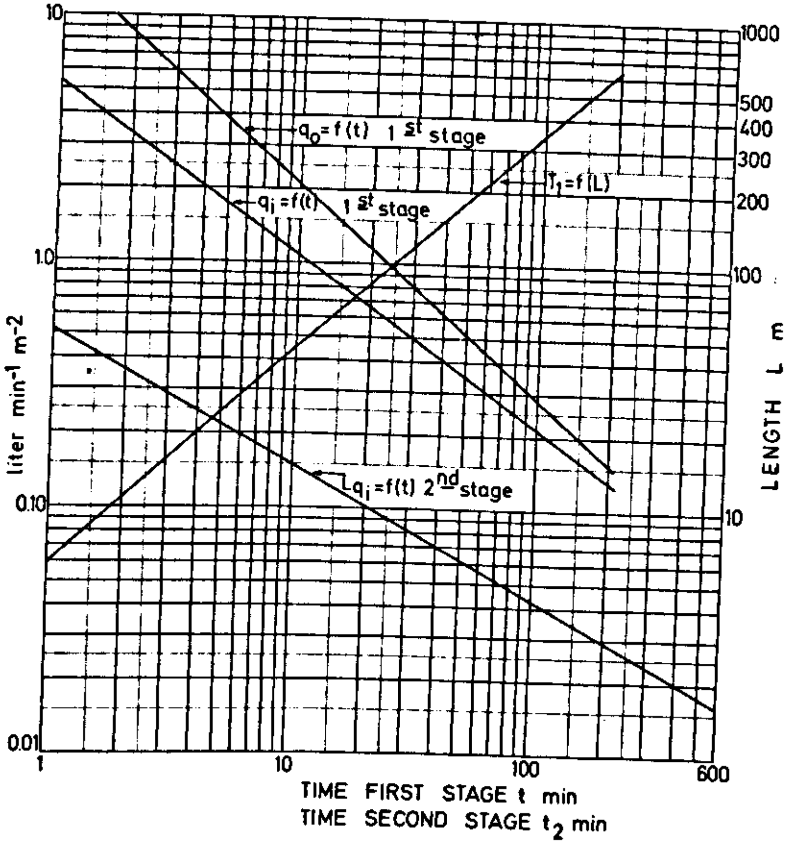

FIG. 49. Composite figure: L, q_0 and q_i, as a function of t first stage ($w = 1.00$ m) and q_i as a function of t_2 second stage. Treatment 3, third irrigation.

7. DISCUSSION

1. *Rate of advance of the water front*

The advance rates of each treatment differed widely between the first irrigation, when the furrows were newly made, and later irrigations, if the same furrows were compared. Noteworthy differences between replicates of the same treatments were also recorded. They occurred mainly during the first irrigation, when the soil was loose and the surface rough. Such differences were expected as microrelief and roughness have a great effect on the movement of shallow water.

The single trial data fitted the advance equation (3.1) in exponential form very well, for $12.5 \text{ m} < x < 175.0 \text{ m}$, as is evident from the high values of the multiple correlation coefficient R^2 (Table 24). The coefficient of variation CV of the coefficients and the exponents in the general equations (Section 6.1), however, are rather high even for a smooth surface in the third and fourth irrigations. Hence, the general equations derived from the data of five replicates, are useful for predicting average rates of advance in an irrigated field, but the curve for a single furrow may differ greatly from the average. Consequently, field experiments should include sufficient replicates to provide statistically reliable results. Furthermore, if the irrigation supply is not seriously limited, delivery schedules may provide for a certain margin in the delivery time for furrows in accordance with the standard deviation.

The differences in advance curves between first and third irrigation (figures 20 and 21) became smaller as flow increased. This could be attributed to less remodelling of the furrow bed by a small flow in a loose, newly made, furrow than in case of a large stream of greater velocity. In Treatment 4, the flow is such that differences between the first and later irrigations become insignificant.

The analyses of data show that: (i) during the first irrigation, with loose soil, a great variation in the advance rate is to be expected; (ii) the advance rates of subsequent irrigations do not differ much when the furrow is smooth and free of vegetation; (iii) flow reduction – at least for greater inflows – does not affect the average rate of advance, if three quarters of the length has been covered before the inflow is reduced.

If in Eq. 3.5 the exponent $r = 1.0$, the advance rate $dx/dt = p$, which can be considered a constant. For given constant conditions regarding inflow, slope, furrow size, shape and roughness the exponents, however, must be less than unity. The data for single trials (Table 24) show, on the contrary, some r values greater than 1.0, which can be attributed to variabilities in one or more of these factors under the conditions of the trials.

One factor worth mentioning, wich could have been a source of such variability is the increase of the flow size along the length of the run by leakage from the adjacent buffer furrows. To prevent leakage through cracks connecting the test furrow with the buffer furrows, inspections were continously carried out during the trials, but in some cases it may have happened that leakage had increased the flow substantially before this was detected.

Another variation in the above indicated condition, might have been a deformation of the stream bed, during the advance period, resulting in a smoother wetted perimeter. This, possibly, may have caused the majority of treatments 2 having an exponent larger than unity.

As the soil involved is of fine texture, the diffusive action during the initial infiltration may dominate the gravity action, and, therefore, exponents of t close to unity in the advance equation were expected. Then, although advance equations with an exponent of t greater than 1.0 are theoretically unexplainable, it is possible that under field conditions they do occur, as a consequence of variations in furrow conditions during the advance.

2. *Aspects of infiltration*

The equations for $V_i = f(t)$ of the first stage (Table 30), consistently show an exponent of t greater than 1.0. If $V_i = f(t)$ is developed as in Eq. 6.10, the terms can be presented in a graph (Fig. 50) as a function of the advance time t. The inflow volume $Q\ t$ is proportional and $V_s = a_f\, p\, t^r$ is a parabolic function of time. If V_s is substracted from $Q\ t$, a curve of V_i against t is obtained with a time exponent greater than 1.0. In an indirect way it can also be stated that, as $I_{cum} = V_i/w\, p\, t^r$, in order to arrive at a positive exponent $(b + 1)$ of t with r approaching 1.0 (Table 25), the exponent of t in the $V_i = f(t)$ equation must be greater than unity.

There is a discontinuity in the curves representing $Q_i = f(t)$ over the period of both stages (figures 32 and 33). In the first stage infiltration takes place and is recorded over an increasing area, as the water front moves ahead over dry soil, whereas in the second stage, infiltration results from the difference between Q and Q_{out}. The peak values of Q_i at the beginning of the second stage, as compared to those at the end of the first stage could be ascribed to errors in best fit functions near the boundary of validity. During the second stage, a change in water storage at the beginning of that stage, contributed to the apparent discontinuity.

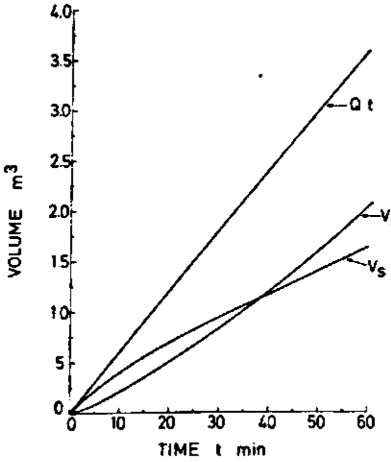

FIG. 50. Curves showing the inflow volume $V_{in} = Q\ t$, surface volume V_s and infiltrated volume V_i, as a function of the advance time t.

The infiltration parameters for the advance stage, show some differences between the third and fourth irrigations. The coefficient $A = a/(b + 1)$ (Eq. 2.6) of the accumulated infiltration function is greater, and the exponent, $B = b + 1$, is smaller in the fourth than in the third irrigation. The differences in values of the infiltration parameters can be ascribed to the degree of soil cracking. Although it was not quantitatively assessed, the furrow channels at the start of the fourth irrigation showed more cracks than in the third irrigation. More severe cracking would have yielded a greater initial capacity to absorb water and would have led to a greater decrease of intake rate with time.

The effort made in measuring the furrow section parameters h and T, appears justifiable in order to obtain the infiltrated volume V_i as the difference between supplied volume $Q\,t$ and stored volume V_s for different advance phases ($x = 87.5$ m, $x = 137.5$ m and $x = 175.0$ m). Furthermore, the furrow section parameters allowed to compute the average wetted perimeter and to get equations for the net area of infiltration $A_i = f(t)$. Therefore, infiltration equations were expressed for the net infiltration area and for the gross infiltration area.

Table 31 shows that the coefficients A and a of the infiltration equations, for the gross area, can be directly adjusted to the furrow spacing, and, further, that the exponents B and b differ very little between the infiltration equation for the net and gross area. In view of the advantages, for the design and management of furrow irrigation systems, of expressing infiltration in relation to the furrow spacing, the analysis of data in this thesis is mainly related to the gross infiltration area. It is noted, however, that with spacings less than 0.70 m slight changes in the infiltration function may occur due to coalescence of adjacent wetting patterns in the soil profile.

3. *Effect of flow size on infiltration rate*

The effect of flow size on infiltration has been clearly shown for both stages (figures 31 and 38). The effect of increasing flow on furrow infiltration is usually explained by a greater net infiltration area in relation to gross area. But in view of the values given for the net area, a more elaborate analysis is required. Differences in head recorded for each one of the treatments could be a cause for the increase of infiltration rate with the flow size, but not the only one, since the measured differences in h (tables 4 and 5) are small.

The effect on infiltration of different heads as a result of unequal water levels in buffered cylinder infiltrometers has been analysed by BOUWER (1963). The differences in infiltration due to this factor are greater than those found between treatments in the experiments. ZASLAVSKI (1969) discussed the lack of proportionality between head and infiltration at low heads, and concluded that proportionality is obtained only at heads in excess of about 10 cm.

Values of D_{in} and I_{cum} for four advance stages are compared for the third irrigation (Table 39). The differences in D_{in} and hence in I_{cum} are small between treatments 1 and 2. But I_{cum}-values increase consistently with the inflow Q. The differences observed in the experiments should then be ascribed to a larger volume of water in the furrow. Next to the effect of the larger perimeter for larger flow sizes, it is probable that the edges of the wetted surface account for a relative increase of infiltration, when these are closer to the top of the ridges, since the soil in this area is undoubtely of a much lower soil moisture content before irrigation than the average of the profile.

Data from Holmen cited by HENDERSON and HAISE (1967) showed that the rate doubled with an increase of furrow flow from 22.7 liter min^{-1} to 53.0 liter min^{-1} for a slope of less than 0.5%. Other data for sloping lands obtained by Mech, also cited by HENDERSON and HAISE (1967), indicate a less significant increase in rate with an increase in flow. COLLINS and CAMPBELL (1967) found a linear relation between accumulated intake and flow size for a silty clay loam soil. This agees with the findings in this thesis for the second stage (Fig. 38).

4. *Advance and intake function parameters*

The advance equations for single trials, third and fourth irrigations (Table 24) show that the coefficient p tends to increase with the inflow Q. The general equations (Table 25) and Fig. 24, show the relationship of p with Q. As the exponent (Eq. 3.4) may vary with slope (VIERHOUT, 1971) the agreement amongst irrigations in the same furrows is understandable. The parameter u (Eq. 3.4) is the same for both irrigations (Fig. 24), even though the furrow surface appeared to be more cracked in fourth than in the third irrigation.

The exponent of the advance equation r did not remain constant as was expected from earlier studies (Section 3.4). The exponents of the equations for single furrow trials (Table 24) tend to be lower when Q increases, as is also the case in the general equations (Table 25). Equations found by NUGTEREN (1969) with data from Wonji and from Criddle *et al.* for different Q-values show a constant value of r. Other trials of GRASSI *et al.* (1965) in a silty loam soil with variable roughness and Q show also a small variation in the exponent.

The differences found for r are rather small, and statistically not significant, nevertheless the physical significance of such a trend merits some discussion. The soil was certainly the same, but infiltration rates depended on inflow size. If it is certain that a difference in infiltration between treatments may be attributed to the effect of flow size, then such a difference has an apparent influence on the exponent of t in the advance equation as well. FOK and BISHOP (1965) relate the

TABLE 39. Values of D_{in} and $\bar{I}_{cum}$ in mm, for 15 min time increments during the advance stage. Third irrigation, gross area $w = 0.70$ m.

Treat.	$t = 15$ min.		$t = 30$ min		$t = 45$ min		$t = 60$ min	
	D_{in}	$\bar{I}_{cum}$	D_{in}	$\bar{I}_{cum}$	D_{in}	$\bar{I}_{cum}$	D_{in}	$\bar{I}_{cum}$
1	22.6	8.7	23.6	10.6	24.1	11.9	24.5	13.0
2	25.2	9.8	25.2	11.9	25.2	13.3	25.2	14.4
3	31.6	15.1	34.7	18.5	36.7	20.9	38.2	22.8
4	35.5	18.1	40.4	23.7	43.5	27.9	45.9	31.2

Table 40. Actual values of r and estimated values of r. Third irrigation, gross area.

Treat.	Actual		Estimated r
	r	b	$r = l^{-0.6(b+1)}$
1	0.942	−0.714	0.843
2	1.003	−0.725	0.849
3	0.864	−0.702	0.837
4	0.815	−0.605	0.790

exponent r of the advance equation with the exponent $(b + 1)$ of the infiltration equation as: $r = e^{-0.6(b+1)}$. The values of r computed by the Fok and Bishop equation are compared with the actual values for the case of the third irrigation with a gross area (Table 40). From that table can be concluded that all r-values are higher than follows from the Fok and Bishop equation.

Due to small differences in the b-data no correlation with r can be derived from the experiments. As the result of the available data can be given an approximation, valid within the scope of the experiments only: $r = -1.35\, b$.

5. *Predicting advance*

Hall (1956), Philip and Farrel (1964), Fok and Bishop (1965) and others offered procedures, based on the balance equation to predict the advance in surface irrigation. The procedures require an approximation of the average depth of water on the soil surface at a given advance time. The surface storage coefficient C_1 and the infiltration coefficient C_2 to solve the balance equation (3.8) for predicting advance can be obtained with the data from the experiments.

The surface storage coefficient $C_1 = \bar{D}/D_0 = V_s/a_{f_0}L$, wherein V_s is the volume of water in the furrow channel when the end of the run $x = 175.0$ m is reached (tables 4 and 5), and a_{f_0} is the streamflow cross-section at the furrow intake $x = 0$ m. In the experiments a_{f_0} was not measured. However, in view of the very small infiltrated flow Q_t in relation to the inflow Q, at the time of the second stage $t_2 = 120$ min, the value of $a_{f_0}L$ can be approximated with the value of $a_f\, L$, taken at that time (Table 6). As can be seen in figures 32 and 33 for treatments 1 and 3 of the third irrigation, the rate of change of the infiltrating flow is very small at time $t_2 = 120$ min. The values of $C_1 \cong V_s/a_f\, L$ and the ones obtained according to Fok and Bishop (Eq. 3.20) are included in Table 41.

The results in the last column indicate that the assumption: $h = D_0\,(1 - t_x/t)$, on which Eq. 3.20 is based, is apparently not applicable to the conditions, of the experiments. The high values of $C_1 \cong V_s/a_f\, L$ are not unexpected considering the soil, the topography and the length of run. $C_1 \rightarrow 1.0$ for steep slopes, large advance distances and small intake rates (Bishop *et al.*, 1967). The trials were conducted on gently sloping land $S_0 = 0.18\,\%$, but the infiltration rate was certainly low and the advance distance ($L = 175.0$ m) rather large.

Table 41. Values of the surface storage coefficient C_1 obtained from data of the third irrigation.

Treat.	r	$a_f L(t_2=120 \text{ min})$	$V_s(t_2=0 \text{ min})$	$C_1=V_s/a_f L$	$C_1=1/1+r$
1	0.942	1.720	1.562	0.908	0.515
2	1.003	2.191	1.701	0.776	0.500
3	0.864	2.487	2.121	0.853	0.536
4	0.815	2.773	2.377	0.857	0.551

Table 42. Values of the infiltration coefficient C_2 obtained from data of the third and fourth irrigations.

	Third Irrigation			Fourth Irrigation		
Treat.	F	b	C_2	F	b	C_2
1	1.008	−0.714	0.784	1.000	−0.890	0.901
2	1.000	−0.725	0.784	1.001	−0.837	0.861
3	1.021	−0.702	0.786	1.007	−0.839	0.867
4	1.040	−0.605	0.745	1.011	−0.811	0.850

The values of the infiltration coefficient $C_2 = I_{cum}/I_{cum_0}$ were obtained (Table 42) by substituting in Eq. 3.19, b and F from Table 31 for the third and fourth irrigations. The high C_2 ratios for the third and fourth irrigations may be acceptable for fine texture soils that crack severely upon drying (Bishop *et al.*, 1967).

The values of the factor F, derived from the binomial series to calculate the average infiltrated water depth, remained very close to unity in both irrigations. This implies that there is practically no difference between equations 3.12 and 3.16 under the prevailing soil conditions.

6. *Initial soil moisture content*

As Philip's sorptivity S is a function of the difference between saturated and initial soil water content, the increase in the Kostiakov parameter $A = a/(b+1)$ (Section 6.4), in accordance with the preceding soil dryness, is understandable. The equations of the second series of experiments were obtained for a time of 90 min, within which differences in intake rate were rather small between Treatment 2 (moderately moist) and Treatment 3 (nearly saturated). As the exponents are practically the same (Fig. 43), the infiltration rate for Treatment 3 was 80% of that of Treatment 2 (14.35/17.86 = 0.80).

Because in this series of experiments, the replicates were taken in the same block, and Treatment 1 was not carried out in the block where treatments 2 and 3 were taking place, the comparison of Treatment 1 with the two other treatments can be affected by differences in soil physical characteristics. The treatments 2 and 3, however, can very well be compared, but the differences were not statistically significant.

7. *Furrow length and spacing*

CRIDDLE *et al.* (1956) plotted the furrow infiltration rate as a function of the average time from the beginning of the flow at the furrow intake in an attempt to include the effect of the upstream furrow wetting. In a similar way the influence of the furrow length on infiltration characteristics of the experiments was considered for the second irrigation stage as shown in Fig. 44.

The increase in infiltration rate per unit gross area, when the furrow length decreases, could be explained by a smaller advance time and because less moisture has previously infiltrated the soil. Furthermore, a greater flow per unit of gross area resulted in a greater net infiltration area per unit furrow length and thus a larger gross infiltration.

The experiments were conducted with a furrow spacing of $w = 0.70$ m, but the infiltration equations have been presented for the net infiltration area, $A_{i_n} = P\,x$, and for the gross infiltration area $A_{i_g} = w\,x$. Then the values of the intercepts $A\,w$ and $a\,w$ for $t = 1.0$ (tables 31 and 36) are usable for different spacings. Two problems are involved:

(i) The equations for the gross infiltration area are only presented in order to specify the quantities of infiltration rate or cumulative infiltration as an average over the field. In this way a direct link is established with the usual determination of the irrigation requirements and water distribution, which are also expressed as average depth per time unit and average depth respectively. It is obvious that, both due to the infiltration pattern caused by the furrow shape and as a consequence of variation in furrow spacing, these depths vary widely at specific points.

(ii) It is further noted that the equations with furrow spacing w as a parameter have a restricted value, since the infiltration process, as far as the lateral movement is involved, of a single furrow, is not completely independent of the adjacent furrows. The experiments have not clearly shown whether the infiltration of two adjacent furrows at 0.70 m spacing mutuallly interfered.

However, in the soil of the experimental field, which shows a compacted soil layer at a depth of 55–75 cm, a great lateral movement may occur as a result of variation in infiltration between strata, which secure a more uniform moistening of the root zone.

8. *Unit inflow-infiltration function*

The unit inflow-infiltration function presented in Section 3.6 has been analysed with the data from the experiments. The unit inflow $q_0 = f(t)$ (Table 32) depends on the advance and infiltration equation parameters (equations 3.27 and 3.28). The equations for $Q_i = f(t)$ together with the advance functions $x = p\,t^r$ obtained for each treatment of the third and fourth irrigations gave the opportunity to apply some of the theoretical approaches and to check these with field data.

A general equation (6.24) for $q_0 = f(t)$ was obtained based on data from the four treatments of the third and fourth irrigations. The factors affecting the coefficient of Eq. 6.24 are included between brackets in Eq. 6.28, i.e.: flow size

Q, roughness, slope and hydraulic characteristics of the furrows as expressed in the parameter u, and the exponent s depending mainly on the slope. The physical significance of the flow function (Eq. 6.27) is expressed by Eq. 6.30, where $\phi(Q) = Q^s u/C_3$.

The exponent of t in the average equation (6.24) is the average of the exponents of t in the advance equations (Table 25) for the four treatments of the third and fourth irrigations. For re-used furrows, having a channel bed smoothed by preceding irrigations, equations 6.27 and 6.31 can be used for predicting advance in furrow irrigation, for the conditions of the soils under which the experiments have been conducted. A family of curves was drawn (Fig. 51) for different inflow sizes, within the range for which the flow function (Fig. 37) has been

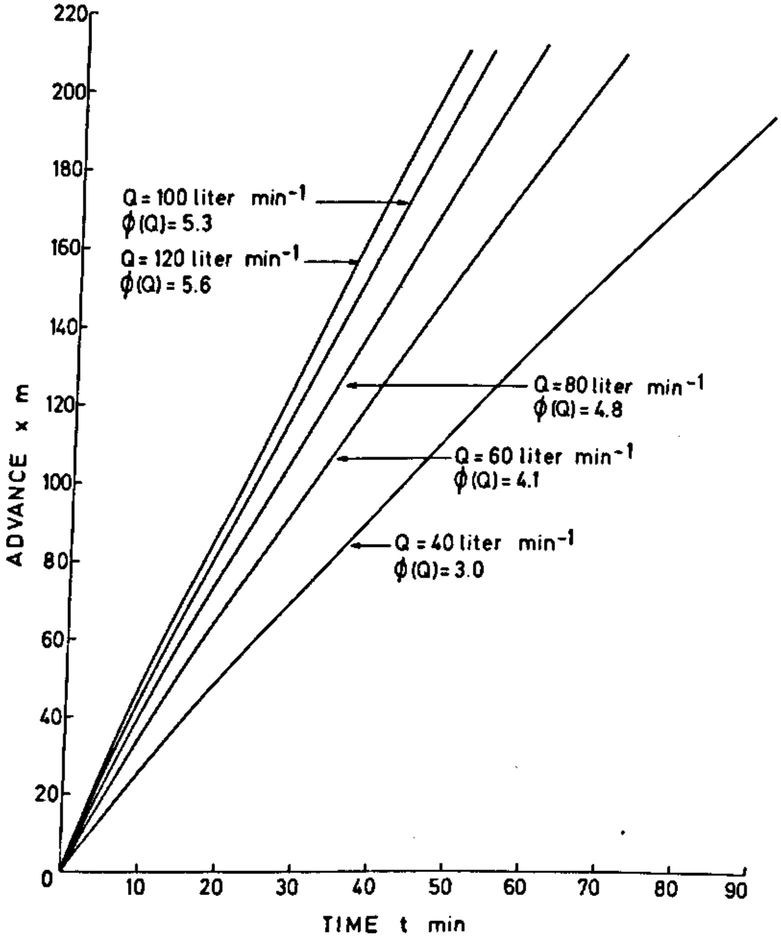

FIG. 51. Family of advance curves for re-used furrows for different inflow sizes derived from Eq. 6.27.

obtained for 12.5 m $< x <$ 175.0 m. Fig. 52 shows the advance curves derived from Eq. 6.27 for the inflow sizes applied in treatments 1 and 3. Points representing the advance, taken from the averages of 5 replicates for the third and fourth irrigations, were also plotted in the same figure. The plot of these points show a good fit with the curves obtained by using the Eq. 6.27.

Equations for $q_i = f(t)$ for the same irrigation and treatment (Table 32) show a lower coefficient and a greater exponent than the equations for $q_0 = f(t)$. This means that a convergence will occur at the advance time for which $q_0 = q_i$, which would imply that the total inflow equals the average infiltration rate. Since the average infiltration rate decreases with time, the wetting front may still advance after this time, but the velocity hereof will be extremely small. For the conditions of the experiments, the front becomes stationary at a distance very much greater than the tested length of the furrows (L = 175.0 m).

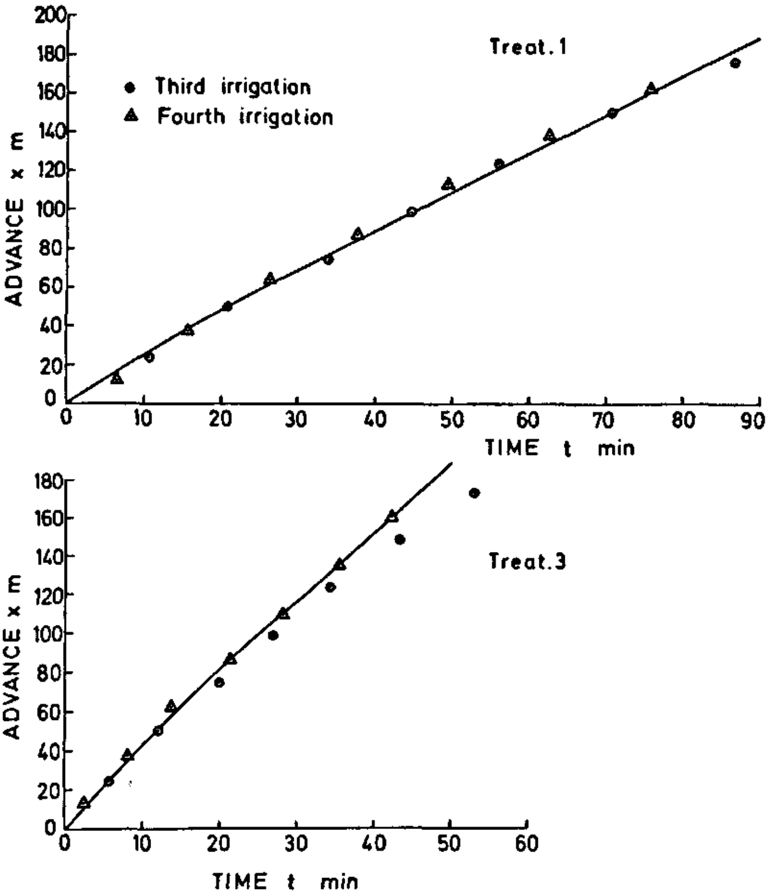

FIG. 52. Advance curves for treatments 1 and 3, re-used furrows, derived from Eq. 6.27 and plot of points representing average advance in third and fourth irrigations.

Eq. 6.36 gives the unit infiltration flow $q_i = f(t)$ in a more generalized equation, depending on the average infiltration $I_{av} = I_{cumo}/t$ at the furrow intake for $x = 0$, and a correction factor related to the advance equation and infiltration parameters. This agrees with other findings in the literature as has been presented in Section 3.6.

The unit inflow-infiltration function is an approach to determine the size of flow to be used in furrow irrigation. Specially a good estimate can be made of the cut-back stream required for the period after the end of the run has been reached. In Fig. 53 an example of reducing the inflow when the wetting front reached the end of the run, is presented with data of Treatment 1 of the fourth irrigation. The total reduced inflow for the second stage becomes then: $Q_r = q_{or}\, w\, L$. Where q_{or} is the reduced inflow per unit of gross area ($A_{tg} = w\, L$).

Expressions in which the inflow per unit area q_0 is used have the advantage that q_0 in liter min^{-1} m^{-2} is comparable to infiltration rate $\bar{I}$ in mm min^{-1}.

9. *Irrigation efficiency*

BISHOP (1961) has shown that deep percolation, as related to the amount of water absorbed, is a function of the exponent b of the infiltration equation and the ratio of the time needed to wet the root zone and the time needed to reach the end of the run. According to this approach, deep percolation decreases with increase of the indicated time ratio and increase of the absolute value of b. This

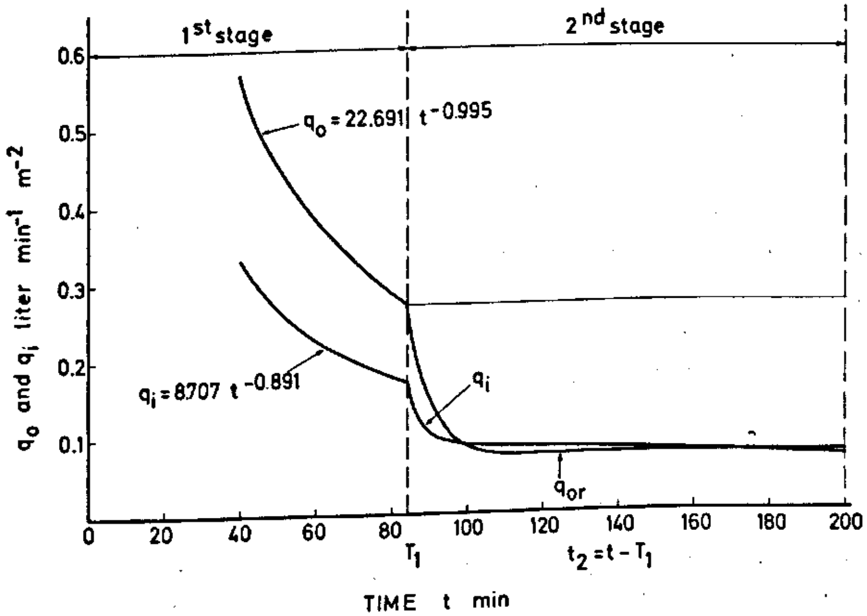

FIG. 53. Inflow per unit area q_0 for both irrigation stages, when flow reduction is applied. Fourth irrigation, Treatment 1.

implies that, for conditions similar to those of the experiments, for values of the time ratio of approximately four, in accordance with the proposal of CRIDDLE *et al.* (1956), as a starting point for the design of furrow irrigation systems, deep percolation will be rather small because all values of b (Table 31) in absolute sense are rather large. In the third and fourth irrigations, the values range for the case of the gross area from -0.890 to -0.605, which represent a maximum percolation loss of 5.8% of the total infiltrated quantity.

Losses from run-off at the end of the run are significant if the flow rate is not reduced in the second stage (Section 6.6). The data of the fourth irrigation show, that, run-off was high, even when flow reduction was applied before the end of the first stage was reached (treatments 3 and 4).

The values of irrigation efficiency approximated by (V_i/V_{in}) 100, apparently are lower than the ones attainable according to WILLARDSON and BISHOP (1967). These authors related deep percolation and run-off losses to the exponent b of the infiltration equation and to the advance time expressed as a percent of the total irrigation time $(T_1 + t_2)$. They provided a series of efficiency curves supported with some field data, and concluded that 60% water application efficiency is probably attainable under most conditions. In this analysis no flow reduction is applied, but the efficiencies arrived at are based on a constant run-off-inflow ratio ranging between 0 and 40%.

In case of the use of a constant inflow for the first and the second stage (third irrigation), low efficiency involves large amount of tail water to be removed, therefore requiring extensive drainage facilities for such areas. If it is not removed by surface drains, this tail water accumulates in the depressions and may cause salinization. This is also an aspect of efficiency, necessary to include in the evaluation of cost related to different degrees of application efficiency.

In trials with flow reduction (fourth irrigation), the recession-time curve was recorded. Although the time of recession varied slightly between replicates, for practical purposes the values were processed and listed (tables 8, 9, 10, 11) 30 min in treatments 1 and 2 and 45 min in treatments 3 and 4. As in all cases the recessions were a large portion of the wetting time, it must be pointed out that differences in contact time between supply end and far end of the furrows were relatively small. Deep percolation losses then become unimportant.

The volumes of water infiltrated during the recession period of the fourth irrigation (Table 38) show an increase with the flow size. A greater volume of water stored at the time the flow cut-off was executed, gives a longer recession period and a longer time-intake opportunity. The infiltrated volume during the third stage are relatively high in proportion to the volume infiltrated during the second stage, and even greater than the second stage volume, in the case of treatments 3 and 4. These results were partly due to the short time assigned to the second stage (60 min), but mainly because ponding water remained in the furrows after tail water had receded, due to irregularities of the furrow bed. This clearly points out that recession must be taken into consideration in furrow irrigation, particularly, when a shallow depth of water is restored to the soil in each application, and in case of flat slopes.

8. CONCLUSIONS

1. The advance of the water front along the furrow, very well fitted the exponential type of equation $x = p\,t^r$, for $12.5\ \text{m} < x < 175.0\ \text{m}$.
2. The increase of the coefficient p of the advance equation, with increase in flow size Q, was found to be significant, and can be expressed by the equation $p = 0.0645\,Q^{1.00}$. The above exponent r tended to decrease with Q, although not statistically significantly.
3. The variation of the coefficient p and the exponent r, between replicates, showed that advance rates for design purposes, must have a proper statistical basis.
4. The infiltrating flow increased with the increase of the flow size in both irrigation stages.
5. The parameters of the infiltration equation for the first stage, altered in successive irrigations that were carried out in furrows under the same surface roughness conditions.
6. Furrow length affected the parameters of the Kostiakov infiltration equation, in as far the second stage is concerned.
7. The values of the surface storage coefficient $C_1 = \bar{D}/D_0$ were found to be between 0.85 and 0.91 in the third irrigation. The values of the infiltration coefficient $C_2 = I_{cum}/I_{cum_0}$ were found to be between 0.74 and 0.79 in the third irrigation and between 0.85 and 0.90 in the fourth irrigation.
8. Unit inflow $q_0 = f(t)$ obtained from the experiments agreed with the theory of this function and this quantity apparently provides a possible approach to determine flow sizes in furrow irrigation.
9. It was found that the advance rate of the water front can be predicted, for re-used furrows and for the type of soils and topography of the experiments, by equation $x = \phi\,(Q)\,t^{0.927}$.
10. Deep percolation was not significant in these heavy soils. Run-off losses have a greater decreasing effect on irrigation efficiency than deep percolation, if flow is not reduced when the wetting front reaches the end of the run.

9. SUMMARY

The objective of this thesis is to study the rate and pattern of infiltration of soil water, under the conditions of heavy texture and shallow depth in a tropical furrow-irrigated soil. The analysis is the result of a series of field-experiments and is supported by theories that has been proposed by others.

The experiments were carried out in the Cojedes-Sarare Irrigation Project, Portuguesa State, Venezuela. Furrows with a length of 200 m, spaced at $w =$ 0.70 m, and with an average slope of 0.18 %, were used. Three series of experiments were set out: (i) First series with variable inflow and surface roughness; (ii) Second series with variable initial soil moisture content; (iii) Third series with variable furrow length. Replicates of the treatments were distributed at random.

Five irrigations were applied to the land during the period from January to March, 1970. Subsequently in the first series of experiments, first, third and fourth irrigations for three roughness conditions and four sizes of flow were tested. The second irrigation was used for the second series of experiments. The fifth irrigation served for the third series of experiments.

During the first series of experiments, the following measurements were taken: (i) rate of advance of the water front (distance x in m at time t in min); (ii) furrow section parameters (top width T and depth h); (iii) furrow inflow Q and outflow Q_{out}. During the second and the third series of experiments, only the simultaneous inflow and outflow were recorded.

Advance and infiltration functions were obtained for the period of advance of the water front (first stage), and infiltration functions for the period of wetting the root zone (second stage). Exponential equations were obtained by computer analysis for single furrow trials. Then, by averaging coefficients and exponents of the equations of the replicates, general equations for each treatment were found.

The data of x as a function of t showed a good fit with the equation $x = p\, t^r$. The coefficient p increased significantly with the flow size Q and the exponent r showed a trend to decrease although not significantly, with increasing Q. The coefficients of variation of p and r were rather high. Therefore a single furrow advance trial may not suffice to express the average field advance of the water front under the given conditions.

The advance curves showed that the differences in roughness were great between the first irrigation with loose furrows and those irrigations after two or three applications have taken place. The roughness conditions appeared to be identical for third and fourth irrigations.

With distance-averages of the furrow section parameters h and T, for three water front advance stages ($x = 87.5$ m, $x = 137{,}5$ m and $x = 175.0$ m), the average section a_f and the average wetted perimeter P were obtained for a parabolic section of the furrows. The surface volume $V_s = a_f\, p\, t^r$, and the area of infiltration A_i (net area $A_{i_n} = P p t^r$ and gross area $A_{i_g} = w p t^r$) were then arrived at.

The infiltration functions were found for each treatment during the first stage, as $V_i = f(t)$ by using single furrow data of $V_i = Q t - V_s$. As the average infiltration depth $I_{cum} = V_i/A_i$, the equations for $I_{cum} = f(t)$ were obtained. Equating these functions with the equation $\bar{I}_{cum} = F a t^{b+1}/(b + 1)$ $(b + 2)$, the parameters a and b of the Kostiakov equation $(I = a t^b)$ were derived. For the second stage (when $x = L = 175.0$ m), the infiltration function was obtained by simultaneous measurements of the inflow and outflow, as infiltration flow: $Q_i = Q - Q_{out}$, from which the parameters of the infiltration equations, were found.

The increase of infiltration with inflow size was clearly shown from the data analysis of both stages as being the effect of a larger volume of water. The parameters of the infiltration equation for the first stage altered in successive irrigations.

Some emphasis was put on the unit inflow function q_0 to relate flow sizes for both stages with length of run and infiltration. Equations for the unit inflow $q_0 = Q/A_i$ and for unit infiltration flow $q_i = Q_i/A_i$ per unit area, were obtained for each treatment. Then a generalized type of equation was introduced which relates the unit inflow function with the average depth of water infiltrated during the advance time at the furrow intake. An equation to predict the length of advance is included $x = \phi\,(Q)\,t^{0.927}$, for the surface roughness and soil conditions under which the experiments were carried out. The representation of $q_0 = f(t)$ and $q_i = f(t)$ for both stages, in a composite figure with the advance function as a function of time, provides an illustration of the infiltration process, usable for the design and management of furrow irrigation under the conditions of the experiments.

The relationship between the exponent of time in the advance equation and the exponent of time in the infiltration equation was analysed with the data from the experiments. This analysis confirmed that r increases when $(b + 1)$ decreases. This agrees with findings in the literature, such as the relationship proposed by FOK and BISHOP (1965) Values for the surface storage coefficient $C_1 = \bar{D}/D_0$ and infiltration coefficient $C_2 = I_{cum}/I_{cum_0}$ to solve the balance equation for predicting advance were also obtained.

The second series of experiments, in which infiltration rate was measured during the second stage, as a function of the initial moisture content, showed that the value of the coefficient a of the Kostiakov equation increased not significantly as the initial content of soil moisture decreases.

The third series of experiments – measurements taken during the second stage – showed that upon the increase of furrow length, the coefficient a of the infiltration equation decreases and the exponent b increases.

Water losses by deep percolation and by run-off at the end of the run, were finally analysed on the bases of the equations found and the data available. The analysis was made for the case of constant inflow for both stages (third irrigation), and for the case of reduced inflow during the second stage (fourth irrigation).

The data analysis showed that infiltration is a very variable factor affected by the conditions of the soil and the surface of the channel bed, as well as by the size of the flow, furrow length and stage of irrigation. Soil cracking upon drying was found to be a relevant factor in the entry of water into the soil. Because deep percolation losses are certainly very small under the indicated physical conditions, irrigation efficiency will be rather high if provisions are made to use a cut-back stream, during the second stage, in order to lose a minimum of water by run-off at the end of the run.

10. SAMENVATTING

Het doel van deze dissertatie is het bestuderen van het infiltratiepatroon en de infiltratiesnelheid van water in een zware, ondiepe bodem in de tropen, die door middel van furrows wordt bevloeid. De gepresenteerde analyse is het resultaat van een serie veldproeven en wordt ondersteund door theoriën die door anderen zijn ontwikkeld.

De veldproeven werden uitgevoerd in het Cojedes-Sarare Irrigatieproject in de staat Portuguesa in Venezuela. Furrows van 200 m lengte op een onderlinge afstand $w = 0.70$ m, en met een gemiddelde helling van 0.18 % werden gebruikt. Drie series van proeven werden uitgevoerd: i) met debiet en oppervlakte ruwheid als veranderlijke, ii) met het initiële vochtgehalte in de bodem als veranderlijke, en iii) met de furrowlengte als veranderlijke. De herhalingen van de behandelingen werd a-select over het proefveld verdeeld.

Gedurende de periode van januari tot maart, 1970, werden vijf irrigaties uitgevoerd. In de eerste serie proeven werden de eerste, derde, en vierde irrigatie getest met drie verschillende oppervlakte ruwheden en vier in grootte verschillende debieten. De tweede en vijfde irrigatie dienden voor resp. de tweede en derde serie proeven.

Gedurende de eerste serie veldproeven werden de volgende waarnemingen gedaan: de voortschrijding van het vochtfront (de afstand x, in m, en de tijd t, in min.); de parameters die de natte doorsnee van de furrow beschrijven (breedte van de waterspiegel T, en diepte h); de toevoer van water Q en de afvoer aan het eind van de furrow Q_{out}. Tijdens de tweede en derde serie proeven werden alleen de gelijktijdige toevoer en afvoer gemeten.

Voortschrijdings- en infiltratiefuncties werden verkregen voor de periode dat het vochtfront voortbewoog (het eerste stadium), en infiltratiefuncties voor de periode van voortgaande bevochtiging van de wortelzone (het tweede stadium). Exponentiële functies werden door middel van computer analyses opgesteld voor de voortschrijding in elke furrow. Door het middelen van coëfficiënten en exponenten in deze functies van de herhalingen, werden algemene vergelijkingen opgesteld voor de verschillende debieten. De waarnemingen van x als functie van t bleken een exponentieel verloop te hebben: $x = p\, t^r$. De coëfficiënt p nam significant toe met het debiet Q en de exponent r toonde de neiging om af te nemen met een toename van het debiet, maar dit verschijnsel was statistisch niet significant. De variatie coëfficiënten van p en r waren tamelijk groot. Een voortschrijdingstest in *een* enkele furrow zal derhalve in het algemeen niet toereikend zijn om de gemiddelde voortschrijding van het water op het veld onder de gegeven omstandigheden te kunnen aangeven.

De voortschrijdingskrommen duidden aan dat de verschillen in ruwheid groot waren tussen de eerste irrigatie, wanneer het furrowbed nog los is, en latere irrigaties in een glad furrowbed. Het bleek dat de ruwheid bij de derde en vierde irrigatie gelijk was.

Uit afstand gemiddelden van de parameters h en T, die de furrow doorsnede beschrijven, tijdens het bereiken van drie posities van het voortschrijdingsfront ($x = 87{,}5$ m; 137,5 m en 175,0 m) werd de gemiddelde furrow doorsnede a_f en de gemiddelde natte omtrek P verkregen voor een parabolische doorsnede van de furrow. De hoeveelheid water in de furrow aanwezig $V_s = a_f\, p\, t^r$, en het infiltratie oppervlak A_t (netto oppervlak $A_{t_n} = P\, p\, t^r$ en het bruto oppervlak $A_{t_g} = w\, p\, t^r$) werden daaruit berekend.

De infiltratiefuncties werden door elk debiet bepaald voor het eerste stadium als $V_t = f(t)$ door de gegevens van de enkele furrows te gebruiken: $V_t = Qt - V_s$. Aangezien de infiltratiehoeveelheid, gemiddeld over de lengte, $\bar{I}_{cum} = V_t/A_t$, werden de vergelijkingen voor $\bar{I}_{cum} = f(t)$ verkregen. Door deze vergelijkingen gelijk te stellen aan de vergelijking $\bar{I}_{cum} = F\, a\, t^{b+1}/(b + 1)\,(b + 2)$ werden de parameters a an b van de Kostiakov vergelijking ($I = a\, t^b$) gevonden. Voor het tweede stadium, wanneer $x = L = 175{,}0$ m, werd de infiltratiefunctie gevonden uit gelijktijdige metingen van de toevoer en de afvoer, aldus $Q_t = Q - Q_{out}$, waaruit de parameters van de infiltratievergelijking werden gevonden.

Uit de analyse van de gegevens bleek duidelijk dat de toename van de infiltratie met het debiet voor beide stadia van de infiltratie het gevolg was van een grotere hoeveelheid water in de furrow. De parameters van de infiltratievergelijking voor het eerste stadium veranderden in opeenvolgende irrigaties.

Aandacht werd geschonken aan de eenheidstoevoerfunctie q_0 om op deze wijze het verband te kunnen vinden voor beide stadia tussen het debiet en de furrowlengte en de mate van infiltratie. Voor elk debiet werden de eenheidstoevoer $q_0 = Q/A_t$ en de eenheidsinfiltratie $q_t = Q_t/A_t$, per eenheid van oppervlakte bepaald. Een algemene vergelijking werd zo gevonden die het verband weergeeft tussen de eenheidstoevoer en de gemiddelde dikte van de waterlaag die infiltreerde aan het toevoereinde van de furrow gedurende de voortschrijdingstijd. Ook werd een vergelijking opgesteld om de voortschrijdingslengte $x = \phi\,(Q)\, t^{0.927}$ te voorspellen voor de toestand van de bodem en de oppervlakte ruwheid waaronder de proeven werden uitgevoerd. De uitbeelding van $q_0 = f(t)$ en $q_t = f(t)$ voor beide stadia samen met de voortschrijdingsfunctie (ook als functie van de tijd), in een samengestelde figuur gaf een illustratie van het infiltratieproces die gebruikt kan worden bij het ontwerpen en regelen van furrow irrigatie onder de omstandigheden van de proefopstellingen. Voor de proeven werd ook het verband tussen de exponenten van de tijd respectievelijk in de voortschrijdingsfunctie en in de infiltratiefunctie onderzocht. Deze analyse bevestigt dat r toeneemt wanneer $(b + 1)$ afneemt, wat in overeenstemming is met gegevens in de literatuur, zoals het verband dat door FOK en BISHOP (1965) werd voorgesteld. De waterdieptecoëfficiënt $C_1 = \bar{D}/D_0$ en de infiltratiecoëfficiënt $C_2 = I_{cum}/I_{cum_0}$ werden berekend om de balans vergelijking voor het voorspellen van de voortschrijding te kunnen oplossen.

De tweede serie proeven, waarin de infiltratiesnelheid gedurende het tweede stadium werd gemeten in afhankelijkheid van het initiële vochtgehalte van de bodem, duidden aan dat de waarde van de coëfficiënt a in de Kostiakov vergelijking toenam, hoewel statistisch niet significant, met een afname in het initiële vochtgehalte.

De derde serie proeven waarin gedurende het tweede stadium gemeten werd, gaf aan dat met een toename van de furrowlengte de coëfficiënt *a* van de infiltratievergelijking afnam en de exponent *b* toenam.

Waterverliezen als gevolg van uitzakking en oppervlakte-afvoer aan het einde van de furrow werden tenslotte met behulp van de opgestelde vergelijkingen onderzocht. Deze analyse werd gemaakt voor een constante toevoer voor beide stadia gedurende de derde irrigatie, en voor een gereduceerde toevoer gedurende het tweede stadium bij de vierde irrigatie.

De analyse van de bij deze proeven gedane waarnemingen leidde tot de conclusie dat infiltratie sterk varieert in afhankelijkheid van de toestand van de bodem en het oppervlak van het furrowbed, maar ook van het debiet, de furrowlengte en het irrigatiestadium. Ook het scheuren van de grond bij uitdroging bleek een factor te zijn die de wateropname door de bodem beïnvloedde. Aangezien uitzakkingsverliezen uitermate gering waren bij de aangegeven fysische toestand van de bodem zal de irrigatie-efficiëntie tamelijk hoog kunnen zijn, indien voorzieningen getroffen worden om gedurende het tweede stadium een gereduceerd debiet te gebruiken teneinde afvoerverliezen aan het uitstromingseinde van de furrow tot een minimum te beperken.

REFERENCES

ABREU, R. E. Estudio del desarrollo radicular de los cultivos, maiz, frijol y caraota. División de Edafología, Dirección de Obras Hidráulicas, Caracas (1966) 15 p.

ARISMENDI, R. Estudio agrológico especial del campo experimental del Sistema de Riego Cojedes-Sarare. División de Edafología, Dirección de Obras Hidráulicas, Caracas (1967) 25 p.

ASSED, M. and D. KIRKHAM. Advance of irrigation water on the soil surface in relation to the soil infiltration rate: a mathematical and laboratory model study. Iowa State Univ. Sci. & Techn. Res. Bull. 565 (1968) 293–317.

BISHOP, A. Relation of intake rate to length of run in surface irrigation. Journ. Irrig. Drainage Div. Proc. ASCE 87 (1961) 23–29.

BISHOP, A. A., M. E. JENSEN and W. H. HALL. Surface irrigation systems. Irrigation of Agricultural Lands. Am. Soc. of Agronomy Chapter 43 (1967) 865–884.

BODMAN, G. B. and E. A. COLEMAN. Moisture and energy conditions during downward entry of water into soils. Soil Sci. Soc. Amer. Proc. 8 (1944) 116–122.

BOLT, G. H. with the collaboration of A. R. P. JANSE and F. F. R. KOENINGS. Basic Elements of Soil Chemistry and Physics, Part II Soil Physics. 2nd. ed. Agricultural Univ. Wageningen (1970) 95 p.

BOUWER, H. Theoretical effect of uniqual water levels on the infiltration rate determined with buffered cylinder infiltrometers. Journ. of Hydrology, North-Holland Publ. Co. 1 (1963) 29–34.

CHRISTIANSEN, J. E., A. A. BISHOP, F. W. KIEFER Jr and YU-SI FOK. Evaluation of intake rate constants as related to advance of water in surface irrigation. Am . Soc. Agr. Eng. Trans. 9 (1966) 671–674.

COLLINS, H. G. and R. B. CAMPBELL. Water infiltration in hawaiian sugarcane furrows. Journ. Irrig. Drainage Div. Proc. ASCE 93 (1967) 81–96.

CRIDDLE, W., S. DAVIS, C. H. PAIR and D. G. SHOCKLEY. Methods for evaluating irrigation systems. US Dep. Agr. Handbook 82 (1956) 24 p.

DIVISION DE EDAFOLOGIA, Direction de Obras Hidraulicas de Venezuela. Estudio agrológico semidetallado del sistema de riego Cojedes-Sarare. Caracas (1969) 64 p.

FINKEL, H. J. and D. NIR. Determining infiltration rates in an irrigation border. Journ. Geophys. Research 65 (1965) 2125–2131.

FOK YU-SI. Formulas for the determination of the proper length of farms. Taiwan Water Conservancy, Series 6, 3 (1958) 20–22.

FOK YU-SI. and A. A. BISHOP. Analysis of water advance in surface irrigation. Journ. Irrig. Drainage Div. Proc. ASCE 91 (1965) 101–115.

GARDNER, W. R. Development of modern infiltration theory and application in Hydrology. Am. Soc. Agr. Eng. Trans. 10 (1967) 379–381.

GRASSI, C. J. Estimación de los usos consuntivos de agua y de los requerimientos de riego. CIDIAT, Venezuela. Documento 53 (1968) 40–49.

GRASSI, C. J., P. C. FERNANDEZ and I. PONCE. Velocidad de avance del frente de agua en los surcos de riego. Revista de Investigaciones Agropecuarias INTA, Buenos Aires 2 (1965) 11–34.

HALL, W. A. Estimating irrigation border flow. Agr. Eng. 37 (1956) 263–265.

HENDERSON, D. W. and H. R. HAISE. Control of water intake rates. Irrigation of Agricultural Lands. Am. Soc. of Agronomy Chapter 46 (1967) 925–940.

HORTON, R. E. The role of infiltration in the hidrologic cycle. Trans. Am. Geophys. Union 14 (1933) 446–460.

KIEFER, F. W. Jr. Average depth of absorbed water in surface irrigation Mimiograph Civil Eng. Dep. Utah State Univ. (1965).

KOSTIAKOV, A. N. On the dynamics of the coefficient of water percolation and on the necessity for studying it from a dynamic point of view for purposes of amelioration. Trans. 6th Comm. Intern. Soil Sci. Soc. Russian Part A (1932) 17–21.

LEWIS, M. R. and W. E. MILNE. Analysis of border irrigation. Agr. Eng. (1938) 267–272.

MECH, S. J. and D. D. SMITH. Water erosion under irrigation. Irrigation of Agricultural Lands. Am. Soc. of Agronomy Chapter 48 (1967) 950–963.

NUGTEREN, J. Ingenieurscollege Veldirrigatie. Landbouwhogeschool (1969).

OSTROMECKI, J. Method of computing the borderflow irrigation system. Annual Bulletin International Commission on Irrigation and Drainage. (1960) 73–77.

PHILIP, J. R. The theory of infiltration. Soil Sci. 83 (1957) 345–357, 83 (1957) 435–448, 84 (1957) 163–178, 84 (1957) 257–264, 84 (1957) 329–339, 85,(1958) 278–286,

PHILIP, J. R. and D. A. FARREL. General solution of the infiltration-advance problem in irrigation hydraulics. Journ. Geophys. Research 69 (1964) 621–631.

SKOGERBOE, G. V., M. L. HYATT, J. D. ENGLAND and J. R. JOHNSON. Design and calibration of submerged open channel flow measurement structures, Part 2 Parshall flumes. Utah State Univ. (1967).

US BUREAU OF RECLAMATION. Land Classification Handbook. US Dep. Int. Bur. Reclam. Publ. V, Part 2 (1953) 53 p.

USDA SOIL SURVEY STAFF. Soil classification, 7th Approximation. Dep. Agr., US Printing Office, Washington D.C. (1960).

USDA SOIL SURVEY STAFF. Soil Survey Manual. Agr. Handbook No 18, US Printing Office, Washington D.C. (1951).

VIERHOUT, M. M. Een mathematische methode voor het optimaal ontwerpen van border en furrow irrigatie systemen (Flow irrigation). Landbouwhogeschool (1971).

WILLARDSON, L. S. and A. A. BISHOP. Analysis of surface irrigation application Journ. Irrig. Drainage Div. Proc. ASCE 93 (1967) 21–35.

WILKE, O. and E. T. SMERDON. A solution of the irrigation advance problem. Journ. Irrig. Drainage Div. Proc. ASCE 91 (1965) 23–34.

ZASLAVSKI, D. Saturation-unsaturation transition in infiltration to a non-uniform soil profile. Soil Sci. 107 (1969) 160–165.

APPENDIX A. SYMBOLS

a	coefficient of the Kostiakov infiltration rate equation
a_f	average stream flow furrow cross sectional area
A	coefficient of the Kostiakov accumulated infiltration equation, $A = a/(b+1)$
A_{in}	net area of infiltration
A_{ig}	gross area of infiltration
b	exponent of the Kostiakov infiltration equation
B	exponent of the Kostiakov accumulated infiltration equation $B = b + 1$
c	constant of the modified Kostiakov infiltration equation
C	coefficient of the second term of the Philip equation
C_1	surface storage coefficient, $C_1 = \bar{D}/D_0$
C_2	infiltration coefficient, $C_2 = \bar{I}_{cum}/I_{cum_0}$
$\bar{D}$	average depth of water on the soil surface at a given advance time
D_{av}	average depth of water absorbed by the soil at a given application time
D_{in}	average depth of water supplied to the area under infiltration, at a given time
D_n	net depth of water infiltrated into the soil at the far end of the furrows during second stage
D_0	depth of water on the soil surface at the upper end
D_p	average depth of water percolation, exceeding D_n, $D_p = D_{av} - D_n$
F	factor derived from binomial series to calculate average infiltrated water depth
h	average depth of the wetted furrow cross section
I	infiltration rate
I_{av}	average infiltration rate at a given time, $I_{av} = I_{cum}/t$
$\bar{I}$	length-average infiltration rate
I_b	basic infiltration rate
I_{cum}	accumulated depth of water infiltrated at a given time
$\bar{I}_{cum}$	average depth of water infiltrated at a given advance time
I_{cum_0}	accumulated depth of water infiltrated at the upper end at a given advance time
k	hydraulic conductivity
L	length of furrow
n	Manning's roughness coefficient
p	coefficient of the advance function
P	average furrow wetted perimeter
q_0	furrow inflow per unit of infiltration area
q_i	furrow infiltration flow per unit of infiltration area
Q	furrow inflow
Q_i	furrow infiltration flow
Q_{out}	furrow outflow
Q_r	reduced furrow inflow

r	exponent of the advance function
R_h	average furrow hydraulic radius
s	exponent of Q in the advance equation
S	coefficient of the first term of the Philip equation
S_0	slope of the furrow channel bed
t	application time for the first and for the second irrigation stage
t_1	time in which the water front advances x_1
t_2	application time for the second irrigation stage after end of furrow has been reached
t_3	recession time for the third irrigation stage
t_b	time in which the basic infiltration rate has been arrived at
t_x	time to reach distance x between 0 and x_1
T	average top width of the wetted furrow cross section
T_1	elapsed time to reach the end of the furrow length L
u	parameter of the advance function
V_i	infiltrated water volume at a given time
V_{in}	inflow water volume at a given time
V_s	water volume in the furrow at a given time
w	spacing of the furrows
W	throat width of the Parshall flume
x	advance length of wetting at time t_x
x_1	advance length of wetting at time t_1.

APPENDIX B. DESCRIPTION OF SOIL PROFILES

Profile No 1

0–20 cm Texture: clay; color: dark brown (7.5 YR 3/2 moist); structure: medium angular blocky and moderate; consistence: friable (moist), slightly sticky and plastic (wet); permeability: moderately slow; special formations: few fine mica inclusions; biological activity: abundant.

20–32 cm Texture: clay; color: dark brown (10 YR 3/3 moist); structure: medium angular blocky and moderate; consistence: friable (moist), slightly sticky and plastic (wet); permeability: moderately slow; special formations: few fine mica inclusions; biological activity: abundant.

32–42 cm Texture: silty clay; color: yellowish brown (10 YR 5/6 moist); structure: medium angular blocky and moderate; consistence: very friable (moist), sticky and plastic (wet); permeability: moderately slow; special formations: few fine mica inclusions and many medium lime concretions; biological activity: abundant; violently calcareous.

42–75 cm Texture: silty clay loam; color: yellowish brown (10 YR 5/8 moist); structure: medium angular blocky and moderate; consistence: very friable (moist) slightly sticky and slightly plastic (wet); permeability: moderately slow; special formations: many medium lime concretions; biological activity: fair; violently calcareous.

75 + cm Texture: silty clay loam; color: yellowish brown (10 YR 5/8 moist); many medium size, distinct, gray brown (10 YR 5/2 moist) mottles; structure: medium angular blocky and moderate; consistence: very friable (moist), slightly sticky and slightly plastic (wet); permeability: moderately slow; special formations: many medium mica inclusions and lime concretions; biological activity: small; violently calcareous.

Profile No 2

0–15 cm Texture: clay; color: very dark gray brown (10 YR 3/2 dry) and very dark gray (10 YR 3/1 moist); structure: medium angular blocky and moderate; consistence: slightly hard (dry), friable (moist), sticky and plastic (wet); permeability: moderately slow; special formations: few fine mica inclusions; biological activity: fair.

15–32 cm Texture: clay; color: dark brown (10 YR 3/3 dry) and very dark gray brown (10 YR 3/2 moist); structure: medium angular blocky and moderate; consistence: slightly hard (dry), friable (moist), sticky and plastic (wet); permeability: moderately slow; special formations few fine mica inclusions; biological activity: fair.

32–55 cm Texture: silty clay loam; color: light olive brown (2.5 Y 5/6 moist);

structure: fine angular blocky and weak; consistence: friable (moist) slightly sticky and plastic (wet); permeability: moderately slow; special formations: abundant lime concretions; violently calcareous.

55–83 cm Texture: silty clay loam; color: brownish yellow (10 YR 6/8 moist); structure: fine subangular blocky and weak; consistence: friable (moist), sticky and plastic (wet); permeability: moderate; special formations: many medium lime concretions; violently calcareous.

83 + cm Texture: loam; color: olive yellow (2.5 Y 6/8 moist); structure: fine subangular blocky and weak; consistence: very friable (moist), slightly sticky and slightly plastic (wet); permeability: moderate; special formations: few medium lime concretions; violently calcareous.

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