AHMADU BELLO UNIVERSITY, ZARIA
DEPARTMENT OF AGRICULTURAL ENGINEERING

DEVELOPMENT OF DESIGN PROCEDURE FOR BORDER IRRIGATION SYSTEM

BY
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Being a thesis submitted to the Postgraduate School, Ahrnadu Bello University, in partial fulfillment of the requirements for the award of M.Sc. degree in Agricultural Engineering.

AUGUST, 1989

DECLARATION

I hereby declare that this thesis has been composed by myself and that it is a record of my own research work. It has not been accepted in any previous application for a higher degree. All quotations are distinguished by quotation marks and the sources of information are specifically acknowledged by means of references.

.....

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CERTIFICATION

This thesis entitled "DEVELOPMENT OF DESIGN PROCEDURE FOR BORDER IRRIGATION SYSTEM" by M.A. OYEBODE meets the regulations governing the award of the degree of Master of Science (Agricultural Engineering) of Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

To my Father who set standard I strive to reach:

To my Dear Mother who sacrificed all to sustain my choice:

To all my brothers, sisters and cherished friends who care.

ACKNOWLEDGEMENT

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ABSTRACT

A design procedure was developed for border irrigation based on the need to have very high efficiencies of water distribution while at the same time maintaining an acceptable degree of water application efficiency. The water application efficiency for the design was estimated from the analysis of a border strip in which a cut back flow was not used.

The required time of advance was estimated from the analysis of the advance and recession functions, by ensuring that the advance and recession curves be parallel. The desired initial flow rate was estimated from the solution of two standard advance equations, and limiting the advance estimate to an error of + *2%* relative to the expected advance.

The performance evaluations on the border strips in current use were in general satisfactory. The analysis in this study also indicates that a unit stream size of 2.5 l/s/m will give an acceptable field application efficiency. It is therefore concluded that the unit stream size be kept at 2.5 l/s/m for border slope of 0.0/2 percent obtained from border strip 3.2 - 3,

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ABBREVIATIONS AND SYMBOLS

β (m,n)	Beta function of m and n
Γ (n+1)	Gamma function of n+1
a_s	Cross-sectional area of the syphon tube (m^2)
a,n,k,s	Constants
A and B	Empirical Coefficients
C	Coefficient of discharge for syphon tube (dimensionless)
c,m	Empirical Coefficients of the advance function
c_1	Empirical coefficient of the recession function
D_a	Accumulated intake (mm)
$\bar{d}$	Average depth of water stored along the run during the irrigation (mm)
d_{av}	Available moisture capacity of the soil (mm)
D	Mean infiltration depth (mm)
E_a	Water application efficiency
E_d	Water distribution efficiency
F	Correction factor after Keifer
g	Acceleration due to gravity (m/s^2)

h	Elevation difference between water surface elevation in the channel and elevation of the outlet point of application in the field (m)
i	Summation index
I	Infiltration rate (mm/hr)
L	Length of border strip (m)
LF	Low flow
Ma	Soil moisture added (mm)
MD	Moisture deficit
Mu	Soil moisture use by the crop (mm)
HF	High flow
SF	Satisfactory flow
n_r	Manning roughness coefficient
q	Unit inflow ($m^3/s/m$)
q_a	Discharge from a syphon tube (m^3/s)
q_{max}	Maximum inflow rate (m^3/s)
Q	Cummulative infiltrated depth (mm)
r_y	Surface-stream shape factor (fractional)
r_x	Subsurface shape factor (fractional)
S_o	Slope of border strip (dimensionless)
S	Surface storage per unit width of border strip (m^3/m)
T	Time (min)
T_r	Time for completion of recession (min)

t, t_1	Intake time (min)
t_x	Time of advance to any point x (min)
t	Inflow time (min)
t_r	Recession time (min)
T_a	Application time (min)
V_f	Cummulative infiltrated volume (m^3/m)
V_r	Volume of water required per unit width of border (m^3/m)
X	Advance distance (min)
X_r	Recession distance (min)
y	Mean depth of flow (m)
y_o	Upstream surface depth (m)
$\bar{y}$	Average numerical deviation from $\bar{d}$
W	Amount of water stored in the soil root zone during irrigation (mm)
W_f	Amount of water delivered to the area being irrigated (mm)
Z, Z_o	Infiltrated depth (mm)

1. INTRODUCTION

In surface irrigation, two general methods are used; uncontrolled flooding or controlled flooding. In irrigating by uncontrolled flooding or wild flooding, water is applied to an area which has undergone no prior land preparation for irrigation. In most cases, this unsystematic method produces inefficient irrigation. Low spots in a field are over-irrigated whereas high areas are under-irrigated. In the controlled flooding methods, predetermined rates and quantities of water are applied to areas which have been prepared for irrigation. Such methods include, for example, border dyke, furrow and check basin systems. For proper design of these systems, the size of the stream is balanced against the intake rate of the soil, the depth of water to be stored in the root zone and the area to be covered by the stream.

With the Federal Government's accelerated programme on wheat production, it is expected that the irrigated acreage in the Kadawa sector of the Kano River Project will increase substantially. Further, it is expected that most of the new areas coming under irrigation will be irrigated by some

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surface irrigation method, in particular, the border dyke method which is most suitable for close-growing crops. As a result, a comprehensive study on some of the existing border dyke systems in the Kadawa Sector has been done in order to obtain information which can be used to set up design procedure for border irrigation.

The border irrigation method is most suitable for close-growing, non-cultivated, sown or drilled crops, except rice and other crops grown in ponded water. Legumes, grasses and small grains are commonly irrigated by the method.

In the border method of irrigation, the field to be irrigated is divided into strips that are separated by parallel borders or levees. At the upper end, water is introduced to irrigate the strips.

The Kadawa Irrigation Research Station is one of the main places where irrigation development has taken place in Northern Nigeria. The Kano River Project is a major irrigation scheme of Kano State, covering about 93,000 ha, comprising 52,000 ha as Kano River Project area (NEDECO, 1974). It lies between longitudes 8^{o} 30'E and 9^{o} 40'E and latitudes 11^{o} 30'N and 12^{o} 03'N within the Hadejia Jama'are River Basin

in Nigeria (Nwa, 1980). The boundaries of the project area are defined by natural features, namely Kano River in the North, West and South, Guska River in the North-East and rocky hills near Kano in the South-East (NEDECO, 1974).

The climate of the area is divided into three main seasons, namely:

1. The cool dry season from October to February
2. The hot dry season from March to May and
3. The warm rainy season from June to September.

The current study which is aimed at development of design procedure for border irrigation systems was conducted in this area. The study also includes the evaluation of the existing border irrigation method. It is obvious from available literature that adequate work on the design of border irrigation system has not been carried out for the Kadawa Sector.

It is thus clear that no design standards have been established for the border irrigation system in the area. Thus, there is a need for proper design procedures in the planning of large areas suitable for border irrigation and in the improvement of existing ones.

1.1 Objectives

The objectives of this study, therefore, are:

1. To set up a design procedure that could be used both for the modification of existing border irrigation system, and the establishment of new ones. The design procedure suggested would be based on the estimated parameters: the average slope of the border strip, the infiltration rate process, the need to ensure uniformity of water distribution and the prevention of erosion hazards on the border strips.

2. To evaluate the performance of the existing border system with a view to ascertaining whether the irrigation is being done efficiently as obtained from the design procedure being developed; and

3. To determine any modifications that may be required in the existing water distribution network in the project area in order to meet the requirements of the design procedure.

2. REVIEW OF LITERATURE

2.1 Introduction

In the design of a surface irrigation system, the factors to be considered include: the hydraulics of water application and the measurement of efficiencies in the water application and distribution processes. For the purpose of clarity, the review of literature will be discussed under the subheadings:

1. Hydraulics of surface irrigation and
2. Water application and distribution efficiencies.

2.2 Hydraulics of Surface Irrigation

The rate of water advance down an irrigation border is affected by the unit inflow q (l/s/m); the slope S_o (m/m) of the border strip; the forces retarding the flow; and the infiltration characteristics of the soil, amongst other factors.

The first major factor which is the unit inflow q, may vary throughout the irrigation, or remain essentially constant. Only the latter situation will be considered in the analysis to follow. The water may be shut off before the advancing flow reaches the

end of the border, but this represents a non-idealized case not considered in this study.

The slope of the border determines the rate at which energy is added to the flowing water. Although slopes can, and often do, vary spatially, only a single average for the slope of the entire irrigation run is considered in the analysis of this study.

The forces ratarding flow are those due to resistance - both from the ground surface and vegetation growing on it. These factors combine to make the roughness representation a complicated one. However, most analysis to date consider only a single roughness parameter, such as the Manning's roughness coefficient n_r.

Another factor affecting the advance rate is the infiltration characteristics of the soil. As with the other factors mentioned, infiltration rate varies with time (during and between irrigations) and space (location within the field).

It has been shown that the infiltration process can be approximated by a power function of time given by Kostiakov - Lewis (1932):

$$Z = kt^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.1$$

where Z is the depth infiltrated in time t, and k and n are constants. However, Eq. (2.1) is commonly used because of the ease with which the parameters can be determined.

In addition to the above factors, the analysis of water advance down an irrigation border strip is complicated by the fact that as the sheet of water advances over the land, part of the water infiltrates into the soil. As a large area of land is covered by the advancing stream, a relatively larger part of the inflow is required for infiltration and less of it is available for advance. Hence, advance rate tends to decrease with the distance of the advance front from the border head.

Rawitz (1973) observed that a mathematical formulation of the advance of water over a strip of land would have to involve two phenomena:

1. Open - channel flow described by equations such as the Manning's equation given by:

$$q = \frac{1}{n_r} y^{5/3} S_o^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots \quad 2.2$$

where

q = inflow per unit width of border

n_r = roughness coefficient

y = mean depth of flow

S_o = average slope of border strip

and 2. the infiltration function having the general form:

$$D_a = at + k_1 t^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.3$$

where

D_a = accumulated intake

t = time; and

a, k_1, n = empirical constants.

Due to the complicated nature of the hydraulics of surface irrigation a more common approach to the design of border irrigation is through field experimentation which supplies design data after the system has been constructed. However, numerous attempts have been made to provide theoretical basis for the design of border irrigation. Hall (1956) presented a method for obtaining the advance of the water front as a function of time, surface roughness, slope of the field and soil characteristics, amongst

other factors while Christiansen et al (1966) gave an evaluation of intake rate constants in relation to the water front advance, and Hall (1960) presented a design procedure for a border based on the predicted advance of water front down the border strip.

The time of advance that is adequate to meet the irrigation requirements has been one of the constraints to be satisfied in the design of border irrigation systems. The solution of the advance problem can be attained by the assumption that the advance distance can be represented by a power function of time. Gray and Ahmed (1965) amongst others verified the validity of the power functional relationship. The resulting expression can be given by:

$$X = ct_x^m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.4$$

where

X = advance distance

t_x = time of advance to any point x; and

c, m = empirical coefficients

The values of c and m in Eq. 2.4 are not constant for a given border strip but vary with the inflow rate and the infiltration characteristics of the soil.

The continuity equation has been widely used in surface irrigation hydraulics. This is based on the fact that the cummulative inflow at any time, t, is equal to the sum of the cummulative intake and the surface storage. Evaporation losses are generally very small and can therefore be neglected.

2.3 Advance Equations

Fok and Bishop (1965), used the continuity equation to develop an advance equation for border irrigation as:

$$X = \frac{qt}{y + \bar{D}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.5$$

where

y = mean depth of flow

$\bar{D} = \frac{FK}{(n+1)(n+2)} t^{n+1}$, mean infiltration depth

$F = m(n+2,m)\ \beta(n+2,m)$, a correction factor after Keifer (1959).

$\beta(n+2,m)$ = Beta function of $(n+2)$ and m;

T = time of advance, and all other terms as defined previously.

Based on the assumption that the accumulated intake can be represented by a power function of time, Philip and Farell (1964), developed an Advance Equation as:

$$X = \frac{qT}{y} \sum_{i=o}^{\infty} \frac{\left\{\left(\frac{-kt^n}{y}\right) \Gamma(1+n)\right\}^i}{\Gamma(2 + in)} \quad \ldots\ldots \quad 2.6$$

where

T = advance time

k,n = accumulated intake coefficients

i = summation index; and

Γ = symbol for the gamma function and other terms as previously defined.

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Wilke and Smerdon (1965) observed that Eq. (2.6) predicts the advance reasonably well when the value of $\frac{kt^n}{y}$ is less than 3; and for $\frac{kt^n}{y}$ value greater than 3 the solution is better represented by the expression:

$$X = \frac{qT}{y} \sum_{i=o}^{\infty} \frac{1}{\left[\frac{-kt^n}{y}\Gamma(1+n)\right]^i \Gamma(1-in)} \quad \ldots\ldots \quad 2.7$$

Strelkoff (1977), solved the well-known volume balance for advance distance X, as a function of time, t as:

$$X = \frac{q_o T}{r_y y_o + r_z z_o} \quad \text{..... 2.8}$$

where

r_y = surface-stream shape factor, set at

$r_y = \frac{y}{y_o}$

y_o = upstream surface depth

Z_o = infiltration Depth

r_x = subsurface shape factor set at

$r_x = \frac{1}{1 + n}$

and all other terms as previously defined.

2.4 Irrigation Efficiencies

The over-all irrigation efficiency is often subdivided into components in order to evaluate the efficiency of the components of the system. Merriam (1980) observed that the aim of evaluating irrigation systems is fourfold:

1. to determine the efficiency of the system as it is being used.
2. to determine how effectively the system can be operated and whether it can be improved.

3. to obtain information which can assist engineers in designing other systems and

4. to obtain information to enable comparison of various methods, systems and operating procedures as a basis for economic decisions.

The efficiencies of the system components are usually expressed as percentages.

2.4.1 Water Application Efficiency

According to Israelson (1962), the water application efficiency is defined as the ratio of the volume of water stored in the soil root zone during the irrigation to the volume of water delivered to the field. Operationally, Israelson's definition is given as:

$$E_a = \frac{W_s}{W_f} \times 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2.9$$

where

W_s = amount of water stored in the soil rootzone during irrigation

W_f = amount of water delivered to the area being irrigated.

Water application efficiencies below 100 percent can be attributed to seepage losses from the field distribution channels and also deep percolation below the crop rootzone.

Sometimes, in case of very long fields, there may be runoff losses at the tail end of borders and furrows. Generally, water application efficiency decreases as the amount of water applied during each irrigation increases. However, very small irrigation may not fill the rootzone adequately and may reduce crop yields, and in the long run give rise to salt problems due to inadequate leaching (Michael, 1978).

2.4.2 Water Distribution Efficiency

Sharma (1974), observed that the uniformity with which water is distributed throughout the rootzone is evaluated by distribution efficiency. It can be expressed as:

$$E_d = \left(1 - \frac{\bar{y}}{\bar{d}}\right) \times 100 \quad \ldots\ldots\ldots\ldots\ldots \quad 2.10$$

where

E_d = water distribution efficiency in percent

$\bar{d}$ = average depth of water stored along the run during the irrigation

$\bar{y}$ = average numerical deviation from $\bar{d}$

Uneven distribution of water has many undesirable characteristics. Drought areas appear in a field which is not irrigated uniformly unless excess water is applied, which in turn results in a waste of water. Whenever a tendency exists for salt accumulation, those areas receiving less than the desired depths of water will show the greatest accumulation of salt.

2.5 Advance Function

One of the constraints to be satisfied in the design of border irrigation system is the time of advance that is adequate to meet the irrigation requirements. Gray and Ahmed (1965) in analysing the rate of advance of the water down the border to develop a method for determining infiltration

rates for border systems assumed that the rate of advance of water down the border could be represented by a power function of time. The design of a border irrigation system is aimed at equalizing the intake time at all points along the strip in order to have high uniformity in water application. This leads to the requirement that the advance and recession curves (will have to) be parallel. Therefore, the recession curve can also be described by a power function of time having the same exponent as the advance function.

Thus,

$$X = ct_x^m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.4$$

and

$$X_r = c_1 t_r^m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.11$$

where

X_r = recession distance

t_r = time of recession; and

c, c_1, m = empirical coefficients

In practice the complete recession function can not be represented by a power function of time because the last part of the recession curve tends to have a reverse curvature which would make the use of Eq. (2.11) questionable (Mudiare, 1982). In the

analysis of this study, the recession function is approximated by a power function of time which represents only the first part of the recession curve (that is, ignoring the points on the part with the reverse curvature). This approach is justified because the reverse curvature is small.

In order to limit the intake time to the time for water flow into the border strips, the lag time or the time between the shut off of flow and the onset of recession must be small. This condition will also reduce runoff losses that may occur. The assumption of negligible time lag is not expected to introduce any appreciable errors in the design under consideration because, as pointed out by Hart (1980) lag time may be ignored in the determination of inflow rates on borders steeper than 0.4%. Since the advance and recession curves are also to be parallel, the time for completion of recession, T_r would have to be equal to the time of advance, T. Consequently,

$$X(T) = X_r(T_r) = L \quad \ldots\ldots\ldots\ldots \quad (2.12)$$

where

T = time to complete advance

T_r = time to complete recession

L = length of field; and

all other terms are as previously defined.

Since Eqs. (2.4) and (2.11) are both subject to the condition expressed in Eq. (2.12), c_1 will have to be equal to c in the required advance and recession functions.

2.6 Surface Storage Expression

From the consideration of continuity equation that governs the water flow, it is necessary that the volume of water on the soil surface be estimated at all times during the period of advance. In the analysis of surface irrigation hydraulics, the average flow depth concept has been used by several investigators with acceptable degree of accuracy in their predicted values (Mudiare, 1982).

The average water surface profiles based on the average depths were obtained for all the border strips under study. The surface storage is estimated by determining the area under the curve representing the

average water-surface profile by graphical integration. The surface storage at any distance from the border head is the area under the curve up to that point. The surface storage can be expressed as a function of the advance distance, and hence time of advance by curve fitting techniques. Mudiare (1982) observed the surface storage curves developed for border strips by Ahmed (1963) and suggested that the surface storage expression can be represented by a polynomial of the form:

$$S = \sum_{i=1}^{\infty} A_i (T^{\frac{1}{2}})^i \quad \ldots\ldots\ldots\ldots\ldots \quad 2.13$$

where

S = surface storage per unit width of border strip;

T = time of advance; and A's are empirical coefficients to be determined.

For easy computation Eq. (2.13) can be approximated by a two parameter equation of the form:

$$S = AT^{\frac{1}{2}} \exp (BT^{\frac{1}{2}}) \quad \ldots\ldots\ldots \quad 2.13a$$

where A and B are empirical coefficients to be determined, and the other terms remain as previously defined.

2.7 Accumulated Intake Expression

During the period of advance along an irrigation border, when an inflow of q ($m^3/s/m$) is introduced at the upper end, the cummulative inflow, Q is equal to the sum of the surface storage, S and the cummulative infiltrated volume, V_f, assuming that losses due to evaporation are negligible. This can be expressed as:

$$Q = S + V_f \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.14$$

where

$$Q = \int_o^T q\, dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.14a$$

where

Q = cummulative inflow

T = time of advance to a point, L $(0 < tx \leq T)$

x = distance to any point along the field $(0 < x < L)$; and

all other terms remain as defined previously.

The quantity, V_f, in Eq (2.14) can be evaluated by assuming that the infiltration rate can be represented by a power function of the intake time; and also that the advance distance can be given by a power function of time of advance (Gray and Ahmed, 1965). That is,

$$I = kt^n \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2.15$$

and

$$X = ct_x^m \quad \ldots\ldots\ldots\ldots\ldots \quad (2.4)$$

where

t = intake time, $(T - t_x)$ and

other terms remain as defined previously.

By assuming that the infiltration rate and the advance distance can be expressed as a function of time, Mudiare (1982), gave an expression for the accumulated depth infiltrated, Da, as:

$$Da = mk/(n+1)\ T^{n+1} \quad \beta(n+2,m) \quad \ldots\ldots\ldots \quad 2.16$$

The solution of Eq. 2.16 for the intake coefficients, k and n, requires determination of the advance function, the cummulative inflow, Q, and the surface storage expression.

2.8 Volume Balance Equation

The continuity equation can be given as:

$$Q = \frac{cmk}{n+1} T^{m+n+1} \beta(n+2,m) + S \quad \ldots\ldots \quad 2.17$$

By putting $S = yX$ in which y is the average flow depth, and $Q = qT$,

$$qT = \frac{cmk}{n+1} T^{m+n+1} \beta(n+2,m) + yX \quad \ldots\ldots\ldots \quad 2.18$$

Since $X = cT^m$

$$qT = (\frac{mk}{n+1} T^{n+1} \beta(n+2,m) + y) X \quad \ldots\ldots \quad 2.19$$

which is the volume balance equation for estimating the inflow rate.

2.9 Water Requirement Equation

In the operation of surface irrigation system, it is conventional to raise the moisture content of the rootzone to its value at the field capacity. The available moisture capacity is generally used as a basis for estimating the water requirement of the crops, sometimes, it may be required to over-irrigate in order to leach out undesirable salts from the rootzone, and since it is difficult to make surface

irrigation systems flexible enough to respond to varying water demands of the crops, the operational requirement posses some problems. What could be done in this respect is to design the supply channel for a conservatively high flow rate, using the maximum allowable flow rate into the strips. The amount of water needed at each irrigation can be controlled by adjustment of the duration of water supply and/or the inflow rate. However, the water requirement in the current study is taken as the available moisture capacity of the soil.

If the available moisture capacity of the soil is dav, then the volume of water V_r required per unit width of border is given by

$$V_r = \frac{dav\ L}{E_a} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.20$$

where

E_a = water application efficiency, and

other terms remain as previously defined.

2.10 The Flow Rate Equation

The flow of water along a border strip is a kind of open-channel flow and can therefore be represented by any of the existing equations describing this kind of flow. Hydraulic calculations in border irrigation design are normally based on the Manning's equation, which includes a coefficient, n_r, that expresses the flow retardance effects of different hydraulic boundary conditions (Hartz, 1980). The coefficient varies with the types of crop, stage of crop growth, and degree of roughness of the soil surface.

As pointed out by Hall (1956), when water is introduced into a border strip at a flow rate q ($m^3/s/m$), a depth y, will be reached such that the flow rate down the strip is equal to inflow rate. The flow rate can be given by

$$q = \frac{1}{n_r} \; y^{5/3} \; S_o^{\frac{1}{2}} \qquad \ldots\ldots\ldots\ldots\ldots \quad 2.2$$

Chow (1959) stated that the flow of water through vegetations is adequately described by Eq. (2.2), thus it could be used to estimate average flow depths for use in estimating the advance of the water front.

3. FIELD DATA COLLECTION AND MATERIALS

3.1 Introduction

The current study on border irrigation system was conducted at the Kadawa Sector of the Kano River project where the field layout has been limited to a maximum length of irrigation run of 100m. The experimental field was divided into strips 4m wide and 90m long separated by low parallel dykes or border ridges. The lower end of the strips were open to allow for free drainage of surface runoff. Water was applied at the upper end of the strips by means of syphon tubes and flowed down the field as sheet flow. The inflow rate was measured by means of the syphon tubes and parshal flumes were installed at the lower end of the field for runoff measurements. The field was seeded to wheat crop (Siete cerros) during the dry cool season of December, 1987 to April, 1988.

The following measurements were taken on the experimental plots during the study.

1. Advance and recession rates
2. Ground water-table
3. Volumetric soil moisture content

4. Inflow rate
5. Flow depth
6. Field slopes in the direction of water flow on the border strips.

3.2 Advance and Recession Curves Development

In any method of water application to a field, the objective is to achieve a high level of application and distribution efficiencies. Efficient and uniform water application in surface irrigation can be achieved by equalizing the intake at all points along the strip. The advance and recession curves would have to be parallel for this to be possible; thus giving an indication that the recession function could also be represented by a power function of time (Mudiare, 1982).

The recession curve has been found to be reasonably independent of the inflow rate (Michael, 1978). Thus, when the intake time is known from knowledge of the available soil moisture capacity of the soil, the required advance curve can be developed parallel to the recession curve using the intake time. The design advance equation can

therefore be determined and subsequently used to estimate the inflow rate from some of the existing advance equations (Philip and Farell, 1964 and Strelkoff, 1977).

From actual field operation, an advance curve was obtained from field data; by obtaining the times of advance of the water front to marked points at a spacing of 15m intervals along the centre-line of the border strip on three border strips. The times during which the water receded to the established points after cut-off of supply were also noted.

The water requirement of crops vary with the stage of growth. When water supply is limited, it is necessary to take into account the stages at which the crop is severely affected by water stress. The flowering stage (anthesis) is found to be the stage at which the crop yield is considerably reduced in cereal grain crops (Michael, 1978). Thus, the flowering stage has been used for the purpose of the design under consideration herein.

During the period of advance along the irrigation border, when an inflow of q was introduced at the upper end, the rate of advance of the water front was determined by noting the times of advance of the water

front to marked points at a spacing of 15m intervals along the centre-line of the border strip. After the irrigation stream was cut off, the tail water receded downstream. The rate of recession of the tail water was also determined by noting the times at which water disappeared from the upstream end and receded to the established points at 15m intervals along the border strip.

The advance and recession curves were plotted on a logarithmic paper with distance being the ordinate and time the abscissa. The best fit line was determined by curve-fitting techniques. The intercept on the y-axis of the logarithmic paper and the slope of the line gave the values of c and m respectively of Eqs. (2.4) and (2.11) given previously as

$$X = ct_x^m \quad \text{..... 2.4}$$

and

$$X_r = c_1 t_x^m \quad \text{..... 2.11}$$

which approximate the advance and recession functions for the border strip. The advance and recession curves for the three border strips are given in Figs. 3.1 to 3.3.

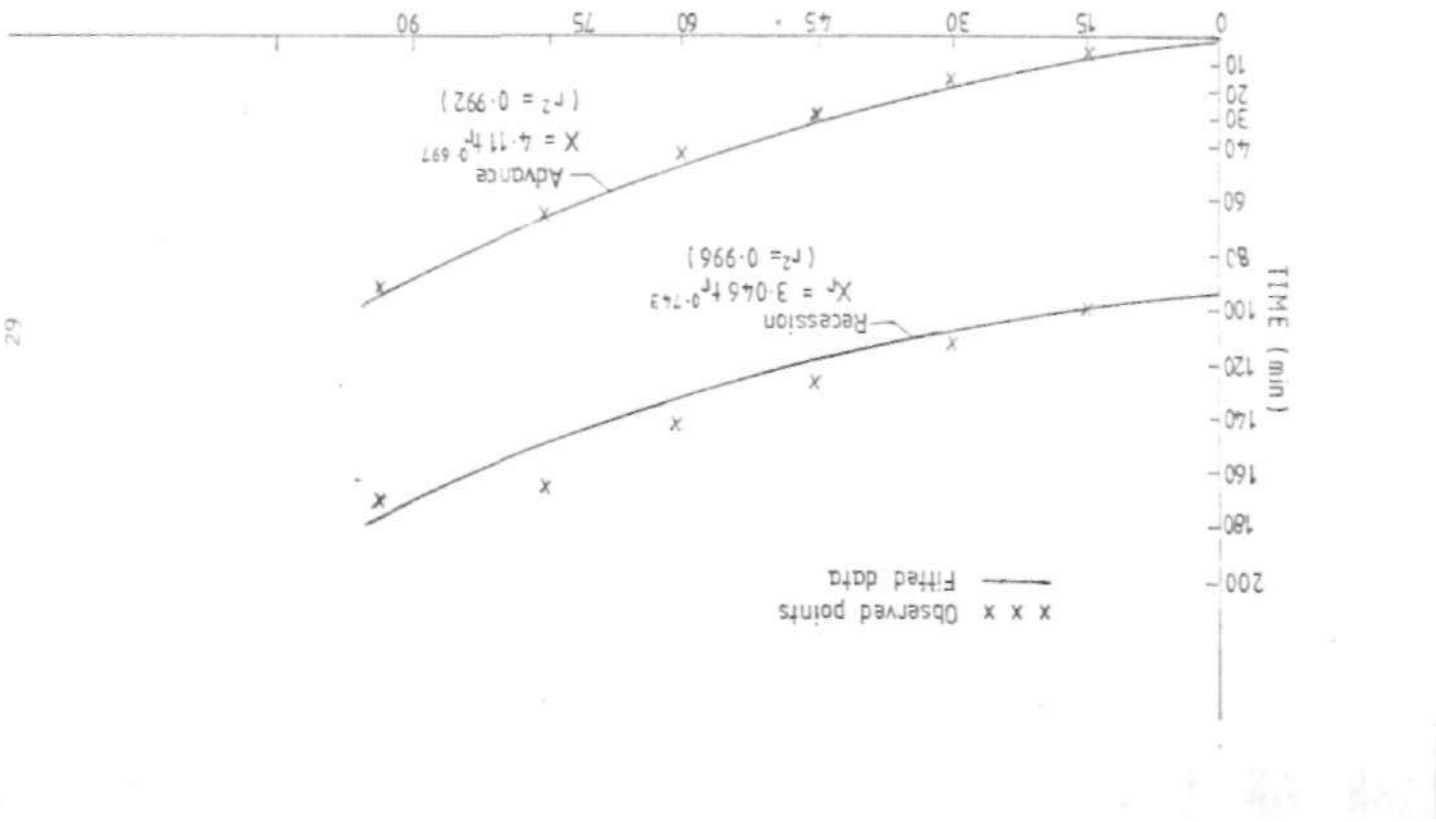


Fig. 3·1 Advance and Recession curves for border strip 3·2 —1.
[Eight weeks after planting]

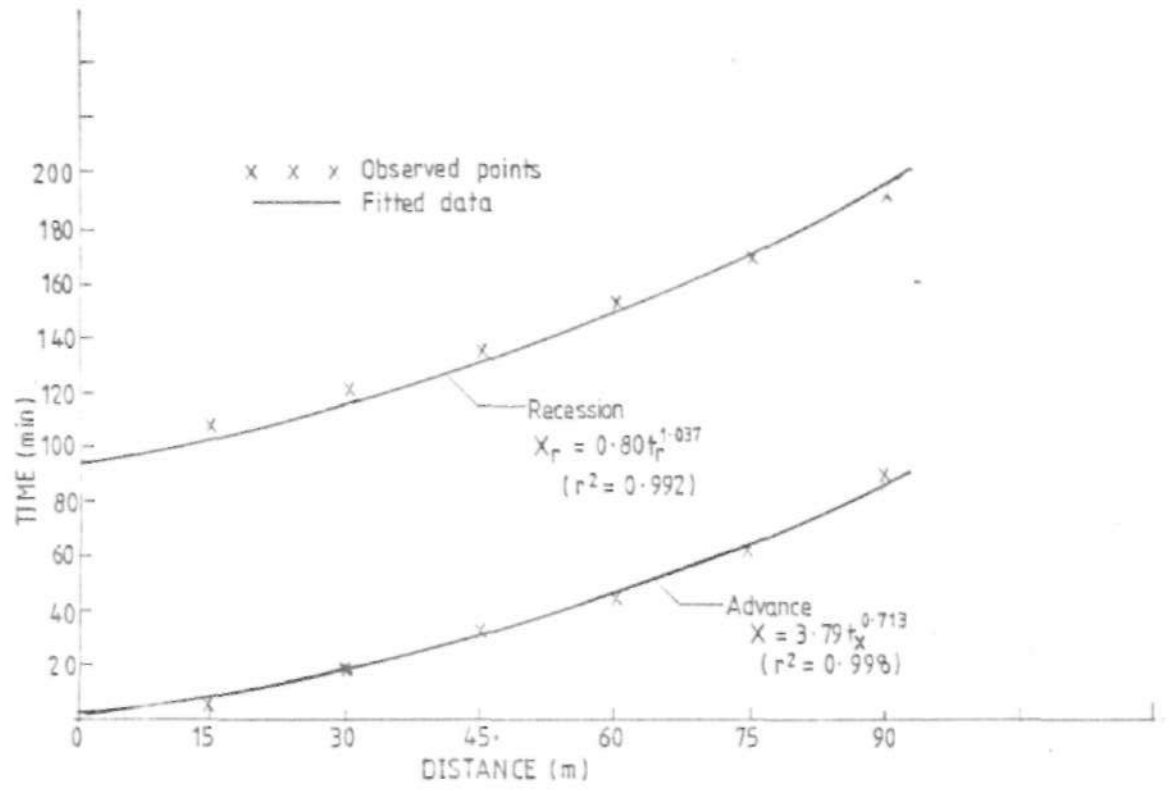


Fig. 3·2 Advance and Recession curves for border strip 3·2 —2
[Eight weeks after planting]

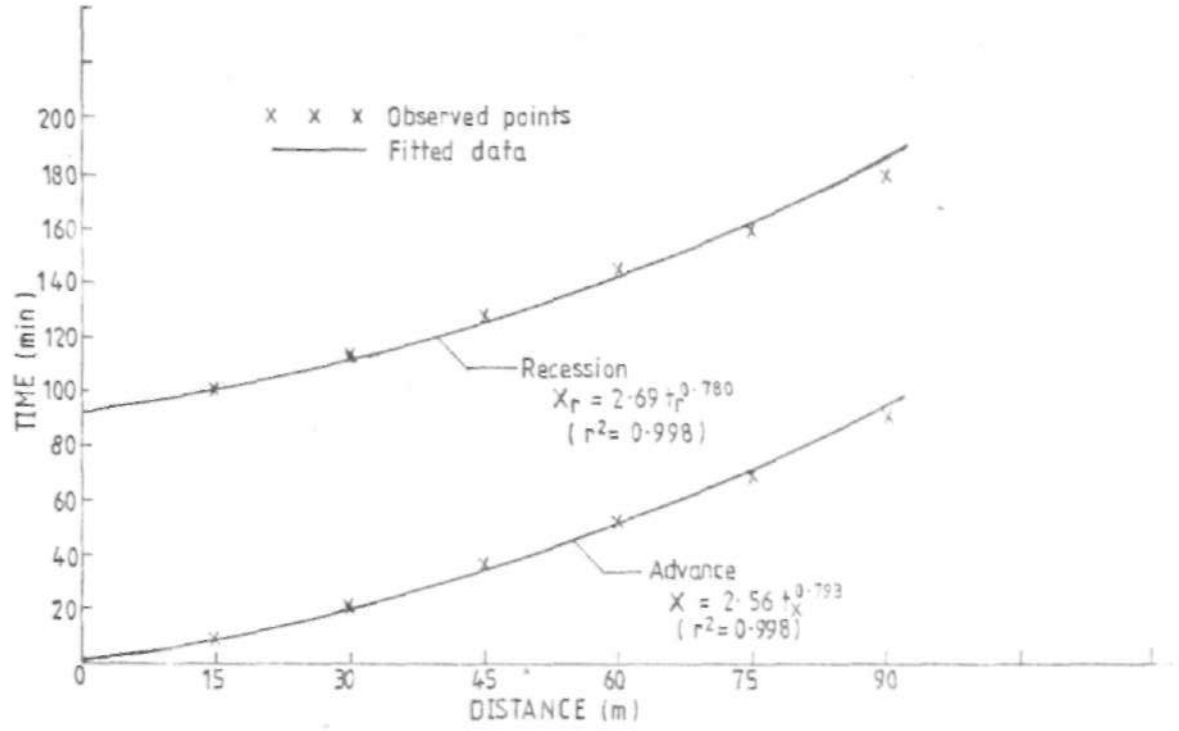


Fig. 3·3 Advance and Recession curves for border strip 3·2 — 3
[Eight weeks after planting.]

In Figs. 3.1 to 3.3, the observed points during the period of advance and recession are shown together with the fitted curves obtained using the advance and recession functions for all the three border strips under study. The degree of association between the observed points and the fitted data is represented by the coefficient of determination (R^2), obtained through regression method. The curves indicate that the advance and recession curves were reasonably parallel (see Fig. 3.1 - 3.3). This shows that the water intakes at all points along the strips were approximately equal which indicates that an efficient and uniform water application was achieved for all the border irrigation trials. The advance functions for Figs. 3.1, 3.2 and 3.3 are given in Table 3.1 for the test conducted on 20th February, 1988 on the border strips at the 2-week irrigation intervals recommended for the Kadawa Sector where high water table has been reported.

Table 3.1: Fitted Advance Functions of the three Border Strips.

Border strip No	Advance Functions
3.2-1	$X = 4.11\ t_x^{0.697}$
3.2-2	$X = 3.79\ t_x^{0.713}$
3.2-3	$X = 2.56\ t_x^{0.793}$

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3.3 Determination of Surface Storage

For the determination of surface storage in this study, five values of water depths were measured at established points at a spacing of 15m intervals along the strip during the period of advance. The depth of flow at each established point was taken as the average of the measured depths at the point. The surface storage estimate is required for the purpose of solving the continuity equation that governs the water flow. The average flow depth at each established point was used to develop water surface profile by plotting the flow depth against the distance along the border strip length (see Figs. 3.4 - 3.6). The

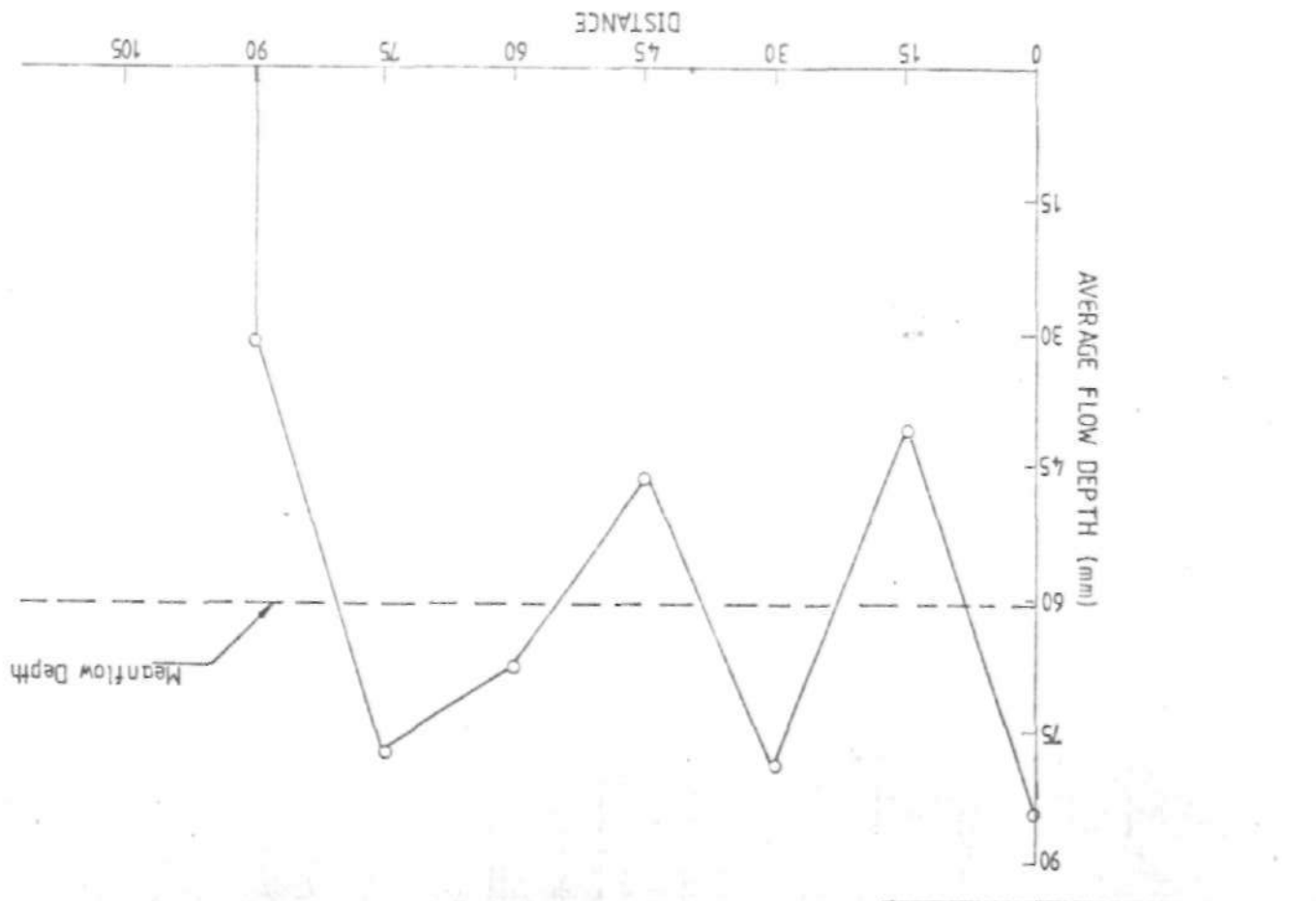


Fig 3.4 Average flow depth profile: Border strip 3·2—1
[Eight weeks after planting.]

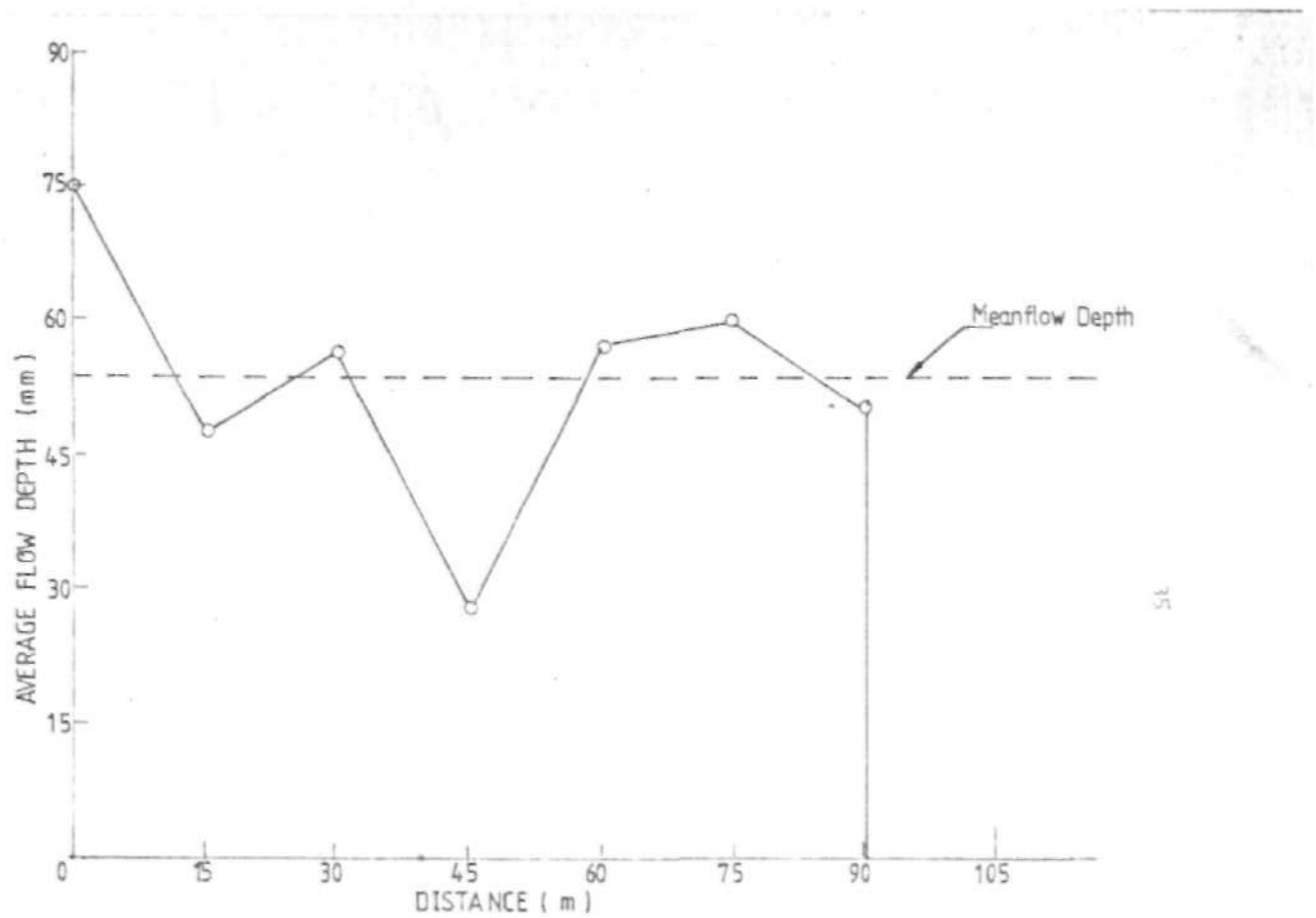


Fig. 3.5 Average flow depth profile: Border strip 3-2-2

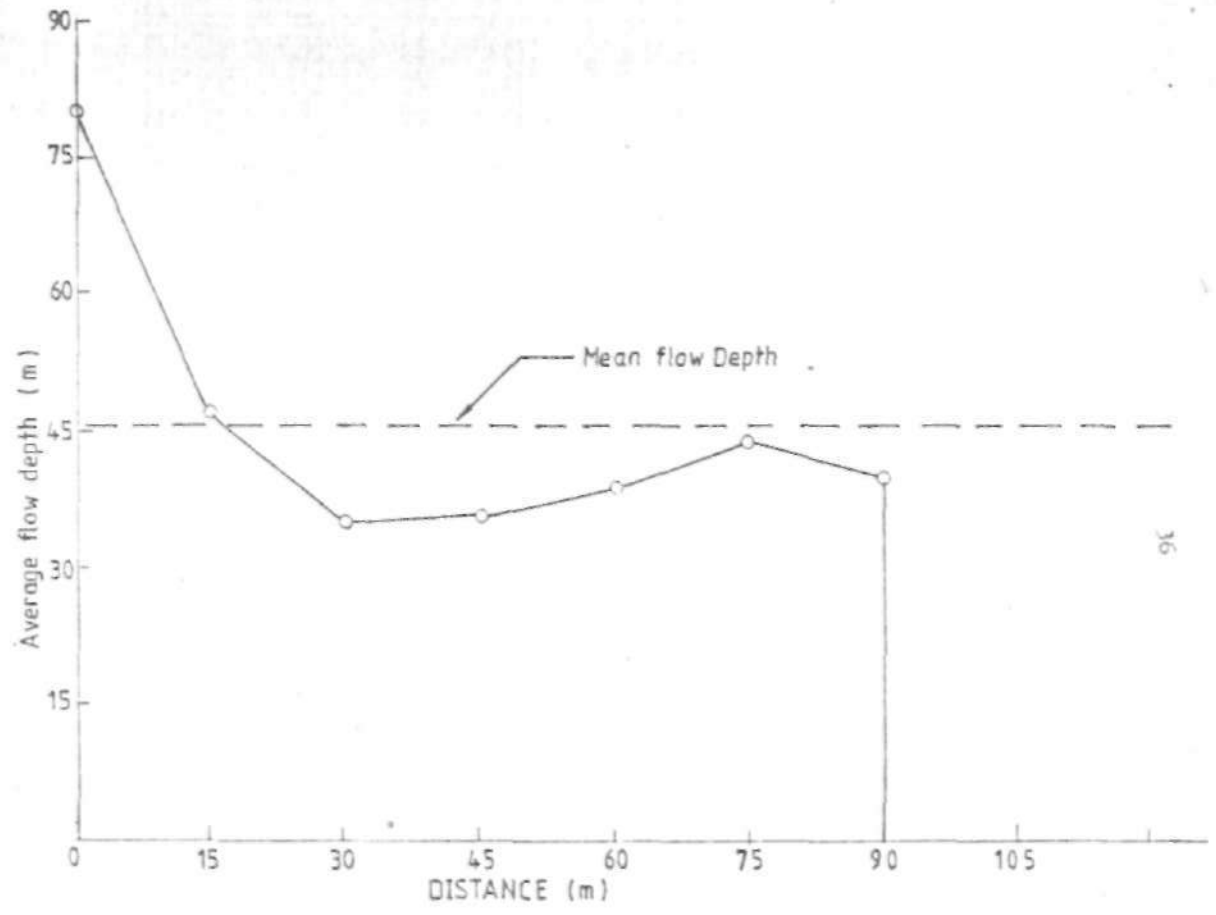


Fig. 3·6 Average flow depth profile: Border strip 3·2 — 3·

scatter of the points may be attributed to the changes in the slopes and infiltration rate.

Mudiare (1982) observed that results obtained from trial regression analysis have shown that surface storage estimate can be adequately represented by the expression.

$$S = AT^{\frac{1}{2}} \exp (BT^{\frac{1}{2}}) \quad \ldots\ldots\ldots\ldots\ldots \quad 2.13a$$

where all terms are as previously defined.

The surface storage was determined by graphically integrating the curve representing the water surface profile shown in Figs. 3.4-3.6. The surface storage curves shown in Figs 3.7 - 3.9 were obtained by plotting the cumulative surface storage at the established point against the time of advance. The expressions for the surface storage and the coefficient of determination R^2 were obtained through regression method. A summary of the surface storage equation is given in Table 3.2.

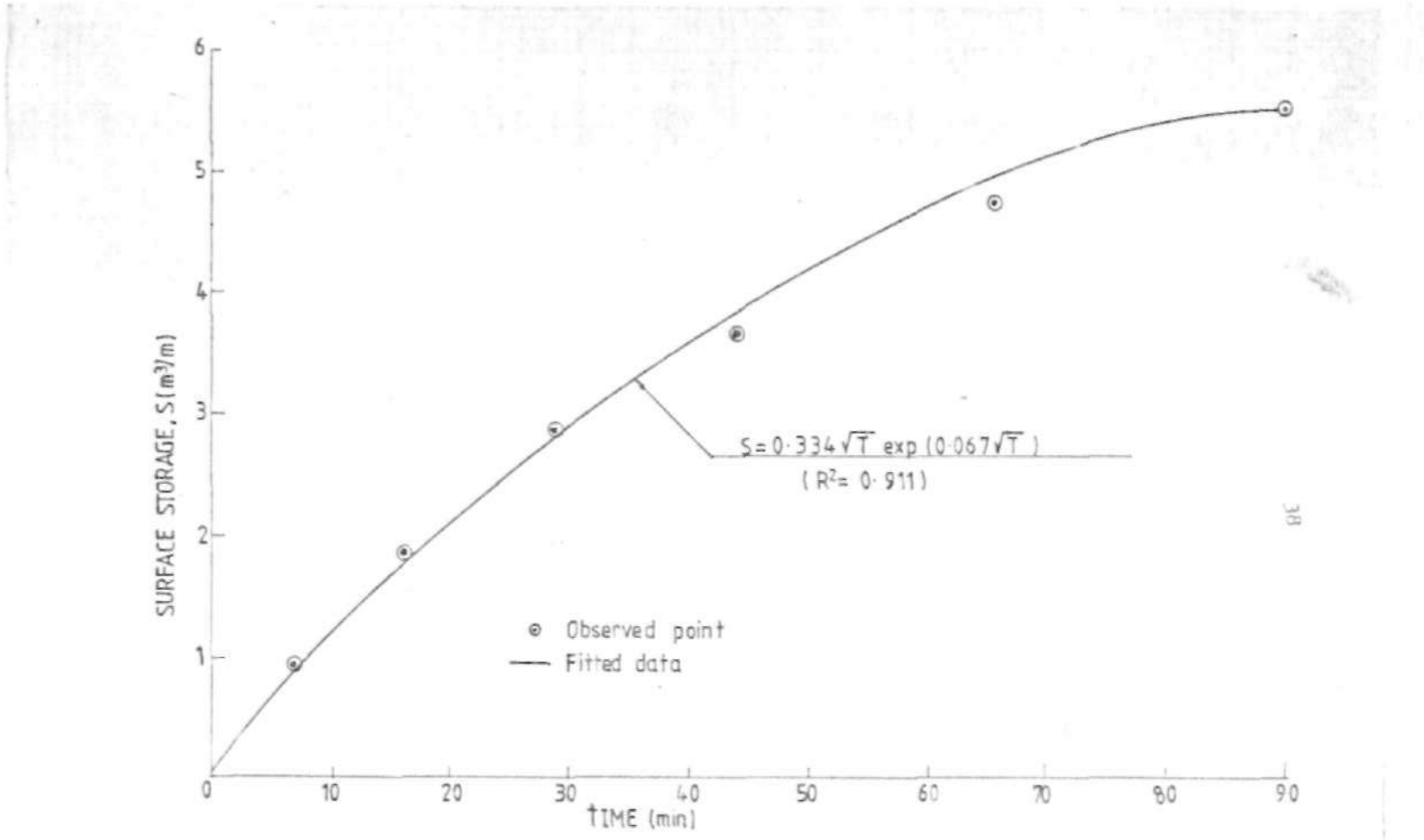


Fig. 3·7 Surface storage curve: Border strip 3·2—1
[Eight weeks after planting]

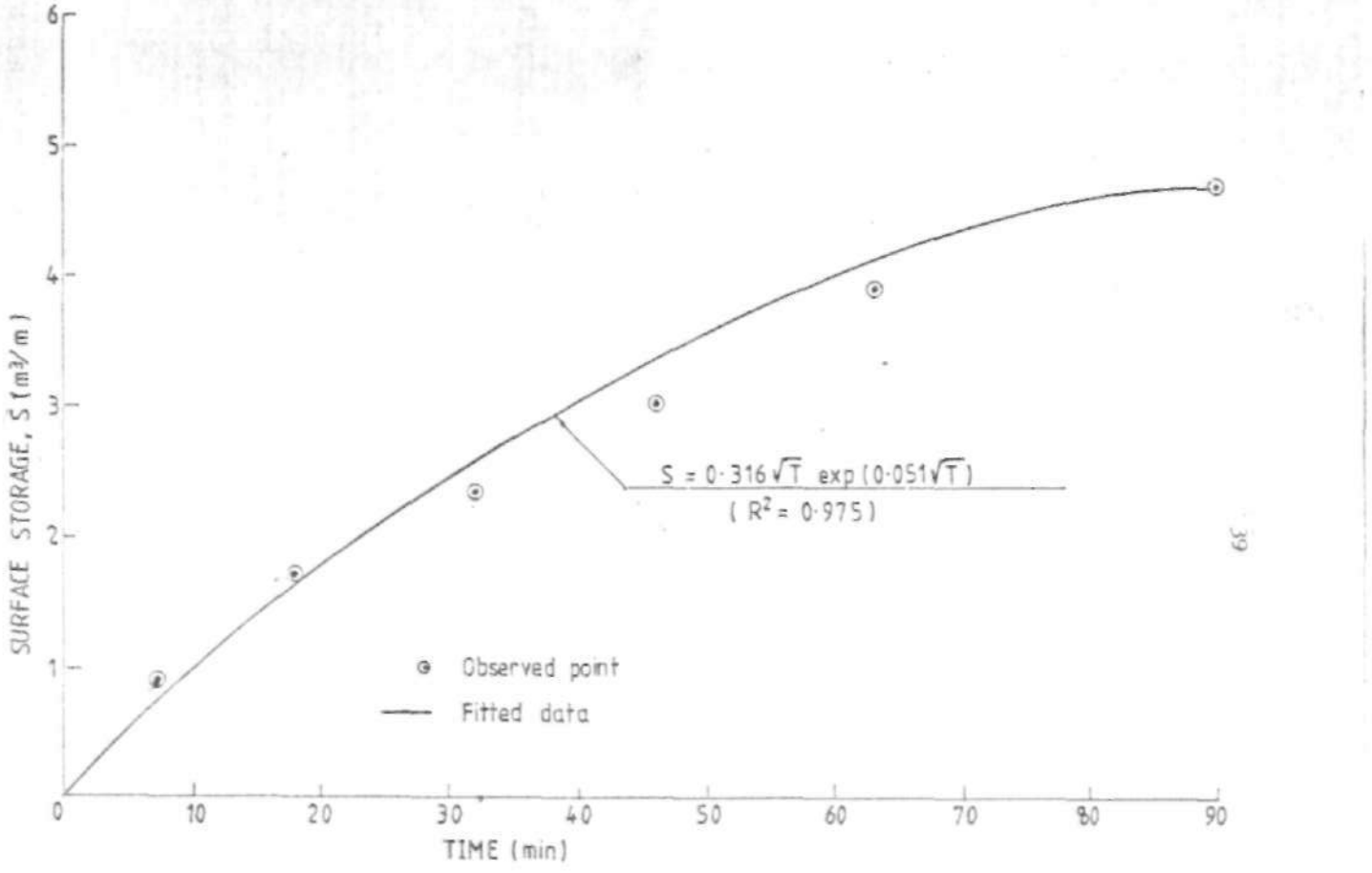


Fig. 3·8 Surface storage curve : Border strip 3·2-2.
(Eight weeks after planting)

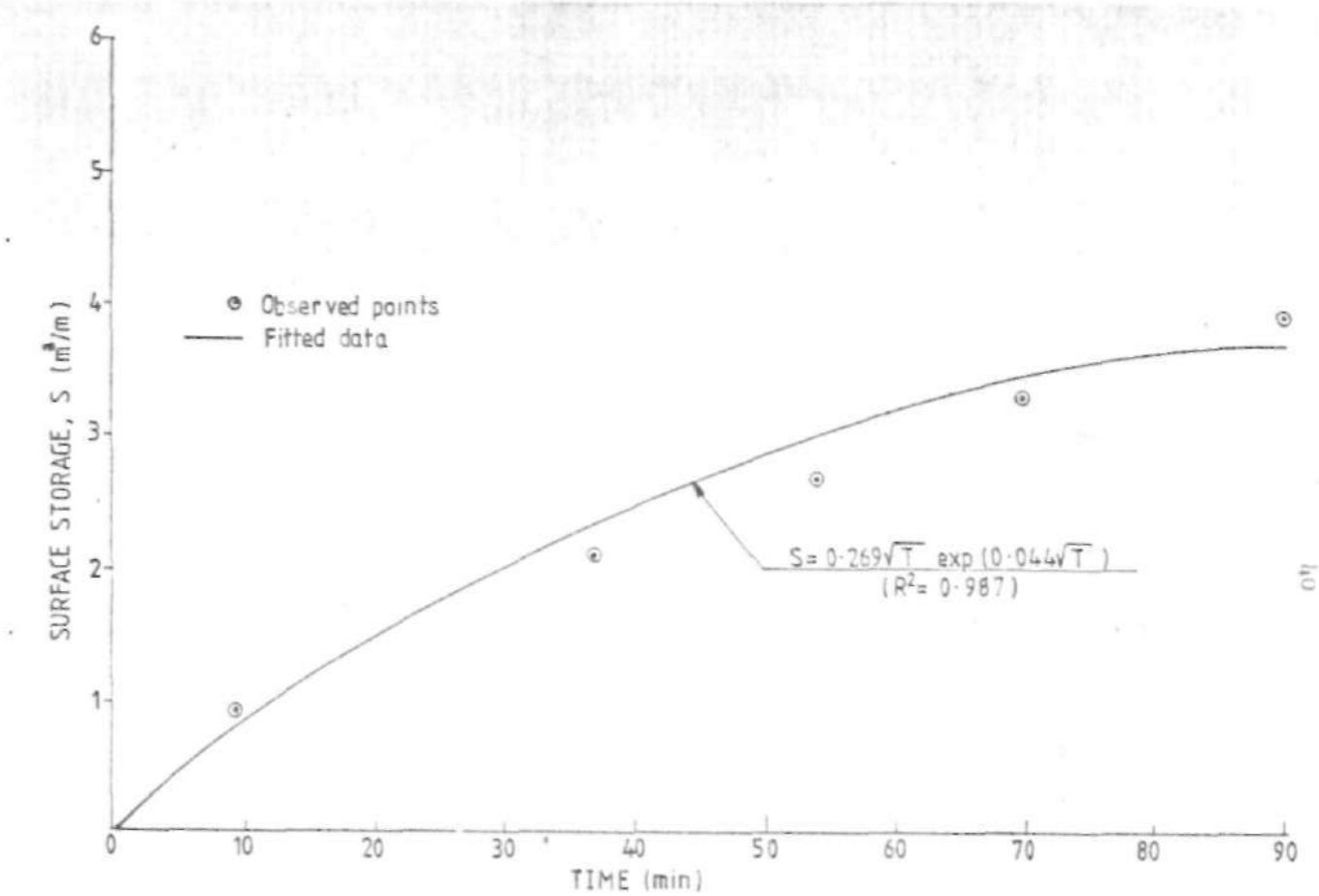


Fig 3·9: Surface storage curve: Border strip 3·2 — 3
[Eight weeks after planting]

Table 3.2: Surface Storage Equations

Border strip	Surface storage Expression, S (m^3/m)	Coefficient of determination R^2
3.2-1	$S = 0.334\ T^{\frac{1}{2}}\ \exp\ (0.067\ T^{\frac{1}{2}})$	0.911
3.2-2	$S = 0.316\ T^{\frac{1}{2}}\ \exp\ (0.051\ T^{\frac{1}{2}})$	0.975
3.2-3	$S = 0.269\ T^{\frac{1}{2}}\ \exp\ (0.044\ T^{\frac{1}{2}})$	0.987

3.4 Accumulated Intake Expression

For each border strip, the inflow was estimated by applying the orifice flow formula to the turnout syphon. The cumulative inflow at any time during the advance was therefore determined. The accumulated intake at any time was obtained by subtracting the surface storage from the cumulative inflow (that is by solving the continuity equation). The procedure is set out as shown in Table 3.3. The accumulated depths (col. 6) for all the border strips tested were plotted against the time of advance on a logarithmic paper, and the best fit line obtained by curve fitting techniques. The intake coefficients of Eq. (2.16) were then determined. The equation obtained for the

Table 3.3: Evaluation of Intake Coefficients: Border Strip 3.2-1

Date of measurement	(1) Advance distance X (m)	(2) Time of advance T (min)	(3) Cumulative inflow Q (m^3/m)	(4) Surface storage S (m^3/m)	(5) Cumulative infiltrated volume Q-S (m^3/m)	(6) Accumulated infiltrated depth (Q-S)/X (mm)
20/2/88	15	7	1.12	0.95	0.17	11
	30	16	2.56	1.86	0.70	23
	45	29	4.64	2.81	1.83	40
	60	44	7.04	3.67	3.37	56
	75	66	10.56	4.77	5.79	77
	90	90	14.40	5.59	8.81	97

Table 3.4: Evaluation of Intake Coefficients: Border Strip 3.2-2

Date of measurement	(1) Advance distance X (m)	(2) Time of advance T (min)	(3) Cumulative inflow Q (m^3/m)	(4) Surface storage S (m^3/m)	(5) Cumulative infiltrated volume Q-S (m^3/m)	(6) Accumulated infiltrated depth (Q-S)/X (mm)
20/2/88	15	7	1.12	0.93	0.92	13
	30	18	2.88	1.72	1.16	38
	45	32	5.12	2.36	2.76	61
	60	46	7.36	3.01	4.35	72
	75	63	10.08	3.89	6.19	82
	90	90	14.40	4.72	9.68	97

Table 3.5: Evaluation of Intake Coefficients: Border Strip 3.2-3

Date of measurement	(1) Advance distance X (m)	(2) Time of advance T (min)	(3) Cumulative inflow Q (m^3/m)	(4) Surface storage S (m^3/m)	(5) Cumulative infiltrated volume Q-S m^3/m	(6) Accumulated infiltrated depth (Q-S)/X (mm)
20/2/88	**15**	9.4	1.15	0.95	0.19	13
	30	**22**	2.68	1.78	0.90	30
	45	**37**	4.51	2.31	2.20	48
	60	**54**	6.58	2.87	3.71	61
	75	**70**	8.54	3.49	5.05	67
	90	**90**	10.98	4.12	6.86	76

average accumulated intake using this procedure was found to be

$$Da = 2.68\ T^{0.799} \quad \text{..... 2.16}$$

for time of advance and for intake time the expression

$$Da = \frac{kt_i^{n+1}}{(n+1)(n+2)} \quad \text{..... 3.1}$$

was used to obtain

$$Da = 2.45t_i^{0.799} \quad \text{..... 3.1}$$

where

t_i = intake time and other terms as previously defined.

3.5 Ground water Table Measurements

PVC piezometer tubes were installed at a depth of 1.3m below the soil surface at different locations in the study area. Ground water levels in the tubes were measured by employing the use of a locally made water level sounder to which a graduated stalk was attached as developed by Nwa (1982). Water table measurements were taken at two week intervals during the irrigation season.

Table 3.6 shows the positions of ground water table during the flowering stage of the wheat crop. As shown, when the water table depth during the period after irrigation is less than that before irrigation, it means that part of the irrigation water applied has contributed to the ground water thereby resulting to a rise in the water table. A constant water table depth before and after irrigation indicates that there has been no appreciable contribution to ground water table by the irrigation.

Table 3.6: Distance to Ground Water Table on 20th February 1988.

Border Strip No.	Border Strip region	Ground water table Before irrigation (mm)	Ground water table After irrigation (mm)
3.2-1	upper end	720	630
	mid-field	800	680
	lower end	750	600
3.2-2	upper end	650	630
	mid-field	810	780
	lower end	700	650
3.2-3	upper and	1020	1020
	mid-field	750	750
	lower end	640	635

3.6 Measurement of Soil Moisture Deficiency

The soil moisture content was determined before and after irrigation using the gravimetric method. Soil samples were taken at incremental depths of 200mm. Sampling was limited to a depth of 600mm because the soil was saturated below the point in the experimental area. Sampling was done just before and two days after irrigation for each trial. Kruse et al. (1978) suggested that field capacity is water remaining in a soil two to three days after the soil has been saturated and after free drainage has practically ceased. The irrigation interval was put at two weeks interval as suggested by Dalhat (1988) for borders and basins at the experimental area. The dry densities of the soil mass for the various soil depth ranges in the sampled horizons were also determined and used to determine the equivalent depth of water held on the various soil depth.

The soil moisture added (M_a) shown in column 3 of Tables3.7-3.9, was obtained as the difference between the moisture contents before and after irrigations and expressed in millimetres of water. Column 4 of the Table shows the values of the soil moisture used (M_u) by the crop within 2-weeks interval and was obtained as the

Table 3.7: Bulk Density and M.D at Flowering Stage of the Crop for Border Strip 3.2-1

Sampling point	Soil depth (m)	Bulk density (g/cm^3)	Soil moisture added (mm)	Moisture used (mm)	Moisture deficit (%)
	(1)	(2)	(3)	(4)	(5)
Upper	0-0.20	1.45	49.9	30.0	60.1
End	0.20-0.40	1.38	29.5	12.0	40.6
	0.40-0.60	1.30	23.1	8.0	34.6
Mid-	0-0.20	1.45	20.0	15.0	75.0
Field	0.20-0.40	1.38	19.9	13.0	65.3
	0.40-0.60	1.30	13.8	9.0	65.2
Lower	0-0.20	1.45	38.60	25.5	66.0
End	0.20-0.40	1.38	28.60	16.0	55.9
	0.40-0.60	1.30	17.7	9.0	50.8

Table 3.8: Bulk Density and M.D at Flowering Stage of the Crop for Border Strip 3.2-2

Sampling point	Soil depth (m)	Bulk density (g/cm^3)	Soil moisture added (mm)	Moisture used (mm)	Moisture deficit (%)
	(1)	(2)	(3)	(4)	(5)
Upper	0-0.20	1.45	41.7	28.0	67.1
End	0.20-0.40	1.38	30.7	15.0	48.9
	0.40-0.60	1.30	24.7	10.0	40.5
Mid-	0-0.20	1.45	36.0	25.0	69.4
Field	0.20-0.40	1.38	34.0	20.0	58.8
	0.40-0.60	1.30	29.0	11.5	39.5
Lower	0-0.20	1.45	36.5	22.5	61.6
End	0.20-0.40	1.38	36.5	18.0	49.3
	0.40-0.60	1.30	21.5	10.0	46.5

Table 3.9: Bulk Density and M.D at Flowering Stage of Crop for Border Strip 3.2-3

Sampling point	Soil depth (m)	Bulk density (g/cm^3)	Soil moisture added (mm)	Moisture used (mm)	Moisture deficit (%)
Upper	0-0.20	1.45	39.3	28.5	72.5
End	0.20-0.40	1.38	26.3	17.0	64.6
	0.40-0.60	1.30	20.3	11.0	54.2
Mid-	0-0.20	1.45	39.0	28.0	71.6
Field	0.20-0.40	1.38	22.0	15.0	68.2
	0.40-0.60	1.30	20.0	11.5	57.5
Lower	0-0.20	1.45	25.9	19.6	75.6
End	0.20-0.40	1.38	14.0	10.0	71.4
	0.40-0.60	1.30	13.0	8.0	61.5

difference between the moisture content after one irrigation and that just before the next irrigation. This was also expressed in millimetres of water. The percentages of the soil moisture added used from the soil before the next irrigation was also calculated for the various depths. This was taken as the moisture deficit (M.D) expressed thus:

$$MD = \frac{M_u}{M_a} \quad \text{.....} \quad 3.2$$

An average value of the soil moisture used within the irrigation interval was obtained for the strips and used to estimate the design water application depth.

Tables 3.7 to 3.9 present the average bulk density and moisture deficit for the various soil depths for the border strips considered in this study. Observation of the tables shows a low moisture use by the crop at some sites in the border strip. This may be attributed to varying degree of moisture contribution from the ground water table.

3.7 Water Application and Distribution Efficiencies

The water application and distribution efficiencies in this study were determined on the experimental border strips using Eqs (2.9) and (2.10) respectively

$$E_a = \frac{W_s}{W_f} \times 100\% \quad \ldots\ldots\ldots\ldots 2.9$$

$$E_d = (1 - \frac{\bar{y}}{d}) \times 100\% \quad \ldots\ldots\ldots\ldots 2.10$$

where all terms remain as previously defined.

The water application efficiency obtained from the border strips ranged from 50.2% to 61.3% which are lower than the range of 60% to 75% suggested by Ogrosky and Mockus (1964), (see Table 3.10). The low values of the water application efficiency may be attributed to Saturated conditions below the rootzone and contribution from the groundwater table, as evidenced by the high runoff values measured at the time of irrigation. The high seepage rate from the channel may also have contributed to the low application efficiency on the border strips.

The distribution efficiency was generally found to be quite satisfactory. The values ranged from 69% to 89% for all the three border strips under consideration. The uniformity of water distribution is more important than the application efficiency in terms of maintaining uniform crop growth and so the irrigation performance in this study can still be taken as being satisfactory. Other values of water application and distribution efficiencies are given in Appendix A.

Table 3.10: Water Application and Distribution Efficiencies at Flowering Stage of Crop. (Eight weeks after planting).

Date	Border strip No.	Application efficiency (%)	Distribution efficiency (%)
20/2/88	3.2-1	50.2	87.7
	3.2-2	60.5	85.0
	3.2-3	60.0	72.0

3.8 Measurement of Inflow Rate

The amount of water applied to the field was measured by calibrated syphon tubes. The flow rate through a syphon tube was computed using Eq. (3.3).

$$q_s = ac\sqrt{2gh} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3.3$$

where

q_s = discharge from a syphon tube in $m^3/sec.$

a = cross-sectional area of the syphon tube in m^2

c = coefficient of discharge for syphon tube

g = acceleration due to gravity in m/s^2

h = elevation difference between water surface elevation in the channel and elevation of the outlet point of application in the field in m.

A graph of q against $\sqrt{h}$ was plotted in which $ac\sqrt{2g}$ becomes the slope of the curve. The value of c was therefore determined as

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$$c = \frac{\text{slope of the curve}}{a\sqrt{2g}} \quad \ldots\ldots\ldots\ldots\ldots \quad 3.4$$

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The value of c was then substituted in Eq. (3.3) to determine the amount of water applied to the field. The amount of water obtained from the above procedure gave the discharge from one single syphon tube. The total amount

of water entering the field depends on the number of syphon tubes being used. In this study, four syphon tubes were used. The equation obtained for the discharge of one syphon tube was

$$q_s = 0.21\sqrt{h} \quad \text{.....} \quad 3.5$$

The discharge per unit width q into the various border strips in this study are given in Table 3.11.

Table 3.11: Discharges into Border Strips

Border strip No.	Inflow, q $m^3/min/m$
3.2-1	0.160
3.2-2	0.160
3.2-3	0.122

3.9 Measurements of Slopes of Border Strips

The slopes of the different borders under study were measured using surveying equipment. The values obtained are given in Table 3.12.

Table 3.12: Slopes of Border Strips

Border Strip No.	Slope (%)
3.2-1	0.648
3.2-2	0.697
3.2-3	0.672

4. DESIGN OF BORDER IRRIGATION SYSTEM

4.1 Introduction

In the design of surface irrigation system, the length and slope are usually fixed for a particular field while other parameters need to be estimated or determined. Design parameters in surface irrigation systems are difficult to estimate with a nigh degree of certainty, because of the wide variability of the parameters both spatially and temporally. This situation is complicated by the lack of homogeneity of soils which introduces variation in the parameters desired. This problem is often resolved by conducting preliminary irrigation trials for a given design and then modifying the design accordingly. The fore-going method is illustrated with data obtained from trial runs conducted on border strips at the Kadawa Irrigation Research Station.

4.2 Determination of Design Parameters

4.2.1 Required Advance Function

The times of advance of the water front to marked points at a spacing of 15m intervals along the centre line of the border strip were determined for three border strips. The times during which the water receded to the established points after the cut-off of supply were also noted. The recession curve is known to depend on the slope of the border. However, in this study, the slopes of the border strips were found to be close, hence, the recession functions of the strips would be expected to be approximately equal. Thus, an average curve was obtained from the recession data for the three strips. The recession data obtained for all the border strips under study were plotted on a logarithmic paper and the best fit line obtained by curve-fitting techniques. The result obtained from the procedure was

$$X_r = 2.359\, t_r^{0.795}, \quad \ldots\ldots\ldots\ldots 2.11$$

which approximates the required recession function shown in Fig. 4.1.

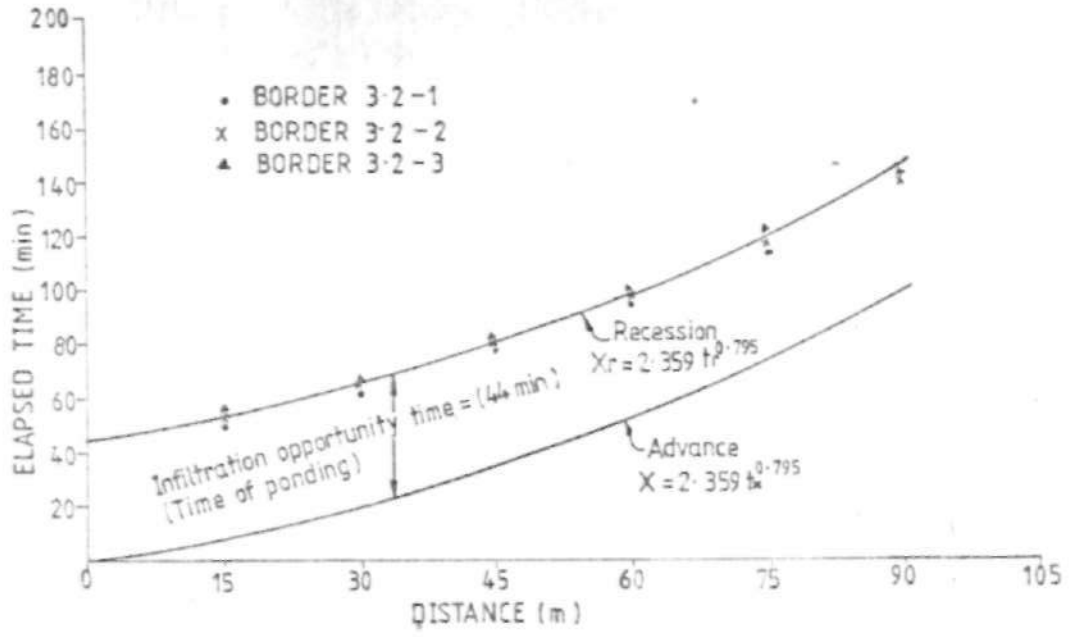


Fig. 4·1 Required advance and recession curves

The required time of ponding was determined from the moisture holding capacity and the accumulated intake expression. The required advance curve was estimated from the required recession curve because the recession curve does not completely depend on inflow rate (Michael, 1978). Thus, the required advance curve was drawn parallel to the recession curve at a distance equal to the time of ponding, since the two curves are to be approximately parallel to ensure efficient water distribution at all points along the border length. The design advance and recession curves are shown in Fig. 4.1. The required advance function was found to be:

$$X = 2.359\ t_x^{0.795} \quad \ldots\ldots\ldots\ldots\ldots\ 2.4$$

From Eq. (2.4), the time of advance for a distance L = 90m was obtained as 97min.

4.3 Retardance Coefficient Estimate

In order to analyse the flow of water on the border strip, it is desirable to have an estimate of the retardance coefficient for the soil-crop complex. In the present analysis, Manning's roughness coefficient of 0.25 taken from Table 4.1 was used. The value was used so as to take into account possible changes that

might occur due to stage of crop growth.

Table 4.1: Common Retardance Coefficients Used in Border Design (Hart, 1980)

Soil Surface Condition	Manning's n
Smooth, bare soil surface	
noncultivated, oil-mulch-treated citrus	0.04
Small grain, drill rows parallel to border strip	0.10
Alfalfa, mint, boradcast small grain and similar crops	0.15
Dense food crops, small grain with drill rows across the border strip	0.25

4.4 Summary of Design Parameters and Equations

Average slope of border strip, $S_o = 0.00672$

Average accumulated intake expression,

$$D_a = 2.45t_i^{0.799} \text{ (mm)}$$

Manning's Equation is given as

$$q = \frac{1}{n_r} y^{5/3} S_o^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots \quad 2.2$$

Required Advance Equation,

$$X = 2.359t_x^{0.795} \quad \ldots\ldots\ldots\ldots\ldots \quad 2.4$$

Advance Equation (Philip and Farell, 1964),

$$X = \frac{qT}{y} \sum_{i=o}^{\infty} \frac{1}{\left[\frac{-kt^n}{y}\Gamma(1+n)\right]^i \Gamma(1-in)}$$

$\ldots\ldots\ldots\ldots\ldots$ 2.7

Advance Equation (Strelkoff, 1977),

$$X = \frac{qT}{r_y y_o + r_z Z_o} \quad \ldots\ldots\ldots\ldots\ldots \quad 2.8$$

4.5 Design Calculations

Equation (2.2) was solved for the inflow rate q for different flow depths using a value of the Manning's roughness coefficient of 0.25 taken from Table 4.1. The value of q was then substituted in Eq. (2.7) and solved simultaneously with Eq. (2.4) until the desired advance distance of 90m was obtained. The corresponding flow rate q was taken as the required estimated flow.

Similarly, the value of q obtained in Eq. (2.2) was substituted in Eq. (2.8) and solved simultaneously with Eq. (2.4) until the advance distance of 90m was obtained. In estimating advance in border irrigation using Eq. (2.8), Strelkoff (1977) observed that errors between computed and measured advance are significantly small, and around 1%. Michael and Pandya (1971), in using Eq. (2.7), noted that the percentage deviation between measured and computed advance values range between 2 and 10%. Thus, the error in the advance estimate relative to the field length at the end of the design advance time was limited to about ±1% for the Strelkoff method and about ±2% for the method of Philip and Farell, (1964). The results obtained from this procedure are presented in Tables 4.2 and 4.3.

Table 4.2: Solution of Advance Equation (Philip and Farell, 1964)

Inflow rate q (m^3/min-m)	Flow depth y (m)	$\frac{k\Gamma(1+n)}{y}$	Values of i					Estimated advance X (m)	Estimated Error (%)	Remarks
			1	2	3	4	5			
0.114	0.045	0.05071	0.55533	-0.11779	-0.03551	-0.01367	0.00034	95.5	-6.1	High flow
0.120	0.047	0.04855	0.58004	-0.12850	-0.04047	-0.01627	0.00042	97.8	-8.6	High flow
0.108*	0.044	0.05186	0.54301	-0.11262	-0.03320	-0.01250	0.00030	91.7	-1.8	Satisfactory flow
0.103	0.043	0.05232	0.53817	-0.11063	-0.03232	-0.01206	0.00029	89.1	+0.98	Low flow

*Required Estimated flow.

Design Parameters

Manning's roughness coefficient, $n_r = 0.25$
Time of Advance, T = 97 min.
Required advance function, $X = 2.359\ t^{0.795}$

Table 4.3: Solution of Advance Equation (Strelkoff, 1977)

Design Parameters

Manning's roughness coefficient, $n_r = 0.25$

Time of advance, T = 97min

Required Advance function, $X = 2.359\ t_x^{0.795}$

Inflow rate q (m^3/min-m	Flow depth y_o (m)	Estimated advance X (m)	Estimated Error (%)	Remarks
0.125	0.060	80.3	+10.8	Low flow
0.135	0.063	85.4	+5.2	Low flow
0.147*	0.066	91.0	-1.1	Satisfactory flow
0.156	0.069	95.4	-6.0	High flow

* Required Estimated flow.

4.6 Adequacy of Inflow

The method of Philip and Farell (1964) resulted in an inflow rate of 0.108 m^3/min-m while that of Strelkoff (1977) gave a value of 0.147 m^3/min-m. The required estimate was taken as the higher value of the two flow rate estimates which is 0.147 m^3/min-m, in order not to under design the capacity of the field channels.

An important constraint on the flow rate is the need to prevent erosion on the irrigated strip. The maximum non-erosive flow rate per unit width of a border strip is given by Hart (1980) for small grains and pasture, as

$$q_{max} = (1.059 \times 10^{-2})\ S_o^{-0.75} \quad \ldots\ldots\ 4.1$$

where

q_{max} = maximum inflow rate, m^3/min-m and
S_o = slope of border strip; m/m.

For the current example, q_{max} = 0.451 m^3/min-m. Since the desired inflow rate, q = 0.147 m^3/min-m, is much less than q_{max}, it is considered safe against erosion hazards. Thus the estimated inflow rate q = 0.147 m^3/min-m is considered adequate for the design.

4.7 Water Application Efficiency

The application efficiency obtained from actual field operation is given in Table 3.10. The efficiency range between 50.2 to 61.3% for flow rates ranging from 0.122 to 0.160 m^3/min-m, at the current management level of the farmers at Kadawa Irrigation Project. Nwa (1982), showed that an application efficiency of 60 to 65% may be achieved with an inflow rate of 0.15 m^3/min-m. In addition, the farmers in the project area are not likely to be able to manage the irrigation practices well enough to ensure high water application efficiency values. Furthermore, the advance and recession curves (Fig. 3.3) obtained from Border Strip 3.2-3 and whose slope value was used in the design calculations were found to be approximately parallel, which indicated that the water applied was uniformly distributed along the length of the border strip. The water application efficiency value corresponding to the border strip was found to be 60%. Thus, a water application efficiency value of 60% is considered adequate for the present design.

4.8 Summary of Design Procedure

For proper understanding, the steps to be followed in using the design procedure are given sequentially as follows:

1. The first step is to carry out an advance and recession test including measurements of flow depths on one or more border strips.
2. From data obtained in step 1, plot advance and recession curves and using curve fitting techniques determine the advance and recession functions, and thus obtain values of c, c_1 and m.
3. The required recession curve is obtained from the average of the recession curves for the three strips tested and thus the required recession function ($X_r = c_1 t_r^m$).
4. The required advance function ($X = ct_x^m$), is then obtained for the required advance curve by regressing advance distance against advance time and the time required for the water front to reach the lower end of the field, a distance, L, can be determined from the established advance function.

5. The data on surface storage from the first test runs are used, and a surface storage versus time curve is drawn. Curve-fitting then allows the determination of the surface storage equation from the general function

$$S = AT^{\frac{1}{2}} \exp(BT^{\frac{1}{2}})$$

6. Using the test inflow rate, and the surface storage equation, and knowing the advance exponent m, the equation

$$Da = \frac{Q - S}{X} = \frac{mkT^{n+1}}{n+1} \beta(n+2, m) \quad .. \quad 2.16$$

can be solved for k and n. The equation can be easily solved by using two values of T, Q, S and X.

7. An estimate of the depth of water to be applied is made from the results of laboratory tests of available moisture capacity on soil samples taken from the rootzone. The available moisture capacity estimate is taken as the depth of water to be applied. The estimated water application efficiency is used to determine the gross depth of water to be applied and the corresponding time of application (ponding time) determined from Eq. (3.1).

8. Select appropriate retardance coefficient, n_r, for the stage of crop growth from Table 4.1.

9. Using the selected n_r from step 8, calculate q from Manning's equation for the value of average flow depth y.

10. Using Eq. (2.7) or (2.8), calculate the advance distance that would occur in the advance time obtained in step 3, and compare with $L(1\pm0.02)$ or $L(1\pm0.01)$.

11. If the estimated advance distance from step 9 lies in the given range, the corresponding values of q and y are satisfactory; otherwise they are unsatisfactory and a new value of flow depth is used in step 9.

12. Select the higher value of q from the results of Eqs. (2.7) and (2.8) and check the flow rate against erosion hazards using Eq. (4.1).

13. Establish the channel slope from the consideration of the slopes in the field and select appropriate value of Manning's coefficient to be used from literature and design the field channel.

5.0 DISCUSSION OF RESULTS

The illustrative design indicates that the estimated inflow rate of q = 0.147 m^3/min-m is adequate for attaining the design efficiencies. The use of average recession curve is not expected to introduce any appreciable error since the slopes of the three border strips were approximately equal.

The suggested design has been based on the need to have uniform water application by ensuring that the advance and recession curves be parallel. The inherent variability in the infiltration characteristics of the soil, however, would make it difficult to obtain perfect uniform water application. The design parameters: the infiltration rate, and the water application efficiency, both vary with the stage of crop growth, and surface condition of the soil. The design would have to be modified to take into account the anticipated changes in the parameters being used. It is believed that the suggested design procedure would be very useful not only for the modification of existing border systems, but also the establishment of new ones.

The results obtained for the water application and distribution efficiency from the border systems showed that the distribution efficiencies were satisfactory in that they agree quite well with the values given by previous investigators for the same area. The water application efficiency ranged from 50.2% to 61.3%. The low value in the water application efficiency could be due to drainage problems in the rootzone because drilled holes for the installation of piezometer tubes indicated that the soil was extremely wet as from 0.60m below the surface. The results of moisture deficit test carried out showed discrepancy in moisture use by the crop. This may be attributed to varying degree of moisture contribution from the water table.

6. SUMMARY AND CONCLUSIONS

A suggested design which could be used for the modification of existing border systems as well as the establishment of new ones was developed. It was based on the need to obtain high uniformity of water distribution by ensuring that the advance and recession curves be parallel, while at the same time maintaining a satisfactory level of water application efficiency. The design could be modified to take into account changes in the parameters used that may occur from time to time on the border strips.

The study also include measurements of ground water table (by the use of piezometer tubes) and soil moisture (by taking samples of the soil in the experimental area).

The following conclusions could be drawn from the results of the present study:

1. The developed design is adequate both for the modification of the existing borders and the establishment of new ones. The design can be used for any field that is suitable for border

irrigation by using the design parameter estimates that can be obtained from the field.

2. The performance on the border strips was satisfactory, except for a low value of water application efficiency which could be due to drainage problems below the rootzone.

3. The estimated inflow rate q = 0.147 m^3/min-m is adequate to attain design efficiencies and safe against erosion hazards.

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APPENDIX A

Evaluation of Intake Coefficients and Water Application and Distribution Efficiences.

APPENDIX A

Table A1: Evaluation of Intake Coefficients (border strip 3.2-1).

1 Advance distance X (m)	2 Time of advance T (min)	3 Cumulative inflow Q (m^3/m)	4 Surface storage S (m^3/m)	5 Cumulative infiltrated volume Q-S (m^3/m)	6 Accumulated infiltrated depth (Q-S)/X (mm)
15	6	0.96	0.77	0.19	13
30	12	1.92	1.28	0.64	21
45	20	3.20	1.80	1.40	31
60	34	5.44	2.47	2.97	49
75	48	7.68	3.23	4.45	59
90	74	11.84	3.66	8.18	90

Accumulated Intake Expression:

$Da = 3.09\ t^{0.765}$ (for Intake time)

$Da = 3.19\ T^{0765}$ (for Advance time

$R^2 = 0.998$

Table A2: Evaluation of Intake Coefficients (border strip 3.2-2)

1 Advance distance X (m)	2 Time of advance T (min)	3 Cumulative inflow Q (m^3/m)	4 Surface storage S (m^3/m)	5 Cumulative infiltration volume Q-S (m^3/m)	6 Accumulated infiltratei depth (Q-S)/X (mm)
15	7	0.98	0.8	0.18	12
30	16	2.24	1.46	0.78	26
45	23	3.22	1.79	1.43	31
60	32	4.48	2.29	2.19	36
75	45	6.30	3.00	3.30	44
90	59	8.26	3.40	4.86	54

Accumulated Intake Expression:

$Da = 3.11\ t^{0.675}$ (for intake time)

$Da = 3.52T^{0.675}$ (for advance time)

$R^2 = 0.989$

Table A3: Evaluation of Intake Coefficients (border strip 3.2-3)

1	2	3	4	5	6
Advance distance	Time of advance	Cumulative inflow	Surface storage	Cumulative infiltrated volume	Accumulated infiltrated depth
X	T	Q	S	Q-S	(Q-S)/X
(m)	(min)	(m^3/m)	(m^3/m)	(m^3/m)	(mm)
15	6	0.95	0.82	0.14	9
30	15	2.4	1.52	0.88	29
45	27	4.32	2.17	2.15	47
60	40	6.40	2.71	3.69	61
75	57	9.12	3.24	5.88	78
90	70	11.20	3.83	7.37	81

Accumulated Intake Expression:

$Da = 1.47\ t^{0.8}$ (for intake time)

$Da = 2.11\ T^{0.8}$ (for advance time)

$R^2 = 0.987$

Table A4: Water Application and Distribution Efficiencies (Ten weeks after planting).

Date	Border Strip No	Application Efficiency (%)	Distribution Efficiency (%)
5/3/88	3.2-1	50.5	89.0
	3.2-2	60.2	69.0
	3.2-3	61.3	79.8

APPENDIX B

Advance and Recession Curves

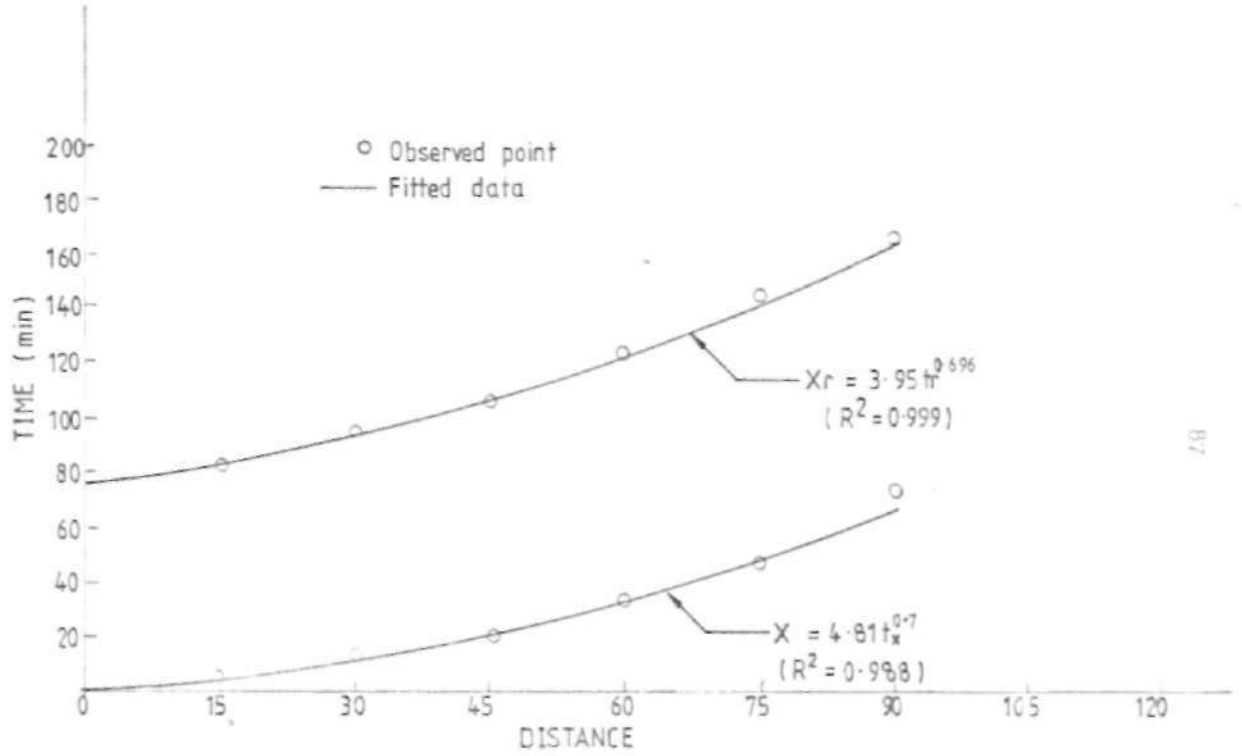


Fig. B1: Advance and Recession curves for border strip 3·2—1: Ten weeks after planting.

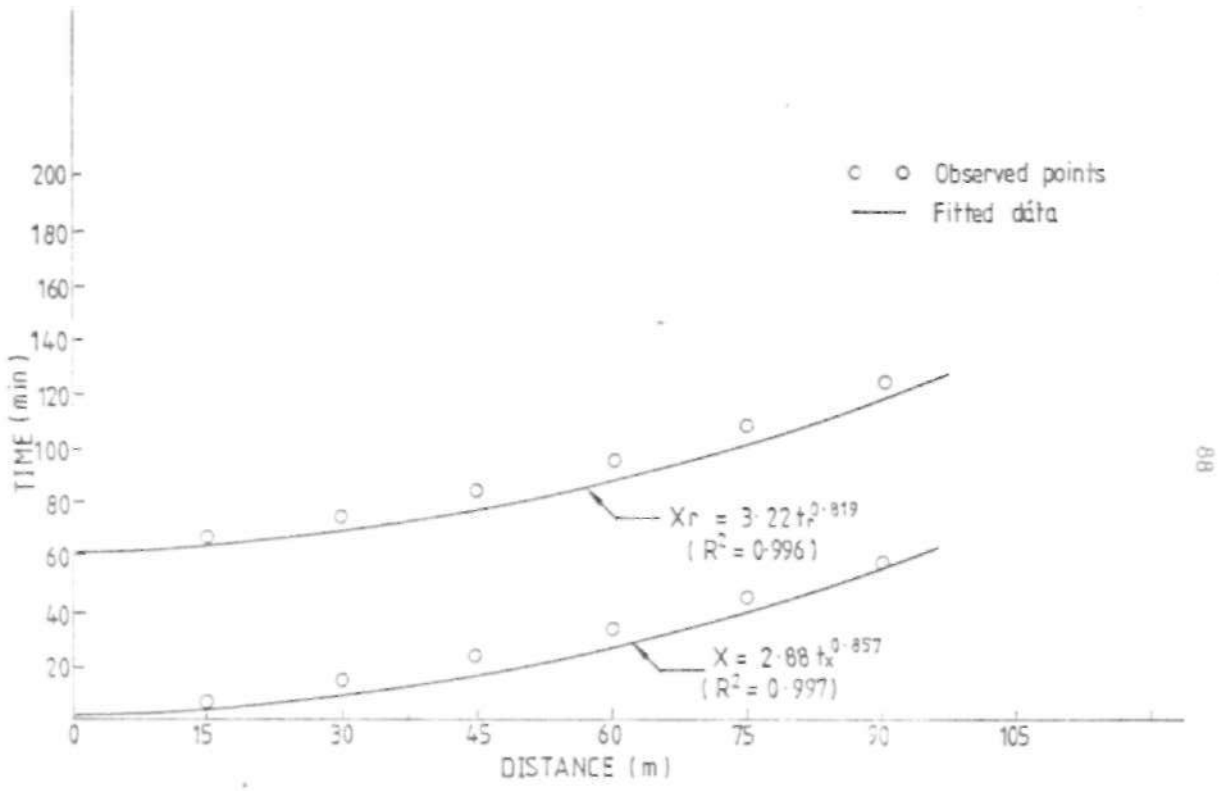


Fig. B2 : Advance and Recession curves for border strip 3·2–2. Ten weeks after planting.

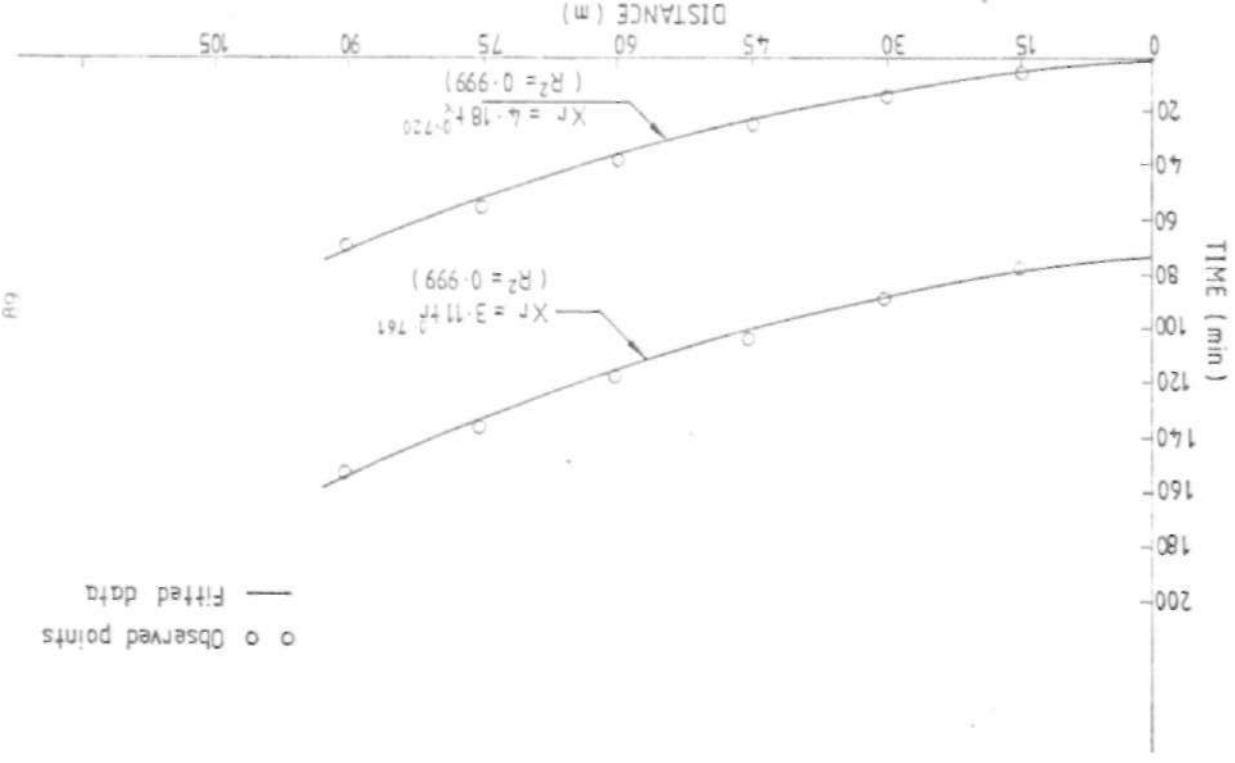


Fig. B3: Advance and Recession curves for border strip 3·2 — 3. Ten weeks after planting

APPENDIX C

Average Flow Depth Profile and Surface Storage Curves.

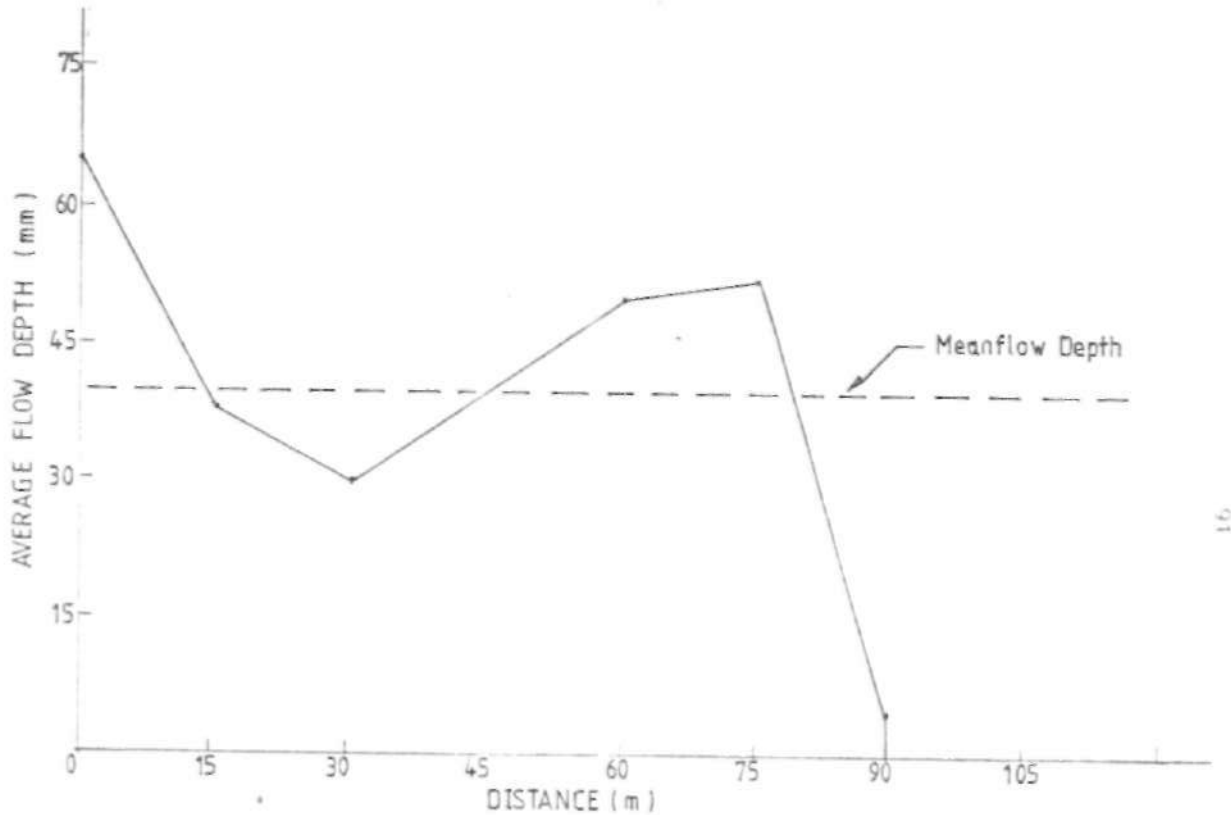


Fig. C1 Average flow depth profile : Border strip 3·2 — 1. Ten weeks after planting

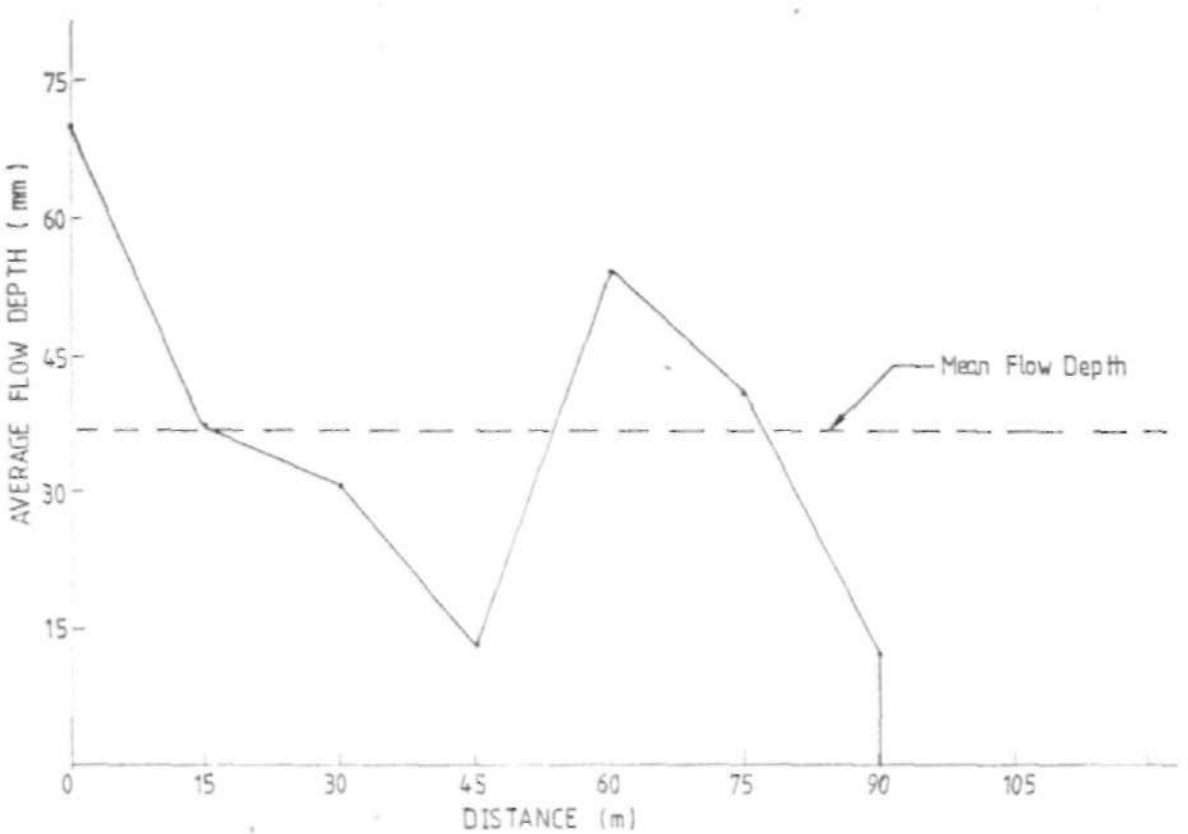


Fig C2. Average flow depth profile ; Border strip 3·2 – 2. Ten weeks after planting.

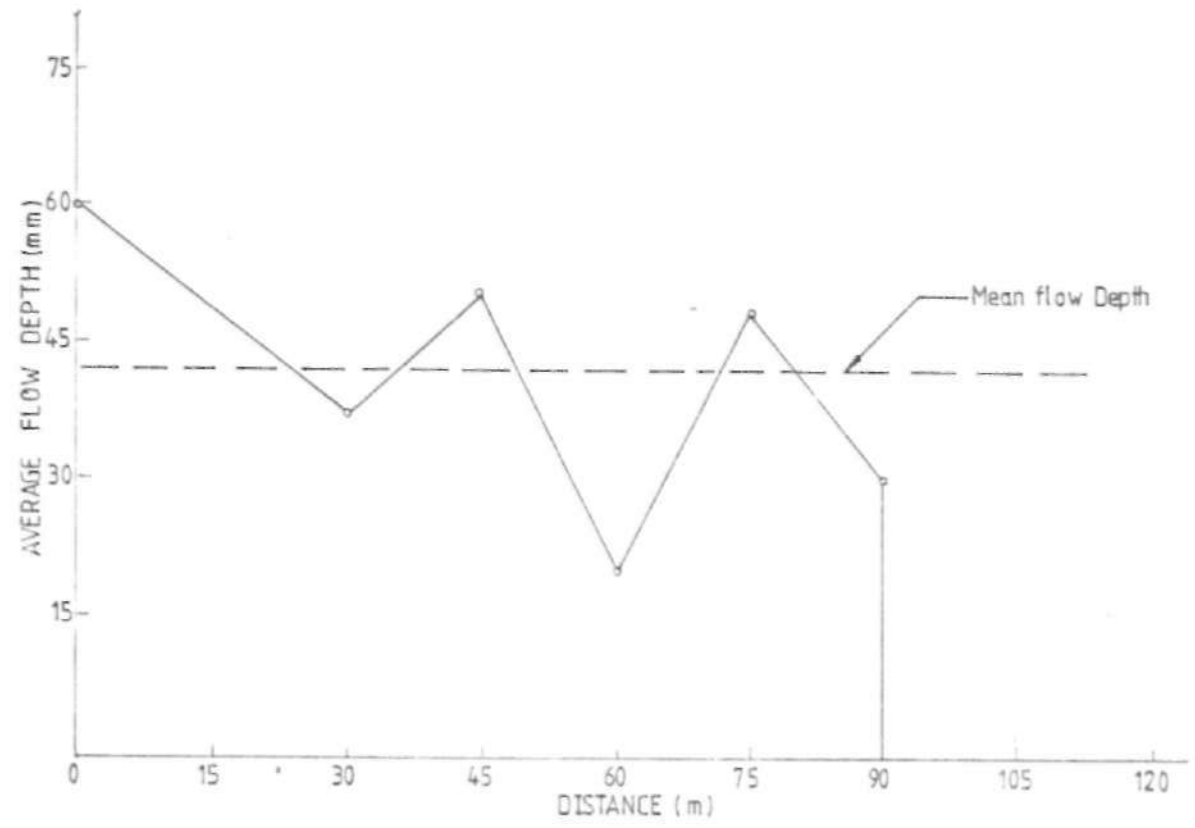


Fig. C3 Average flow depth profile : Border strip 3·2–3 . Ten weeks after planting.

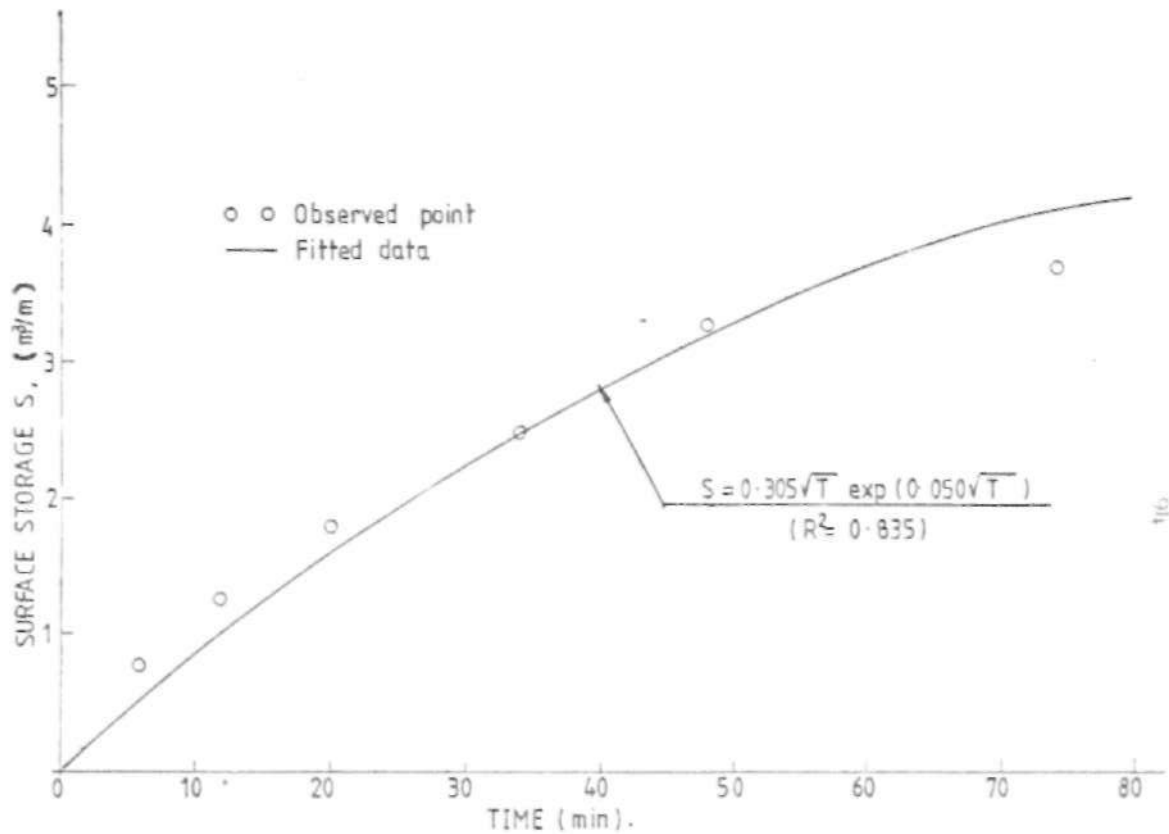


Fig. C4 Surface storage curve; Border strip 3·2—1 · Ten weeks after planting.

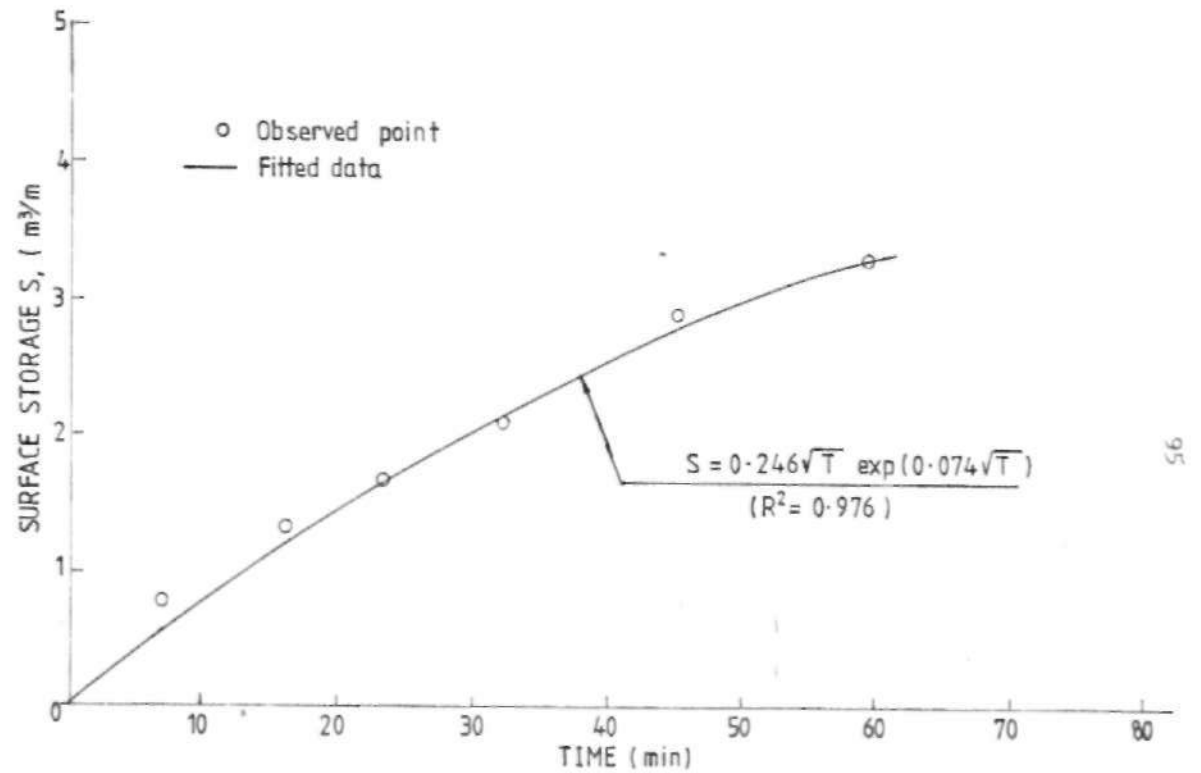


Fig. C5. Surface storage curve: Border strip 3·2−2. Ten weeks after planting

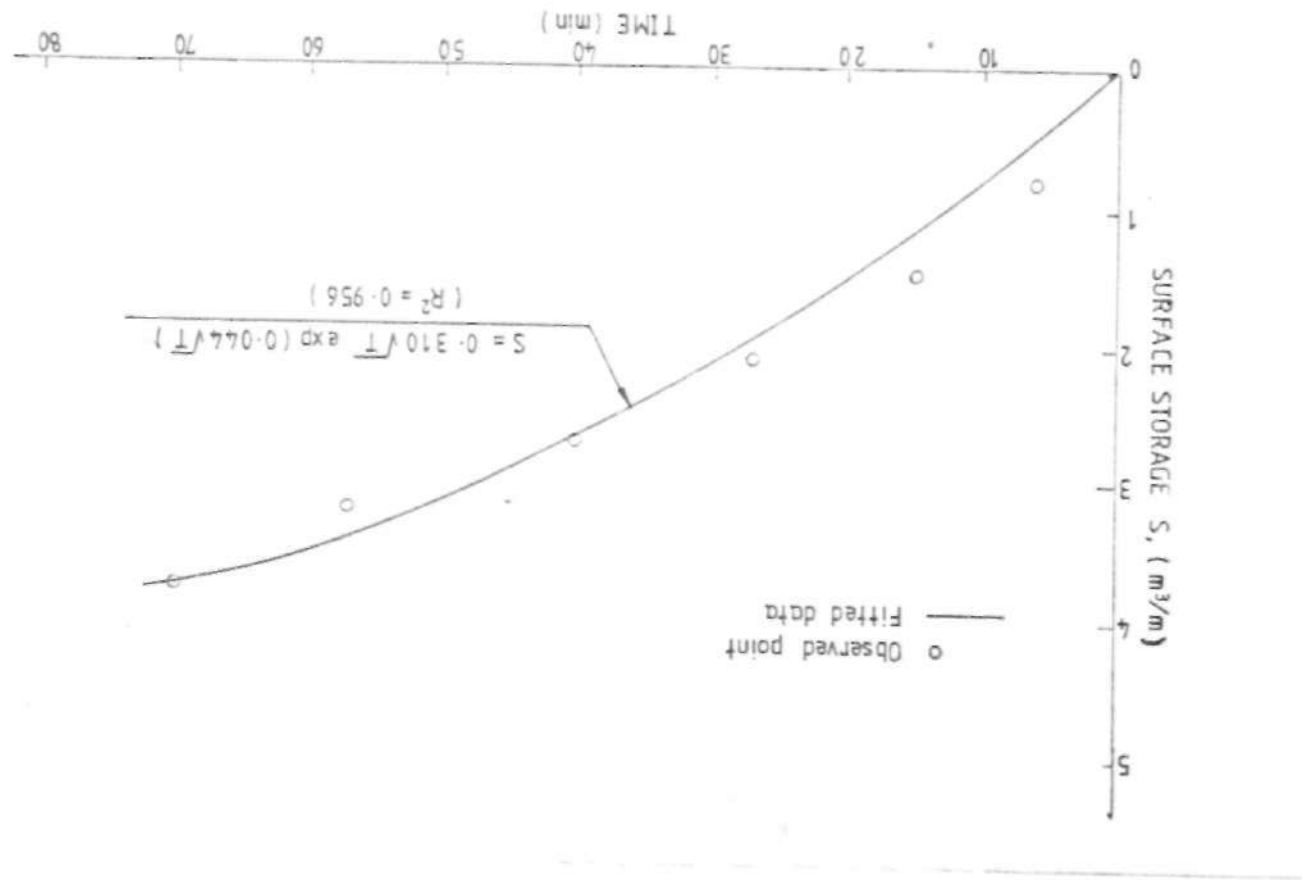


Fig. C6 Surface storage curve ; Border strip 3·2 — 3 Ten weeks after planting

APPENDIX D

Bulk Density and Moisture Deficit Evaluation

APPENDIX D

Table D1: Bulk Density and MD for Border Strip 3.2-1

Sampling point	Soil depth (m)	Bulk density (g/cm^3)	Soil moisture added (mm)	Moisture used (mm)	M.D (%)
Upper	0-0.20	1.45	36.3	27.0	74.4
End	0.20-0.40	1.38	23.3	14.0	60.0
	0.40-0.60	1.30	19.2	10.0	52.0
Mid-	0-0.20	1.45	19.4	16.5	85.0
Field	0.20-0.40	1.38	14.4	12.0	83.0
	0.40-0.60	1.30	12.4	9.0	72.5
Lower	0-0.20	1.45	28.7	24.7	86.0
End	0.20-0.40	1.38	24.7	18.0	76.0
	0.40-0.60	1.30	21.6	11.0	51.0

Table D2: Bulk Density and M.D for Border Strip 3.2-2

Sampling point	Soil depth (m)	Bulk density (g/cm^3)	Soil moisture added (mm)	Moisture used (mm)	M.D (%)
Upper	0-0.20	1.45	29.0	22.0	75.8
End	0.20-0.40	1.38	14.6	10.0	68.5
	0.40-0.60	1.30	14.6	8.8	60.3
Mid	0-0.20	1.45	29.0	21.0	72.4
Field	0.20-0.40	1.38	15.0	10.5	70.0
	0.40-0.60	1.30	11.6	7.0	60.3
Lower	0-0.20	1.45	23.0	18.4	80.0
End	0.20-0.40	1.38	17.0	13.0	76.5
	0.40-0.60	1.30	12.0	7.2	60.0

Table D3: Bulk Density and M.D for Border Strip 3.2-3

Sampling point	Soil depth (m)	Bulk density (g/cm^3)	Soil moisture added (mm)	Moisture used (mm)	M.D (%)
Upper	0-0.20	1.45	41.6	25.0	60.0
End	0.20-0.40	1.38	25.6	14.0	54.7
	0.40-0.60	1.30	23.6	10.0	42.4
Mid	0-0.20	1.45	34.9	22.7	65.0
Field	0.20-0.40	1.38	22.9	12.0	52.4
	0.40-0.60	1.30	22.9	10.0	43.7
Lower	0-0.20	1.45	22.5	13.5	60.0
End	0.20-0.40	1.38	18.5	10.0	54.1
	0.40-0.60	1.30	15.6	8.0	51.3