EVALUATION OF WATER ADVANCE MODELS FOR FURROW IRRIGATION SYSTEM

BY

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DECLARATION

I declare that the work in this thesis entitled “Evaluation of Water Advance Models for Furrow Irrigation System” has been composed by me in the department of agricultural engineering under the supervision of Professor O.J Mudiare and Dr M.A. Oyebode.

The information derived from the literatures has been duly acknowledged in the text and a list of references provided. No part of this thesis has been previously presented for another degree or diploma at any university.

……..	……	……..
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CERTIFICATION

This thesis entitled “EVALUATION OF WATER ADVACE MODELS FOR FURROW IRRIGATION SYSTEM” by Ogbe, Victor Bameyi meets the regulations governing the award of the degree of master of science (Agricultural Engineering) of Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

To my Father, Sir J.Y. Ogbe (KSJI), my Mother, Lady C.A. Ogbe (KSJI) and my siblings Juliana, Charles, Donald, John and Julius for all they have sacrificed to see that I completed this course, for their love and encouragement through the period.

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Finally, “TO GOD BE THE GLORY”.

ABSTRACT

The problems of on-farm water management and irrigation system design parameters which are often chosen with limited or no analysis of a unique local condition leads to the poor performance of most irrigation systems today. In this study, three furrow irrigation water advance models, referred to as Walker and Skogerboe model, Michael's advance model and Philip and Farrell model were verified and evaluated for their prediction of water advance distances under specific field conditions at the Galma Irrigation Scheme, kilometer 16 along Zaria – Jos road.

Fifteen irrigation events were monitored. Several parameters were measured including the furrow geometry, slope, furrow length, furrow width, advance and recession time, and infiltration characteristics. The models were applied to all the events and the results were compared to those obtained from the field measurements. Thereafter, the predictions by the different models were compared with one another. The indices used in evaluating the performance of the models include slope of the best-fit line λ, standard error of estimate σ, coefficient of determination R^2 and the absolute error E (%).

This study shows that the Walker and Skogerboe model performed best in predicting advance distances with average indices values of $\lambda = 1.0381$, $\sigma = 0.42$, $R^2 = 0.9985$ and E = 4.40%. It is followed by Michael's advance model which performed reasonably well with average indices values of $\lambda = 1.0175$, $\sigma = 1.40$, $R^2 = 0.9837$ and E = 9.67% while the performance of Philip and Farrell was poor with average indices values of $\lambda = 0.3508$, $\sigma = 7.43$, $R^2 = 0.9499$ and E = 37.08%. Considering the overall suitability of the models to the field condition encountered in this study, both the Walker and Skogerboe model, and Michael's model are suitable for predicting water advance distance.

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NOTATIONS

A parameter related to saturated hydraulic conductivity (m^2/min)

A_f area shape factor (m^2)

A_i subsurface water area function (m^2)

$\overline{A_i}$ average subsurface water area (m^2)

A_0 inlet flow area (m^2)

A_{0z} infiltrated volume per unit furrow length at upstream end (m^3/m)

A_S surface flow area function (m^2)

$\overline{A_S}$ average surface water area (m^2)

a Kostiakov – Lewis infiltration exponent

b recession equation constant

C_1 and C_2 inlet flow area parameters

C_f free flow coefficient

c intercept

d average depth of water stored along the furrow run during irrigation (m)

Ea water application efficiency (%)

E_d water distribution efficiency (%)

f_0 basic infiltration rate (m^3/m/min)

g acceleration due to gravity (m/s^2)

H_u upstream flow depth (cm)

k Kostiakov – Lewis infiltration constant (m^3/m/min)

k_f flume length coefficient

L laplace transformation

L^{-1} inverse of laplace transformation

l field length (m)

M_1 is the Walker and Skogerboe model

M_2 is the Michael's advance model

M_3 is the Philip and Farrell model

m recession equation exponent

N number of observed and predicted advance distances.

n manning's coefficient

n_f flume exponent

p advance equation constant

q inflow per unit width (m^3/min/m)

Q inflow rate (m^3/min)

Q_{in} inflow rate (m^3/min)

Q_{out} inflow rate (m^3/min)

r advance equation exponent

S_0 slope

S sorptivity ($m^2/min^{0.5}$)

S_f slope of energy grade line

S_0 longitudinal slope of furrow

s incremental distance within distance x (m)

T top width of furrow (m)

T_1 bottom top width of furrow (m)

T_2 upper top width of furrow (m)

t time from beginning of irrigation (s)

t_i intake opportunity time (min)

t_l advance time to the end of the field (min)

t_s time of advance to distance (s)

t_x time of advance to distance x_a (s)

$t_{0.5l}$ advance time to one-half the field length (min)

v velocity of flow (m/s)

V_b volume of soil core (cm^3)

W throat width (m)

W_b dry weight of soil sample (g)

W_f water delivered to field (m^3)

W_S water stored in the root zone of the plants (mm)

WP wetted perimeter

WP_1 bottom wetted perimeter

WP_2 upper wetted perimeter

X advance distance (m)

x_a advance distance at time, t (m)

y mean depth of flow (m)

$\bar{y}$ average numerical deviation from d (m)

y_1 depth from bottom of furrow (m)

y_2 depth at the upper end of furrow (m)

Z cumulative infiltration (mm)

z infiltration rate (mm/hr)

ρ_b bulk density (g/cm^3)

β beta function

Γ gamma

λ slope of the best-fit line

σ_y surface storage shape factor

σ_z subsurface shape factor

σ_1 and σ_2 area shape factor parameter

α_1 and α_2 top width factor parameters

γ_1 and γ_2 wetted perimeter factor parameters

CHAPTER ONE

INTRODUCTION

The pressure of human survival and the need for additional food supplies or production require increased intensities of irrigated agriculture throughout the world because rain-fed agriculture limits agricultural production. Irrigation is used to lengthen the cultivation season or make up the failure of rainfall. Irrigation has greatly expanded the amount of arable land and the production of food throughout the world. In 1800 about 8.1 million hectares were under irrigation, a figure that rose through the centuries to more than 273 million hectares by 2005, (Encarta, 2005). It has been estimated that as little as 15-20 percent of the total land cultivated worldwide is irrigated. Comparing irrigated and rain-fed agricultural yield, this small level of irrigated agriculture may be contributing as much as 30-40 percent of gross agricultural output. Majority of this land is irrigated using surface methods which constitute as much as 95 percent of common irrigation activities(FAO, 1993).

Even though irrigation is of prime importance in the arid and semi-arid regions, it is becoming increasingly important in the humid regions too. The technology of irrigation is more complex than many appreciate. A reliable and suitable irrigation activity can result in vast improvements in agricultural production and assure the economic fortune of a region. Many civilizations have been dependent on irrigated agriculture to provide the basis of their people. Apart from the limited water resources, one other major problem irrigated agriculture faces is the poor efficiency with which water resources have been

used for irrigation. An estimate of about 40 percent or more of the water diverted for irrigation is wasted at the farm level through either deep percolation or surface runoff. Irrigation, however, can also waterlog soil, or increase soil's salinity over time due to high water application rates, which exceed the natural rate of drainage. Saline high water tables is now jeopardizing about one-third of the world's irrigated land (Encarta, 2005).

Surface irrigation method is favoured over other methods on the basis of lower capital and operating cost, the simplicity of maintenance, the utility of unskilled labour but management is more complicated. There is one problem of surface irrigation that confronts every researcher, designer, and irrigator, which is, the soil must be used to convey and infiltrate the water over the field. Unfortunately, soil properties vary widely both spatially and temporally that they become extremely difficult to characterize (Walker and Skogerboe, 1987) owing to soil anisotropy. Soil infiltration plays an important role in irrigation design efficiency and in the selection of irrigation methods (Eldeiry et al., 2004). Furrow irrigation is a common type of surface irrigation, second only to border irrigation system, but in most cases the design and management of the furrow system is not optimal for water use in the arid and semi-arid region with unique infiltration characteristics. Furrow irrigation under surface irrigation systems provides better water management on the farm. Furrows are used to cultivate row crops such as vegetable, cotton, corn, potatoes, maize and sugarcane which are subject to injury if the crown or stem is submerged in water. While irrigators may be satisfied just to get the water to the end of the furrow, consideration should be given to how much water is applied and how it is distributed (Yonts et al., 2003). Other considerations are what should be the flow rate and how long should the inflow be maintained at each application

so that a desired application efficiency be obtained. According to Doorenbos et. al., (1980), the amount of irrigation water to be applied is determined by the crop water requirement.

In furrow irrigation system, the two basic considerations are not easily met because the solution is unique for a given land slope and infiltration characteristic of the field. In practice, the required inflow rate for a furrow system is obtained by field measurements of the rate of advance of the wave front as water flows down the strip or furrow, and the corresponding rate of recession of the trailing water edge after cessation of inflow. Basic design parameters such as furrow length, slope and cross section, flow rate, infiltration characteristics and hydraulic resistance interact with each other during any irrigation event and consequently affect the shape of the advance and recession curves which determines the uniformity, adequacy and efficiency of irrigation. The two curves (advance and recession) should be approximately parallel for a satisfactory water application and distribution efficiencies; giving uniform infiltration opportunity time along the length of furrow for optimum design and management of irrigation system (Mudiare, 1987; Esfandiari and Maheshwari, 2001).

Management and design of furrow irrigation remain primitive due to limitations of existing on-farm distribution systems, absence of field measurements, lack of proper training and reluctance to change established techniques (McClymont, 1999). Furrow design parameters are often chosen with limited or no analysis of unique local conditions. Although well designed and managed furrow irrigation systems have the potential to operate at water application efficiencies above 90% (Faulkner et al. 1998), many furrow systems generally operate at significantly lower efficiencies.

One of the major constraints to the improvement of furrow irrigation performance has been the difficulty in assessing the many variables associated with the furrow irrigation systems and their interactions, and to utilize these in irrigation management. One potential for improving the efficiency and performance of furrow irrigation systems lies in the use of simulation models to predict furrow irrigation performance and assess changes in management variables, which can lead to improvements in irrigation efficiency (Hornbuckle et al., 1999). A number of such models have been developed which aim to simulate surface irrigation systems. The most common approaches include hydrodynamic, zero-inertia, kinematic wave and volume balance models. However, volume balance models are associated with simplicity compared to the other models, produce accurate results with modest data requirement and contain few assumptions (Eldeiry et al., 2004)

In order for such models to be adopted by practitioners, confidence in the model predictions needs to be demonstrated, with agreement between measured values and those predicted by the simulation model.

1.1 Statement of Problem

Irrigators are faced with intensive competition for limited water resources from other sectors of the economy, problem of on-farm water management and salinity and drainage which occur over time due to high water application rates. Therefore, there is the need to find the best design that would minimize water use and maximize crop yield. Models for border irrigation design and simulation have been tested for specific field conditions in Northern Nigeria in the past(Dalhat, 1988; Oyebode, 1989; Adamu, 1990)

but the suitability of the furrow models under specific field conditions are not well known. This creates a dearth of information that can be easily applied to furrow irrigation system design and management in order to optimize for specific field conditions. Thus, there is the need to validate models and identify those which best suit specific field conditions.

1.2 Justification

Efficient irrigation is obtained by almost filling the crop root zone at each irrigation, applying water uniformly, and minimizing runoff (Yonts et al., 2003). Poor designs and management are generally responsible for inefficient irrigation, leading to wastage of water, water logging, salinization and pollution of surface water and groundwater resources (Esfandiari and Maheshwari, 2001). Therefore, an adequate knowledge of the design and management parameters through the use of furrow irrigation models will result in an efficient irrigation system which reduces water wastage; improve management, higher yield and income for farmers. However, Strelkoff (1977) criticized the use of these models without adequate field verification. This research work was conducted to provide validation of three volume balance models for the simulation of furrow irrigation and to determine their suitability to a specific field condition in Galma Irrigation Scheme.

1.3 Objectives

The general objective of this research, therefore, is to evaluate furrow irrigation water advance models under specific field condition and the specific objectives are;

1) To validate three selected volume balance models for simulation of furrow irrigation design and management in Galma Irrigation Scheme.

2) To identify the model(s) that best suit the design and management of furrow I rrigation system to the unique field condition.

CHATER TWO

LITERATURE REVIEW

2.1 Introduction

The design of a surface irrigation system is very complex. One of the important factors is the prediction of the advance distance – time relationship when estimating advance for a given stream size and land surface slope taking into account the variation in infiltration characteristics of the soil (Sastry and Agarwal, 1972). The rate of coverage (advance) is dependent almost entirely on the difference between the discharge into the field and the accumulating infiltration into the field (FAO, 1993). Secondary factors include field slope, time elapsed since inflow began at the upstream, acceleration due to gravity, hydraulic conductivity of the soil, surface roughness and the geometry or shape of the flow cross-section. Therefore, factors to be considered for literature review include surface irrigation hydraulics, infiltration, irrigation advance and recession, furrow irrigation models, furrow geometry, irrigation efficiencies and soil properties.

2.2 Surface Irrigation Hydraulics

Efficient water application by surface irrigation depends on the knowledge of the hydraulic characteristics of the irrigation stream. The soil initially has no water on it and is permeable; water is introduced at the upper end of the field and advances in a shallow sheet flow down the soil surface. It flows in two directions – vertically and laterally. Due to the pull of gravity, a part of the stream is taken in by the soil while the remainder flows along the plane of the soil surface (Fok and Bishop, 1965).

In furrow irrigation, due to infiltration, there are gradual variations in the depth of flow and flow rate with furrow length. As a result of this, the flow phenomenon in furrow irrigation is a case of unsteady, non-uniform and gradually varied open channel flow over a porous bed. This presents a complex problem in theoretical analysis, owing to the varying intake rate of the soil and the changing water – surface profile on the soil surface (Esfandiari and Maheshwari, 2001).

Dalhat (1988) and Oyebode (1989) quoted Rawitz (1973) to have observed that a mathematical formulation of the advance of water over a strip of land involves three processes;

(a) Open – channel flow described by equations such as the Manning's equation given as:

$$q = \frac{1}{n} y^{\frac{5}{3}} s^{\frac{1}{2}} \qquad (2.1)$$

where:

q = inflow per unit width of furrow (m^3/sec/m)

y = mean depth of flow (m)

s = average slope of the strip of land

n = Manning's roughness coefficient

(b) The infiltration function having the general form as:

$$Z = et_i^{\,m} + bt_i \qquad (2.2)$$

where:

Z = Cummulative intake (mm)

t_i = infiltration opportunity time (s)

e, m and b = empirical constants

(c) The rate of advance of the water down the border which is expressed by

$$X = pt_x^{\,r} \qquad (2.3)$$

where:

X = distance down the furrow (m)

t_x = time of advance to point x (min)

p, r = empirical constants

2.3 Infiltration

Infiltration rate, the rate at which water moves into the soil (Yonts et al., 2003), from the soil surface is the most important process in surface irrigation. Infiltration characteristics of soil are one of the important parameters in the design, evaluation and management of furrow irrigation. The characteristics determine advance and recession times, depth of infiltration and the uniformity of water application during an irrigation(Jobling and Turner, 1973; FAO, 1993).

Infiltration rate varies with the steepness of the slope, soil texture, spacing of furrows and soil compaction. The rate at which soil will absorb water varies with time. Initially, water penetrates rapidly but decreases until a rate which stays relatively consistent (basic infiltration) for the remainder of the irrigation. It also varies from one irrigation to the next and from season to season (Yonts et al., 2003). However, the geometry of furrow causes infiltration to be more complex in furrow irrigation compared with that in border irrigation (Esfandiari and Maheshwari, 1997). Unlike the other factors mentioned, there is the spatial and temporal variability of infiltration rates; therefore, a

quantitative knowledge of infiltration is needed for efficient design and management of the furrow irrigation systems.

Over the years, several mathematical models of infiltration have been developed. Owing to their simplicity and minimal data requirement the most commonly used infiltration equations in surface irrigation modeling are the empirical relationships (Zerihun and Sanchez, 2003) and particularly those of the Kostiakov-Lewis and modified Kostiakov-Lewis equation (Isrealsen and Hansen, 1962; McCornick et al., 1988; FAO, 1993). The Kostiakov-Lewis equation was developed independently by Kostiakov (1932) and Lewis (1938) and has a form in which infiltration is expressed as a single term monotonic decreasing power function of time.

$$Z = kt_i^{\,a} \qquad (2.4)$$

where:

Z = Cummulative infiltration in units of volume per unit length per unit width.

t_i = infiltration opportunity time (min)

k and a = empirical constants

The infiltration rate z, based on Eq. (2.4) is;

$$z = akt_i^{\,a-1} \qquad (2.5)$$

The constants do not possess any specific physical meaning, the values however reflects the effect of soil physical properties of influence on infiltration as well as antecedent soil moisture content and surface conditions(Zerihun and Sanchez,2003). According to the theory of infiltration, the time exponent values should lie between 0 and 1, most observed values lies between 0.2 and 0.9(Blair and Reddell, 1983; Serralheiro, 1988).

According to Philip (1957) and Fok and Bishop (1965) the Kostiakov – Lewis equation describes both the actual and theoretical infiltration accurately on small to medium time scale. However, a more general infiltration function of Kostiakov – Lewis equation is expressed as;

$$Z = kt_i^{\,a} + f_0 t_i\,, \qquad (2.6)$$

in which f_0 is the long term steady or basic infiltration rate in units of volume per unit length per unit time and width and other parameters as previously defined.

The basic infiltration rate in theory should be equivalent to the saturated hydraulic conductivity of the soil. It is, however, in practice less than the saturated hydraulic conductivity because of entrapped air in the soil. Equation (2.4) is more versatile than Eq. (2.6) (Elliott and Walker, 1982).

Another infiltration equation with a form similar to the modified Kostiakov – Lewis equation, but with physically – significant parameters was derived by Philip (1957) which expressed the infiltration as;

$$Z = St_i^{\frac{1}{2}} + At_i \qquad (2.7)$$

where:

S = Sorptivity

A = Parameter related to saturated hydraulic conductivity,

other parameters as previously defined.

The type of data collected depends on the method of measurement used. The most important field measurement techniques include; ring infiltrometer, blocked furrow infiltrometer, recirculating infiltrometer, and inflow – outflow method (Walker and Skogerboe, 1987; Merriam et al., 1980). With the exception of the ring infiltrometer

method all these methods are appropriate for furrow irrigation. Advance and/or water surface profile data can also be used in infiltration parameter estimation (Merriam et al., 1980; Elliott and Walker, 1982; Walker and Busman, 1990)

2.4 Irrigation Water Advance

The advance phase begins when water is turned into the field and ends when water reaches the downstream end of the field. The advance of water in surface irrigation plays an important role in the application of water to the soil and the distribution of water in the soil root zone (Fok and Bishop, 1965). Ideally, shorter advance times result in more uniform irrigation application, due to smaller spread in intake opportunity times across the field. However, due to constraints of supply system or soil properties there is a difference in intake times and in application depths. These makes prediction of advance times one of the most important factors in determining the performance of surface irrigation during an irrigation event (Silva and Or, 1996).

Elliott and Walker (1982) concluded that the simple power function of time – distance relationship of advance (Eq. 2.3) gave the best-fit to the advance rate of water front down the furrow

2.5 Water Recession

For surface irrigated fields, the recession phase begins when the inflow at the upstream is cut off and ends when the surface water disappears at each measuring station towards the end of the field or the flow may recede from both ends of the field simultaneously. The latter condition seldom occurs (Larry, 1988).

Water recedes first vertically and then horizontally due to the combined effect of infiltration and surface flow (Ram and Singh, 1982). Recession flow of surface irrigation plays an important role in the design and evaluation of irrigation efficiency of border irrigation systems. This is particularly true of those borders (check border) which have closed downstream ends where surface storage is large even after the cessation of inflow or where greater depths are infiltrated during the recession phase (Verma, 1981; Ram and Singh, 1982). Like advance, recession rate depends on the inflow rate, field slope, soil infiltration and hydraulic roughness (Verma, 1981). However, Michael (1978) stated that the recession curve has been found to be independent of the flow rate.

2.6 Furrow Irrigation Models

The selection of a model for use in any application is a process of reconciling the conflict between accuracy on the one hand, and cost and complexity on the other. There are many models commonly used to design and simulate furrow irrigation systems today. Several approaches were used for these models to simulate different phases or same phase with varied degree of accuracy and complexity. Depending on this complexity, the furrow irrigation models can be grouped into three main classes; empirical, semi-empirical and mechanistic models.

Empirical models are based mainly on field data for which a typical function is fitted using regression analysis and they are specific for field conditions. Semi-empirical models are based on field and laboratory studies and theoretical principles. They do not simulate all aspects of irrigation. Mechanistic models are based on equations that describe the processes governing the overland flow and infiltration in furrow irrigation.

The equations employed are those describing conservation of mass and momentum known as the Saint-Venant equations. The most common solution techniques applied to the mechanistic model include hydrodynamics, zero-inertia, kinematic-wave and volume balance models depending on the simplifying assumptions applied to the equation of conservation of mass and momentum. The momentum equation is often simplified or in some cases ignored completely to reduce the computational difficulties. The major assumptions made in the derivation of Eqs. (2.8) and (2.9) are reasonably satisfied for most phases of a surface irrigation event. The equations are:

$$\frac{\partial Q}{\partial x} + \frac{\partial y}{\partial t} + \frac{\partial z}{\partial t} = 0 \qquad (2.8)$$

and

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + g\frac{\partial y}{\partial x} = g\left(s_o - s_f\right) \qquad (2.9)$$

where:

Q = Inflow rate (m^3/s)

z = infiltration rate (m^3/s)

y = depth of flow (m)

t = time from beginning of irrigation (s)

v = velocity of flow (ms^{-1})

x = distance along the furrow length (m)

g = acceleration due to gravity (ms^{-2})

S_o = Longitudinal slope of furrow

S_f = slope of energy grade line (friction slope)

2.7 Volume – Balance Models

The volume balance approach of the mechanistic model ignores the entire momentum equation in providing analytical solutions of the flow problem rather than the numerical solution of the full hydrodynamic equations (Esfandiari and Maheshwari, 2001). Therefore, the volume – balance model solve the spatial and temporal lumped form of the principles of mass conservation and assumes a surface storage shape factor that replaces the momentum equation (Eldeiry et al., 2004). The continuity equation for furrow irrigation can be expressed in the following form (Esfandiari and Maheshwari, 2001);

$$Qt_x = \int_0^{x_a} A_s(s, t_s)ds + \int_0^{x_a} A_i(s, t_s)ds \qquad (2.10)$$

where:

Q = inflow rate (m^3s^{-1})

A_s = surface flow area function (m^2)

A_i = Subsurface water area function (m^2)

t_x = time of advance to distance x_a (s)

s = incremental distance within distance x_a (m)

t_s = time of advance to distance s (s)

x_a = advance distance at time t (m)

The volume balance approach based on the continuity equation for furrow irrigation can also be expressed in another simple form as (Esfandiari and Maheshwari, 2001);

$$Qt_x = \overline{A}_S x_a + \overline{A}_i x_a \qquad (2.11)$$

where:

$\overline{A}_s$ = average surface water area (m^2)

$\overline{A}_i$ = average subsurface water area (m^2),

other parameters as previously defined.

First to develop or use a volume – balance approach to predict waterfront advance in border irrigation were Lewis and Milne (1938) with the equation;

$$qt_x = yx_a + \int_0^{x_a} Z(t_x - t_s)ds \qquad (2.12)$$

where

q = flow rate per unit width of border ($m^3/s/m$)

y = average depth of surface storage (m)

$Z(t_x - t_s)$ = cumulative depth of infiltration (m),

other parameters as previously defined.

Davis (1961) was probably the first to use the concept of volume balance in furrow irrigation. Several works with different approaches have been applied to provide solution to the Lewis and Milne equation by different researchers. Philip and Farrell (1964) analyzed the physical restrictions on x and y in the Lewis and Milne equation and using the Faltung or convolution theorem of Laplace transformation, obtained the general solution of the equation as;

$$\frac{x}{q} = L^{-1}\left(\frac{1}{s^3 L(Z) + ds^2}\right) \qquad (2.13)$$

where:

L = laplace transformation

L^{-1} = inverse of laplace transformation,

other parameters as defined previously.

The particular forms of accumulated infiltration equations Z(t) of interest can be applied to the above equation. Fok and Bishop (1965) proposed advance equation on the basis of experimental observations and used it to arrive at the solution of the continuity equation. Strelkoff (1977) developed an equation using the surface and subsurface shape factors. Stelkoff (1977) expressed the advance distance, X, as a function of time as:

$$X = \frac{qt}{\sigma_y y_o + \sigma_z z_o} \qquad (2.14)$$

where:

σ_y = surface storage shape factor, given as

$$\sigma_y = \frac{y}{y_o} \qquad (2.15)$$

y_o = upstream surface depth, taken as normal depth

z_o = infiltrated depth

σ_z = subsurface shape factor, given as

$$\sigma_z = \frac{1}{1+a}, \text{ and} \qquad (2.16)$$

other parameters as previously defined.

A special case of Eq. (2.11) was used by Levien and Souza (1987) using surface and subsurface shape factor as

$$Qt_x = A_0 \sigma_Y x + A_{0z} \sigma_z x \qquad (2.17)$$

in which A_{0z} is the infiltration volume per unit furrow length at upstream end (m^3/m), and other parameters as defined previously.

The volume balance analyses are accurate, require modest data that can be readily collected and contain few assumptions (Eldeiry et al., 2004). Volume balance approach

accurately simulates furrow irrigation (Larry, 1988) and it is applied primarily to the advance phase (Walker and Skogerboe, 1987). It is recommended when quick and rough estimates of system performance are also required, however, volume balance model is limited to steep slope (Zerihun and Sanchez, 2003).

2.7.1 Walker and Skogerboe Model (1987)

The power advance solution of the volume balance analysis is based on the simple power advance function and the modified Kostiakov – Lewis infiltration equation utilizing the equations in the Lewis – Milne equation, the Walker and Skogerboe equation can be written for any time as;

$$X = \frac{Qt}{\sigma_y A_0 + \sigma_z k t^a + \frac{f_0 t}{1+r}} \qquad (2.18)$$

where:

A_0 = cross-sectional area of flow at the inlet, m^2

t = elapsed time since the irrigation started, min

σ_y = surface storage shape factor, which is defined as a constant of 0.70-0.80

σ_z = subsurface shape factor, defined as

$$\sigma_z = \frac{a + r(1-a) + 1}{(1+a)(1+r)}, \text{ and} \qquad (2.19)$$

all other parameters as previously defined

Equation (2.18) is used to determine the time required for water to advance across the length of the field because r in the equation is stream size dependent (Larry, 1988). Inputs required for the model to simulate an irrigation event include infiltration characteristics (modified Kostiakov-Lewis equation), furrow geometry, inflow rate,

surface and sub-surface shape factors and advance equation time exponent. The infiltration characteristic and inflow rate are also difficult to adequately determine. However, the remaining input parameters, furrow geometry, surface and sub-surface shape factors, and advance equation time exponent can easily be measured.

2.7.2 Michael's Advance Model (1968)

Michael (1968) simulates the hydraulics of surface irrigation (border and furrow) at the farm level. He applied the modified Kostiakov infiltration equation, Eq (2.6), into the general solution of the Lewis – Milne equation as presented by Philip and Farrell (1964) and obtained a particular solution to predict the waterfront advance for small time, t as;

$$X = \frac{qt}{f_0 + y}\left(\frac{1}{\Gamma(2)} - \frac{\beta t^a}{\Gamma(2+a)} + \frac{\beta^2 t^{2a}}{\Gamma(2+2a)} - \frac{\beta^3 t^{3a}}{\Gamma(2+3a)} + \frac{\beta^4 t^{4a}}{\Gamma(2+4a)} - .....\right) \qquad (2.20)$$

where:

Γ = gamma function

$$\beta = \frac{k\Gamma(a+1)}{f_o + y}, \qquad (2.21)$$

other parameters are as defined previously.

He gave the limiting condition for the use of the equation as

$$\frac{\beta t^a}{\Gamma(2+a)} < 1 \qquad (2.22)$$

This equation simulates advance of the water front on the basis of the infiltration characteristics of the soil, stream size and average depth of flow. Of these required inputs, the most difficult to determine adequately are the infiltration characteristics and

the furrow inflows which often require either relatively expensive equipment or significant periods of time and skilled operator. It also ignores the surface storage.

2.7.3 Philip and Farrell Model (1964)

Philip and Farrell (1964) presented analytical solutions to the Lewis – Milne volume balance integral equation using several infiltration equations. One of their solutions which apply Philip's (1957) infiltration equation, Eq. (2.7), as the only input, in their general solution arrived at a particular solution which predicts the length of advance distance as:

$$X = \frac{q}{A}\left(1 - \ell^{\frac{4A^2t}{\pi S^2}} erfc\left(\frac{2At^{\frac{1}{2}}}{\pi^{\frac{1}{2}}S}\right)\right) \qquad (2.23)$$

in which erfc is the error function complementary, and other parameters as previously defined.

This equation ignores the surface storage because the only inputs into the integral equation are soil infiltration parameter and the inflow rate. It is assumed that the cumulative infiltration, Z(s,t) is independent of surface water depth and dependent only on intake opportunity time (Walker and Skogerboe, 1987). This model also assumes the depth of flow along the furrow to be zero, which in practice is not true.

2.8 Furrow Geometry

The geometry of flow under furrow irrigation is difficult to describe due to the continuous change of the furrow shape. The cross-sectional geometry of furrow is important when evaluating hydraulic flow characteristic and surface storage. Measurement should be made at 2 or 3 stations for each furrow selected for evaluation. In

most cases, simple power function can be used to relate the depth of water in the furrow with corresponding top width and wetted perimeter. Equation (2.24) approximates this relationship between the depth of flow and top width (Walker and Skogerboe, 1987).

$$T = \alpha_1 y^{\alpha_2} \tag{2.24}$$

where:

T is the top width

y is the depth of flow

α_1 and α_2 are top width factor parameters, defined as;

$$\alpha_1 = \frac{T_2}{y_2^{\alpha_2}} \qquad \text{and} \qquad \alpha_2 = \frac{\log\left(\frac{T_2}{T_1}\right)}{\log\left(\frac{y_2}{y_1}\right)} \tag{2.25}$$

where:

T_2 and T_1 are the upper and lower top width at a point.

y_2 and y_1 are the upper and lower flow depth at a point.

Equation (2.26) approximates the relationship between the depth of flow and wetted perimeter (Walker and Skogerboe, 1987).

$$WP = \gamma_1 y^{\gamma_2} \tag{2.26}$$

in which WP is the wetted perimeter, given as (Walker and Skogerboe, 1987);

$$WP = \left[2((y_i - y_{i-1})^2 + (0.5(T_i - T_{i-1}))^2)^{0.5}\right] \tag{2.27}$$

The wetted perimeter factor parameters γ_1 and γ_2 can be obtained from the following relation.

$$\gamma_1 = \frac{WP_2}{y_2^{\gamma_2}} \qquad \text{and} \qquad \gamma_2 = \frac{\log\left(\frac{WP_2}{WP_1}\right)}{\log\left(\frac{y_2}{y_1}\right)} \tag{2.28}$$

where:

WP_2 and WP_1 are the upper and lower wetted perimeters at a point.

Equation (2.29) approximates the relationship between the depth of flow and the area, A_f as (Walker and Skogerboe, 1987);

$$A_f = \sigma_1 y^{\sigma_2} \tag{2.29}$$

The area shape factor parameters σ_1 and σ_2 can be obtained as;

$$\sigma_1 = \frac{\alpha_1}{\alpha_2 + 1} \quad \text{and} \quad \sigma_2 = \alpha_2 + 1 \tag{2.30}$$

Cross sectional flow area at the field inlet, A_0 can be calculated using the Manning's equation as follows;

$$A_0 = C_1\left(\frac{Q_0 n}{60 S_0^{0.5}}\right) C_2 \tag{2.31}$$

where:

C_2 and C_1 are the inlet flow area parameters obtained as;

$$C_2 = \frac{3\sigma_2}{(5\sigma_2 - 2\gamma_2)}, C_1 = \sigma_1\left(\frac{\gamma_1^{0.67}}{\sigma_1^{1.67}}\right) \tag{2.32}$$

2.9 Irrigation Efficiency

The performance of a farm irrigation system is determined by the efficiency with which water is diverted, conveyed and applied and by the adequacy and uniformity of application on the field. The overall efficiency of a farm irrigation system is defined as the percentage of water supplied to the farm that is beneficially used for irrigation on the farm (Larry, 1988). Irrigation efficiency is the effectiveness of an irrigation system in delivering water to plants or in increasing plant production. Haman et. al.(1988) defined irrigation efficiency as the ratio of the volume of water used or available for use in plant production to the volume delivered for use or expressed as the ratio of crop yield or increase in yield over non-irrigated production to the volume of irrigation water used. Irrigation efficiency thus, provides a basis for the comparison of irrigation system from the standpoint of water beneficially used and from that of yield per unit of water used.

Irrigation efficiency varies with the type of irrigation system and other factors such as soil, plant, and climate characteristics, as well as with the level of maintenance and management of the irrigation system. Solomon (1988) and Aljuneidi and Isaac (1988) stated that irrigation efficiency is influenced by the system design and management. It can be grouped into two components; water losses which are predominantly affected by management and uniformity of application, which is predominantly affected by system design.

2.9.1 Water Application Efficiency

The ability of an irrigation system to apply water uniformly and efficiently to the irrigated area is a major factor influencing the agronomic and economic viability of the

farming enterprise (Solomon, 1988). Individual system application efficiencies will vary more widely as a function of stage of plant development, time of the year, climatic condition and other factors (Haman et. al., 1988).

Water application efficiency, a measure of how efficiently water is applied to a field or a measure of management losses, is expressed by several researchers as the ratio of the volume of irrigation water stored in the root zone and available for plant use (evapotranspiration) to the volume of water delivered to the field, expressed as a percentage (Israelsen and Hansen, 1962; Micheal, 1978; Haman, et al., 1988).

$$E_a = \frac{w_s}{w_f} \times 100 \qquad (2.33)$$

where:

E_a = Water application efficiency (%)

W_s = Water stored in the root zone of the plant

W_f = water delivered to the field

Losses from evaporation, deep percolation, lateral seepage and runoff which occur during irrigation accounts for why this ratio is always less than 1.0. Generally, water application efficiency decreases as the amount of water applied during each irrigation increases (Micheal, 1978). The attainable water application efficiency for furrow irrigation is 60 – 75 % (Solomon, 1988; Al-juneidi and Isaac, 1988).

2.9.2 Water Distribution Efficiency

Water distribution efficiency is a measure of the extent to which water is uniformly distributed along the run and expressed as (Michael, 1978):

$$E_d = \left(1 - \frac{\bar{y}}{d}\right) \times 100 \qquad (2.34)$$

where:

E_d = Water distribution efficiency

d = average depth of water stored along the run during the irrigation

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

Non-uniform distribution of irrigation water over the field results in water-stressed conditions for crops in some parts of the field, while over – irrigation in other parts leads to wastage of water through runoff and deep percolation.

2.10 Soil Properties

The physical properties of soil are often the most important properties for determining the limitations and practical uses for land. Physical properties are properties that can be described with physical measurements such as length, mass and temperature. These properties are texture, structure, bulk density and porosity. Aeration, colour and temperature are also physical properties. However, only soil texture and bulk density are discussed below.

2.10.1 Soil Texture

The relative proportion of sand, silt and clay in a soil sample is used to classify the texture of the soil. The sizes and shape of voids created in the soil is dependent on the soil texture which is more or less constant and does not change with tillage or other practices. Dooneen (1971) and Michael (1978) stated that the textural class of a soil can be determined by mechanical analysis. Mechanical analysis involves sieve and

sedimentation technique, where soil samples taken from the field at desired depths are analyzed in the soil laboratory. Using the result, the textual class of the soil is determined using United States Department of Agriculture (U.S.D.A) Soil Textural Classification Triangle.

2.10.2 Bulk Density

The bulk density of a soil mass is the dry weight of soil per unit bulk volume. It can be expressed in units of g/cm^3. Bulk density varies with depth over an irrigated field (Walker and Skogerboe, 1987). The bulk density of most soil ranges from 1.0g/cc for clay to 1.8g/cc for sands (Michael, 1978). Bulk density is an important soil physical property. It tends to influence the hydraulic conductivity as well as the water holding characteristic of soil.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

Galma Pilot Irrigation Scheme, a division of Zaria Irrigation Scheme in Kaduna State was chosen as the study site for this research on furrow irrigation system. The irrigation system used at this site is majorly furrow irrigation with furrow lengths of between 7 to 10m used by the farmers to improve distribution uniformity. Approximately one twelve of a hectare was used to conduct the study. It is located in the Guinea Savannah vegetation zone on latitude 11^0 05' North and longitude 7^0 44' East and covers an area of about 350ha. The climate of Galma is marked by wet and dry season which is sub-divided into three:

1) the cool, dry season from October to February;
2) the hot, dry season from March to May, and
3) the warm wet season from June to September.

. The rainy season usually starts in the month of May and ends in October. Mean monthly temperature normally ranges from 30^0C – 35^0C and a mean relative humidity ranging from 30 – 70% annually. Irrigation is practiced in the month of December to March which are the driest months in the year.

3.2 Field Layout

The field layout for this research consisted of five furrows selected to monitor irrigation events on the site. The length of the furrows was 40m with a furrow width of

0.8m and an average furrow slope of 0.9%. Measurement stations were established at every 6m along the furrow length, where advance and recession times were recorded. Water was diverted into the field through spiles from the field channel and the discharges into and out of the furrows were measured using cutthroat flumes which were placed at the upper and lower end of the furrow to measure the flow rate and runoff respectively. The field was planted with tomatoes, by the sides of the ridges, as a test crop and a total of 15 irrigation events were monitored. Several parameters were measured before and during the irrigation events which are slope, furrow width, furrow length, furrow shape geometry, discharge, advance and recession time, infiltration, soil texture and soil moisture content.

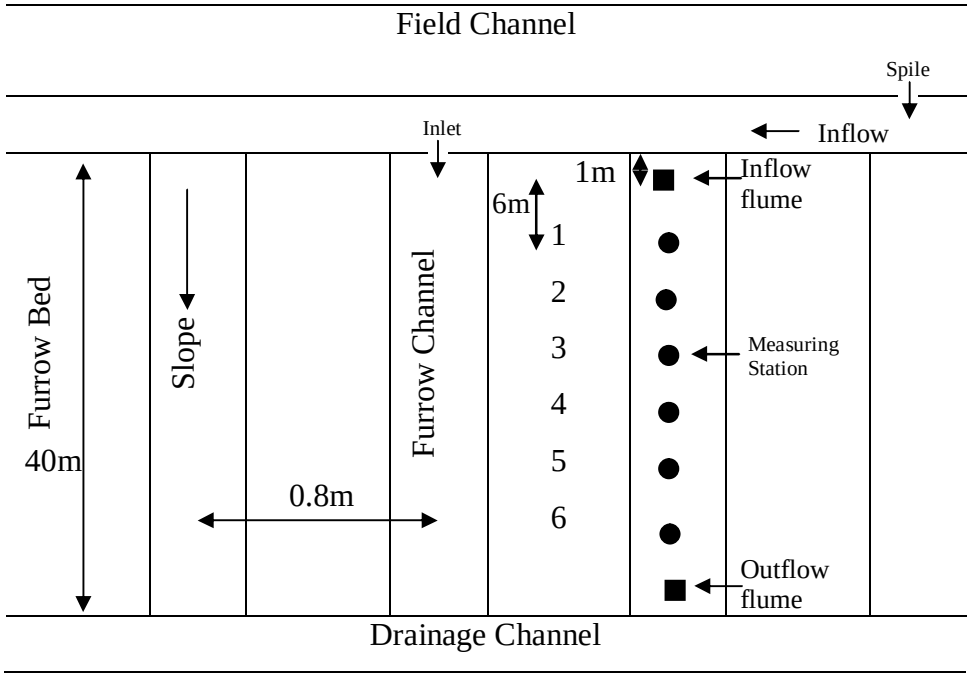


Fig. 3.1. A plan view showing the field layout.

3.3 Determination of Slope

Survey equipment (leveling dump, ranging pool, pegs and measuring tape) were used to determine the elevation of established points in each furrow. The slope was calculated by plotting the elevation of the points against distance along the furrow and determining the slope of the best-fit line.

3.4 Determination of Soil Properties

The soil texture of the site was determined by mechanical analysis method. Soil samples were taken from various points and at incremental depth of 0.2m down to a depth of 0.8m at the site and were taken to the laboratory for analysis. Four replications of the various depth ranges were taken during the sampling and analysed for particle size and the bulk density determined. The United States Department of Agriculture (USDA) Textural Classification Triangle was used to classify the soil based on the results obtained from the analysis.

Bulk density was determined by extracting an uncompacted soil sample with a core sampler. The collected sample was weighed and then oven-dried at 105^0C for about 24 hours until all the moisture was driven off and the sample weighed again. In order to calculate the bulk density, the dry weight of the soil sample was divided by the volume of the soil core. The equation is given as (Larry, 1988);

$$\rho_b = \frac{w_b}{v_c} \qquad (3.1)$$

Where:

ρ_b = bulk density

W_b = dry weight of soil sample

V_c = volume of soil core

3.5 Determination of Furrow Shape Geometry

Cardboard paper was placed in the furrow and used to trace the furrow shape at three different points along each furrow preceding each irrigation event. The average of the three values for each furrow was calculated. The average of all furrows was calculated to get the overall furrow shape parameters used in the different models calculation. Using Eqs. (2.24 - 2.32), the furrow shape parameters were calculated.

3.6 Determination of Inflow Rate

Cutthroat flumes were used to measure the actual flow rate into the furrows upstream and the runoff at the lower end of the furrow. The expression for the discharge through a free-flow cutthroat flume is given by (Larry, 1988).

$$Q = C_f H_u^{n_f} \qquad (3.2)$$

where:

Q = Inflow rate (m^3/s)

H_u = Upstream flow depth (cm)

n_f = Flume exponent

C_f = Free flow coefficient, given as;

$$C_f = k_f W^{1.025} \qquad (3.3)$$

where:

K_f = flume length coefficient

W = throat width (m)

The flumes used are of 100mm throat width constructed and calibrated by Abubakar (1997). He obtained the parameters of Eq. 3.2 as;

$$Q = 0.1862H^{1.61} \qquad (3.4)$$

The depth of water flow in the flumes was determined during the various irrigation events using calibrated tapes placed by the sides of the flumes. The average depth of flow in the flumes was then substituted into Eq. 3.4 and the inflow rate calculated. The flow rate used during the various irrigation events varied from 0.105m^3/min to 0.117m^3/min.

3.7 Measurement of Advance and Recession Times

The centre line of the furrow was marked and stakes placed at 6m interval along the furrow length. After the irrigation water was diverted into the furrow, the time count commenced and the time when the advancing stream reached each successive stake was recorded. The time when water supply at the upstream end of the furrow was cutoff was noted and finally, the recession of the water was determined by noting the times when water just disappears from the upstream end and recedes past each successive stake downstream.

The advance and recession functions for each set of irrigation events were calculated by the two-point fitting using data collected from the field. The empirical parameters p and r of Eq. 2.3 are determined by Eqs. 3.5 and 3.6 (Walker and Skogerboe, 1987).

$$p = t_L \Big/ L^r \qquad (3.5)$$

and

$$r = \frac{\ln\left(t_{0.5L} \Big/ t_L\right)}{\ln(0.5)} \qquad (3.6)$$

where:

t_L = Advance time to the end of the field (min)

$t_{0.5L}$ = Advance time to one-half the field length (min)

L = field length (m)

3.8 Estimation of Infiltration Characteristics

3.8.1 Modified Kostiakov – Lewis Parameters

The volume balance technique, known as the two-point method, presented by Elliott and Walker (1982) and also by Walker and Skogerboe (1987) using data from the irrigation advance phase was applied to find the parameters of the infiltration equation pertinent to each irrigation event. This technique was chosen from among others because of its simplicity and relative accuracy (Elliott and Eisenhauer, 1983; Esfandiari and Maheshwari, 1997). It is very suitable for the purpose of obtaining the infiltration equation for furrow irrigation design and management.

The Kostiakov – Lewis equation was analysed by this method using a three stage procedure: calculation of the final infiltration rate, f_0; calculation of the exponent, a; and calculation of the coefficient, k. The advance characteristics were assumed to follow a power function as given in Eq. (2.3), ($X = pt^r$).

The main input data in the method were inflow rate, flow area at the furrow inlet and elapsed time for advancing the water front to the middle and end of the furrow. Based on the analysis of the volume balance equation at two – points, the parameters ‘a’ and ‘k’ were determined by Eqs. 3.7 and 3.8 (Esfandiare and Maheshwari, 1997)

$$a = \frac{\ln\left[\left(\frac{Qt_l}{l} - \sigma_y A_0 - \frac{f_0 t_l}{1+r}\right) \Big/ \left(\frac{2Qt_{0.5l}}{l} - \sigma_y A_0 - \frac{f_0 t_{0.5l}}{1+r}\right)\right]}{\ln\left(\frac{t_l}{t_{0.5l}}\right)} \qquad (3.7)$$

and

$$k = \frac{\frac{Qt_l}{l} - \sigma_y A_0 - \frac{f_0 t_l}{1+r}}{\sigma_z t_l^{\,a}}\ , \qquad (3.8)$$

all parameters as previously defined.

The value of f_0 was determined by inflow – outflow method (Elloitt and Walker, 1982) as follows;

$$f_0 = \frac{Q_{in} - Q_{out}}{l} \qquad (3.9)$$

where:

Q_{in} = inflow rate (m^3/min)

Q_{out} = outflow rate (m^3/min),

other parameters as defined previously.

From the above equations, the infiltration equation parameters for the modified Kostiakov –Lewis equation were calculated.

3.8.2 Philip's Infiltration Parameters

Since infiltration parameters in all data sets used for this study were determined in the modified Kostiakov – Lewis form, infiltration data was generated from the original

parameters of the modified Kostiakov – Lewis equation for each event to which Philip's equation was fitted. Philip's infiltration equation is expressed as given in Eq. (2.7)**,** **(** $Z = St^{0.5} + At$ **)**

Early time infiltration can be described by the first term of the equation. The sorptivity was determined from the intercept of a non-linear regression of Z as a function of t for small t < 15 minutes. A linear regression was applied to determine A, parameter related to hydraulic conductivity, which is the slope of $Z/t^{0.5}$ as a function of $t^{0.5}$ for large t > 1 hour.

3.9 Estimation of Water Application and Water Distribution Efficiencies

Water application and distribution efficiencies in this study were determined using Eqs. 2.33 and 2.34 respectively,($E_a = \left(\frac{w_s}{w_f}\right)100$ and $E_d = \left(1 - \frac{\overline{y}}{d}\right)100$ **)**

3.10 Evaluation of the Advance Models

The accuracy of the different models for predicting advance distance in furrow irrigation were evaluated by comparing the observed values of measurements on the field, X_0 and the predicted values based on the fitted advance model, X_P. Here a linear regression analysis of the observed and predicted advance distance was used to find the average pattern of variation of data. The form of regression equation used is.

$$X_p = c + \lambda X_o \qquad (3.10)$$

where:

X_P = predicted distance (m)

c = intercept

λ = slope of the best –fit line

The goodness of fit of the above equation to data was determined by calculating the coefficient of determination, R^2 and the standard error of estimate, σ. The absolute error, E in percentage was computed for each model, to measure the goodness of fit, as follows;

$$E = \left(\frac{X_o - X_c}{X_o} \right) 100 \qquad (3.11)$$

Furthermore, the accuracy of the different models was evaluated by plotting the observed advance distance, X_0 during irrigation event and the predicted, X_P and examining where these points fall in relation to a 1:1 line passing through the origin. t-paired test was applied to determine the significance level between the means of the observed values and the predicted values. The t-test was also used to determine the significance of the intercept and coefficient of regression (slope) for the regression equations. The magnitude of absolute error was used to rank the various models and to determine their suitability for field application.

3.11 Validation of the Models

In order to validate the various models, a total of fifteen irrigation events in five furrows from three irrigation treatments were monitored at the Galma Irrigation Scheme during the 2006 / 2007 irrigation season. Furrow inflows and outflows were monitored and measured using cutthroat flumes situated at the entrance of the furrow and at the outlet of the furrow. Advance characteristics were measured at 6m intervals along the

furrow with six advance points measured per furrow. Infiltration characteristics were calculated. Furrow lengths was measured manually and furrow geometry was calculated. Then, advance distances were predicted by a given model by inputting the various variables required by the models. The advance distances were then computed and compared with the observed distances. Predicted advance distances with an error not exceeding 12% limit is satisfactory as suggested by Mudiare (1982).

CHAPTER FOUR

RESULTS

4.1 Soil Properties

The field was found to have soils varying from silt loam at the top soil layer (0.0 – 0.4) to loam in the subsoil layer (0.4 – 0.8) by particle size analysis conducted in the laboratory. The soil bulk density were also found to range from 1.40g/cm^3 to 1.62g/cm^3. Table 4.1 shows the textural classification and the bulk density of the soil at the site where the research was conducted.

Table 4.1: Average soil properties at different depths.

Depth (m)	Clay (%)	Silt (%)	Sand (%)	Texture[a]	Bulk density (g/cm^3)
0.0 – 0.2	11	53	36	Silt loam	1.40
0.2 – 0.4	12	53	35	Silt loam	1.62
0.4 – 0.6	11	47	42	Loam	1.59
0.6 – 0.8	11	43	46	Loam	1.60

a is the USDA classification

4.2 Furrow Shape Parameters

The furrow shape parameters obtained are summarized in Table 4.2. The average furrow shape parameters per irrigation treatment used in the analysis of this study are shown in Table 4.3. These values are in agreement with values obtained by Eldeiry et. al., 2004. The average values of the furrow depth and furrow top width are contained in Appendix A.

Table 4.2: Furrow shape parameters measured before different irrigation treatments.

Furrow number	Irrigation treatment	α_1	α_2	σ_1	σ_2	γ_1	γ_2	σ_z	σ_y	C_2	C_1	A_0 (m^2)
2	4	1.62	0.50	1.08	1.50	2.03	0.55	1.47	0.8	0.704	1.377	0.006
5	4	1.67	0.52	1.09	1.52	2.08	0.58	1.37	0.8	0.731	1.404	0.005
8	4	1.82	0.56	1.16	1.56	2.24	0.61	1.33	0.8	0.710	1.426	0.006
11	4	1.84	0.57	1.17	1.57	2.27	0.62	1.31	0.8	0.712	1.435	0.006
14	4	1.88	0.53	1.23	1.53	2.26	0.58	1.32	0.8	0.706	1.418	0.006
2	5	1.72	0.53	1.13	1.53	2.14	0.58	1.52	0.8	0.708	1.403	0.005
5	5	1.93	0.59	1.21	1.59	2.32	0.63	1.44	0.8	0.712	1.439	0.005
8	5	1.75	0.54	1.13	1.54	2.18	0.59	1.66	0.8	0.709	1.414	0.005
11	5	1.88	0.58	1.19	1.58	2.28	0.62	1.82	0.8	0.711	1.433	0.005
14	5	2.00	0.60	1.26	1.60	2.41	0.64	1.52	0.8	0.714	1.459	0.005
2	6	1.42	0.45	0.98	1.45	1.85	0.52	5.42	0.8	0.700	1.337	0.005
5	6	1.82	0.54	1.18	1.54	2.23	0.58	1.88	0.8	0.708	1.418	0.005
8	6	1.44	0.43	1.01	1.43	1.82	0.49	2.85	0.8	0.694	1.319	0.005
11	6	1.88	0.58	1.19	1.58	2.29	0.62	1.82	0.8	0.712	1.438	0.005
14	6	1.57	0.51	1.04	1.51	2.01	0.57	4.06	0.8	0.707	1.382	0.005

α_1 and α_2 are the top width parameters

σ_1 and σ_2 are the area shape factor parameters

γ_1 and γ_2 are the wetted perimeter factor parameters

σ_z is the subsurface shape factor

σ_y is the surface storage shape factor

C_1 and C_2 are the inlet flow area parameters

A_0 is the cross sectional flow area at the inlet

Table 4.3: Average furrow shape parameters per irrigation treatments.

Irrigation treatment	α_1	α_2	σ_1	σ_2	γ_1	γ_2	σ_z	σ_y	C_2	C_1	A_0 (m^2)
4	1.76	0.54	1.15	1.54	2.17	0.59	1.36	0.8	0.708	1.409	0.006
5	1.85	0.57	1.18	1.57	2.28	0.61	1.56	0.8	0.711	1.435	0.005
6	1.44	0.45	0.99	1.45	2.01	0.55	2.55	0.8	0.708	1.394	0.005

4.3 Advance and Recession Curves

The advance of water over the surface is an important consideration in managing surface irrigation systems. Table 4.4 shows the values of the empirical parameters for the water advance and recession equations. In Figs. 4.1 to 4.3, the observed advance and recession points are shown with the fitted curves. The degree of association between the observed points and the fitted data is represented by the coefficient of determination (R^2), obtained through regression analysis. Appendix B contains the advance and recession times measured from the field per irrigation treatment.

Table 4.4: Average advance and recession equation parameters per irrigation treatment.

Irrigation treatment	Advance parameters		Recession parameters	
	P	r	b	m
4	5.5376	0.8354	5.6447	0.9258
5	4.2412	0.9095	2.9403	1.1401
6	2.7707	1.0863	1.8414	1.3671

4.4 Infiltration Characteristics

The infiltration parameters of modified Kostiakov-Lewis equation and Philip equation per irrigation treatment are shown in Table 4.5; while Table 4.6 shows the average values of the infiltration parameters of modified Kostiakov-Lewis equation and Philip equation per irrigation treatment.

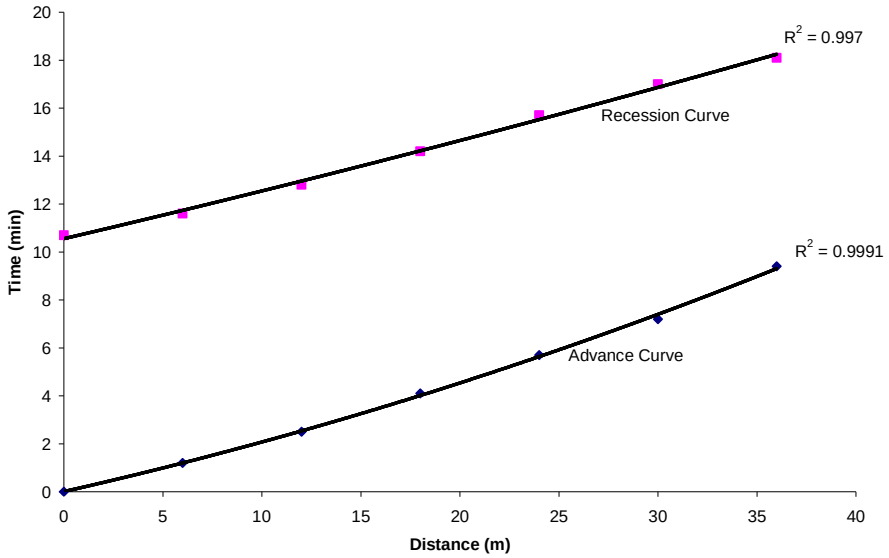


Fig 4.1: Advance and recession curves for treatment 1

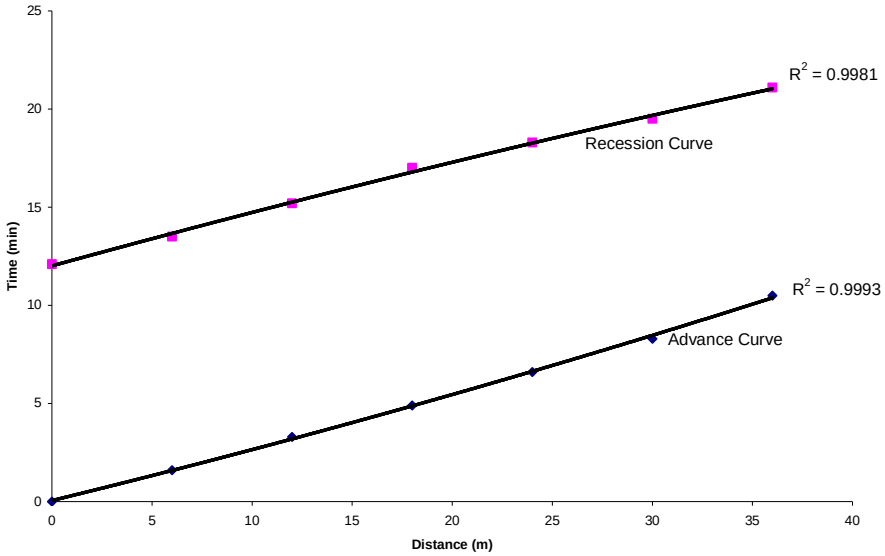


Fig 4.2: Advance and recession curves for treatment 2

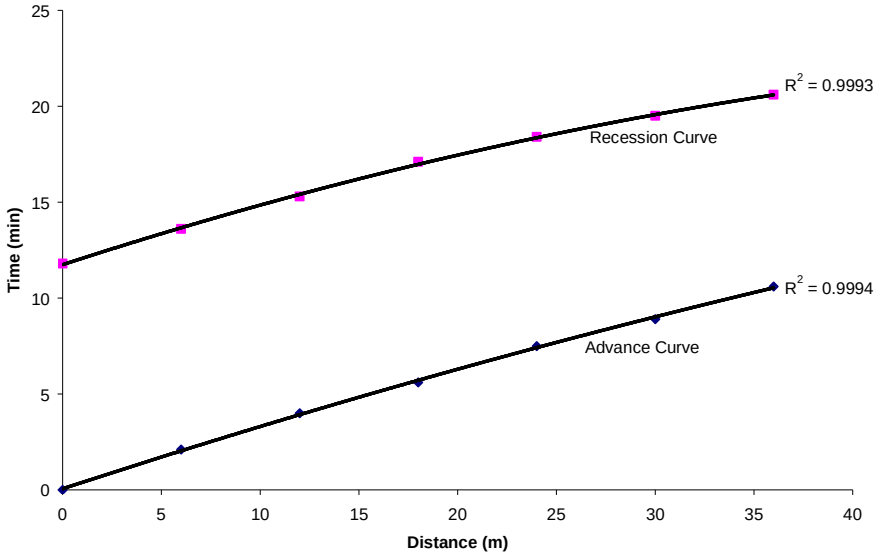


Fig 4.3: Advance and recession curves for treatment 3

Table 4.5: Values of the modified Kostiakov-Lewis equation and Philip equation parameters during different irrigation events.

Furrow number	Irrigation number	Kostiakov-Lewis equation			Philip's equation	
		k	a	f_0	S	A
2	4	0.0166	-0.334	0.00245	0.011159	0.002420
5	4	0.0199	-0.290	0.00259	0.013737	0.002547
8	4	0.0177	-0.265	0.00252	0.012517	0.002478
11	4	0.0175	-0.257	0.00259	0.012480	0.002548
14	4	0.0171	-0.261	0.00252	0.012155	0.002479
2	5	0.0219	-0.355	0.00237	0.012053	0.002333
5	5	0.0211	-0.322	0.00237	0.014144	0.002330
8	5	0.0233	-0.405	0.00237	0.012150	0.002338
11	5	0.0247	-0.455	0.00237	0.012197	0.002342
14	5	0.0219	-0.355	0.00237	0.012053	0.002333
2	6	0.0206	-0.799	0.00226	0.007093	0.002254
5	6	0.0236	-0.469	0.00226	0.011474	0.002235
8	6	0.0246	-0.637	0.00226	0.009898	0.002247
11	6	0.0222	-0.455	0.00226	0.010960	0.002235
14	6	0.0229	-0.737	0.00226	0.008290	0.002252

Table 4.6: Average values of the modified Kostiakov-Lewis equation and sPhilip equation parameters per irrigation treatments.

Irrigation treatment	Kostiakov-Lewis equation			Philip's equation	
	k	a	f_0	S	A
4	0.0178	-0.282	0.00252	0.010654	0.002481
5	0.0226	-0.371	0.00237	0.012223	0.002334
6	0.0248	-0.598	0.00226	0.010427	0.002244

Negative values were observed for all values of the time exponent in the modified Kostiakov – Lewis equation. The infiltration data generated using the modified Kostiakov-Lewis equation and the infiltration-time graphs are presented in Appendix C and D.

4.5 Validation of Walker and Skogerboe model

In validating the Walker and Skogerboe model, the predicted values by the model for the three irrigation treatments were compared with the observed values as shown in Table 4.7, where the mean absolute errors for the first, second and third treatment were found to be 6.94%, 2.78% and 3..47%, respectively, which are less than 12% suggested by Mudiare (1982). It is observed from the values that the predicted advance distances were in good agreement with the observed distances from the field. Consequently, the Walker and Skogerboe model was suitable.

Table 4.7: Observed distance (X_0) in furrow compared with that predicted (X_P) using Walker and skogerboe model.

Observed distance(m)	Predicted distance for Tr_1 (m)	E(%)	Predicted distance for Tr_2 (m)	E(%)	Predicted distance for Tr_3(m)	E(%)
6	4	33.33	5	16.67	5	16.67
12	11	8.33	12	0.00	12	0.00
18	18	0.00	18	0.00	18	0.00
24	24	0.00	24	0.00	25	4.17
30	30	0.00	30	0.00	30	0.00
36	36	0.00	36	0.00	36	0.00
Mean		6.94		2.78		3.47

Tr_1 = irrigation treatment number 1

Tr_2 = irrigation treatment number 2

Tr_3 = irrigation treatment number 3

4.6 Validation of Michael's Advance Model

Table 4.8 shows values of the predicted distances by the Michael's advance model for the irrigation treatments compared with the observed values. The average

absolute errors for the first and third treatments were found to be 11.30% and 4.72%, which are acceptable while the second treatment (13.01) was beyond the limit.

Table 4.8: Observed distance (X_0) in furrow compared with that predicted (X_P) using Michael's advance model.

Observed distance (m)	Predicted distance for Tr_1 (m)	E (%)	Predicted distance for Tr_2 (m)	E (%)	Predicted distance for Tr_3 (m)	E (%)
6	7	16.67	5	16.67	5	16.67
12	10	16.67	10	16.67	12	0.00
18	15	16.67	15	16.67	17	5.56
24	22	8.33	21	12.50	24	0.00
30	28	6.67	27	10.00	29	3.33
36	37	2.78	38	5.56	35	2.78
Mean		11.30		13.01		4.72

4.7 Validation of Philip and Farrell model

Results of the predicted advance distance by Philip and Farrell model were compared with the observed advance distances and are presented in Table 4.9. The average absolute errors were found to be 34.67%, 33.01% and 43.56% for the first, second and third treatments, respectively. These values indicate that there were wide variations between the predicted advance distances by the model and those observed from the field because the values were beyond the tolerance limit of 12% suggested by Mudiare (1982).

Table 4.9: Observed distance (X_0) in furrow compared with that predicted (X_P) using Philip and Farrell model.

Observed distance (m)	Predicted distance for Tr_1 (m)	E (%)	Predicted distance for Tr_2 (m)	E (%)	Predicted distance for Tr_3 (m)	E (%)
6	12	100.00	11	83.33	14	133.33
12	16	33.33	15	25.00	18	50.00
18	19	5.56	18	0.00	19	5.56
24	21	12.50	19	20.83	21	12.50
30	23	23.33	21	30.00	22	26.67
36	24	33.33	22	38.89	24	33.33
Mean		34.67		33.01		43.56

4.8 Performance Indices of the Advance Models

Evaluating the performance of the furrow irrigation models involves determining their overall accuracy to predict different parameters for a given field condition. Tables 4.10 and 4.11 show the values of the various indices for the different models for the three irrigation treatments and the average values for the treatments, respectively for the observed and calculated values while Tables 4.12 and 4.13 present the values of the indices between the models for the irrigation treatments and the average values between models, respectively.

Table 4.10: Values of λ, N, σ, R^2 and E for the different models for predicting advance in irrigation treatments 1, 2 and 3 respectively.

Treatment	Model	λ	N	σ	R^2	E (%)
1	M_1	1.0619	6	0.84	0.9984	6.94
	M_2	1.0048	6	1.72	0.9772	11.30
	M_3	0.3952	6	6.85	0.9570	34.67
2	M_1	1.0238	6	0.41	0.9993	2.78
	M_2	1.0571	6	1.97	0.9760	13.01
	M_3	0.3524	6	7.34	0.9387	33.01
3	M_1	1.0286	6	0.00	0.9978	3.47
	M_2	0.9905	6	0.52	0.9979	4.72
	M_3	0.3048	6	7.84	0.9540	43.56

N is the number of observed and predicted advance distances.

M_1 is the Walker and Skogerboe model

M_2 is the Michael's advance model

M_3 is the Philip and Farrell model

Table 4.11: Average values of λ, N, σ, R^2 and E for the different models for predicting advance.

Model	λ	N	σ	R^2	E (%)
M_1	1.0381	6	0.42	0.9985	4.40
M_2	1.0175	6	1.40	0.9837	9.67
M_3	0.3508	6	7.34	0.9499	37.08

From Tables 4.10 and 4.11, the slope, λ for Walker and Skogerboe model ranged between 1.0238 and 1.0619 and had a mean value of 1.0381, which shows an unbiased prediction by the model. Similarly, the range for Michael's advance model were between 0.9905 and 1.0571 with a mean value of 1.0175, which indicates an unbiased prediction. However, the slope value for Philip and Farrell model ranged between 0.3048 and 0.3958 and had a mean value of 0.3508, which show under prediction by the model.

The error of estimate, σ for Walker and Skogerboe model ranged from 0.00 to 0.84 with a mean value of 0.42. The value for Michael's advance model lied between 0.52 and 1.97 and a mean value of 1.40 while the value for Philip and Farrell model ranged from 6.85 to 7.84 and had a mean value of 7.34.

The coefficient of determination, R^2, for Walker and Skogerboe model lie between 0.9978 to 0.9993 with a mean value of 0.9985. The value for Michael's advance model ranged between 0.9760 and 0.9979 and had a mean value of 0.9837 while the R^2 value for Philip and Farrell model ranged from 0.9387 to 0.9570 with a mean value of 0.9499.

The absolute error, E, for Walker and Skogerboe model lie between 2.78% to 6.94% with a mean value of 4.40% while the value for Michael's advance model ranged between 4.72% and 11.30% and had a mean value of 9.67%. The E value for Philip and Farrell model ranged from 33.01% to 43.56% with a mean value of 37.08%.

Table 4.12: Values of λ, N, σ, R^2 and E for comparison between the different models for predicting advance in irrigation treatments 1, 2 and 3 respectively.

Treatment	Model	λ	N	σ	R^2	E (%)
1	M_1 & M_2	0.9396	6	2.25	0.9651	19.76
	M_1 & M_3	0.3746	6	7.50	0.9706	53.36
	M_2 & M_3	0.3721	6	7.34	0.8763	35.94
2	M_1 & M_2	1.0295	6	2.07	0.9710	10.23
	M_1 & M_3	0.3460	6	7.57	0.9495	39.12
	M_2 & M_3	0.3156	6	8.36	0.8623	43.98
3	M_1 & M_2	0.9626	6	0.52	0.9994	2.61
	M_1 & M_3	0.2979	6	8.14	0.9665	51.93
	M_2 & M_3	0.3095	6	7.71	0.9671	51.64

Table 4.13: Average values of λ, N, σ, R^2 and E for comparison between the different models for predicting advance.

Model	λ	N	σ	R^2	E (%)
M_1 & M_2	0.9772	6	1.61	0.9785	10.87
M_1 & M_3	0.3395	6	7.74	0.9622	48.14
M_2 & M_3	0.3324	6	7.80	0.9019	43.85

In comparing the models, Table 4.13 shows that the mean slope, λ for M_1 and M_2 indicates an unbiased prediction with a value of 0.9772 while that for $M_1$and M_3, and M_2 and M_3 show under predictions with values of 0.3395 and 0.3324 respectively. The mean error of estimate, σ value (1.61) for M_1 and M_2 show minimal prediction error while that for M_1 and M_3, and M_2 and M_3 indicate high prediction error with values of 7.74 and 7.80, respectively.

The mean coefficient of determination, R^2, for M_1 and M_2 was 0.9785. M_1 and M_3 had a mean value of 0.9622 and M_2 and M_3 had a mean value of 0.9019. The mean absolute error, E, for M_1 and M_2 was 10.87% while that of M_1 and M_3, and M_2 and M_3 were 48.14% and 43.85%, respectively.

4.8 Water Application and Water Distribution Efficiencies

The water application efficiency obtained from the irrigation treatments varied between 52% to 59% which is lower than the range given by Solomon (1988) and Aljuneidi and Isaac (1988). The water distribution efficiency obtained ranged from 81% to 87%. Results of the water application efficiency and water distribution efficiency are presented in Table 4.14.

Table 4.14: Values of water application and distribution efficiencies.

Treatment number	Application efficiency (%)	Distribution efficiency (%)
4	59.3	81.6
5	55.1	85.3
6	52.8	87.3

CHAPTER FIVE

DISCUSSIONS

5.1 Infiltration Characteristics.

Negative values were obtained for the time exponent of the modified Kostiakov-Lewis parameter which are physically impossible (Esfandiari and Maheshwari, 1997; Serralheiro, 1995). The reason for this may be that the irrigation advance decreases quite slowly and stays nearly constant at some points along the furrow due to uneven slope observed in the furrows on the field. Also depending on the particular combination of L, $L_{0.5l,}$ Q and f_0, a low value of the exponent of the power advance equation ; Eq 2.3 is required for 'a' to be positive in the modified Kostiakov – Lewis equation (Serralheiro, 1995). He also stated that relatively high values of f_0 which may be due to inaccuracy in determining the outflow may be responsible.

5.2 Advance and Recession Curves.

The graphs (Figs. 4.1 – 4.3) show that the advance and recession curves were reasonably parallel. This means that the water intake at all points along the furrows were approximately equal which indicate that the soil type in the field and the slope of the field are relatively uniform, and an efficient and uniform water application was achieved for all trials.

5.3 Irrigation Efficiencies.

These low values (52% - 59%) obtained for water application efficiency may be attributed to the runoff losses at the end of the field and lateral seepage which occur during furrow irrigation events. These losses could be attributed to poor management practices. However, this range of application efficiency obtained falls within the limit given by Rogers (1995) for continuous flow, no tailwater recovery which is 50-60% and which was the irrigation practice used in this study.

The uniformity of water distribution is more important than the application efficiency in terms of maintaining uniform crop growth (Oyebode, 1989). Runoff and uniformity of the water infiltrated along the furrow are related to soil conditions and field topography (Yonts et. al. 2003). The uneven slope observed in the furrows as a result of design problem may have contributed to the values (81% - 87%) obtained for water distribution efficiency, inspite of the problems stated, the results are still satisfactory.

5.4 Comparison of Observed Values with Predicted Values.

The performances of the models for predicting advance distance for the irrigation events monitored at the Galma Irrigation Scheme were quantified by calculating λ, σ, R^2 and E. The values of the various indices for models evaluation between the observed and the predicted distances for the three irrigation treatments at the site and the average values of the irrigation treatments are given in Tables 4.11 and 4.12, respectively. Considering the limited number of irrigation events (15) in the evaluation of the models, the average values of λ, σ, R^2 and E in Table 4.12 shows that Walker and Skogerboe model predicted the advance distances in the furrows with a higher accuracy (λ = 1.04,

R^2 = 0.999 and E = 4.40%) when compared with the other two models. This means, the Walker and Skogerboe model is superior to the other two models for predicting advance distances at this site, especially for evaluating furrow irrigation systems. The reason for this may be that this model makes use of the modified Kostiakov – Lewis infiltration parameters, surface storage factor and time exponent of the advance equation which could account for its superiority over the others.

The performance of the Michael's advance model for predicting advance was relatively high too as λ, R^2, and E values were 1.02, 0.984 and 9.67%, respectively. A lower value of R^2 and a higher value of the average absolute error for the model indicate that the advance distances predicted with the model will result in considerable errors compared to the Walker and Skogerboe model. The reason for the poor performance of the Michael's advance model might be related to the average depth of flow along the furrow used in computation which is not a true representation of the depth of flow measured at the various stations. There was an increase or a decrease from the actual depth of flow measured at the various measuring stations established along the furrows which may be responsible for the slight variations in the values.

The performance of the Philip and Farrell model for predicting advance was very poor with λ, R^2 and E values of 0.35, 0.950 and 37.08%, respectively. The reason for the poor performance of the Philip and Farrell model is probably related to the fact that the model uses only Philip's infiltration parameters to predict advance distances as compared to Walker and Skogerboe, and Michael's advance models that use surface storage factor and time exponent of advance equation and average depth of flow respectively in addition to the modified Kostiakov – Lewis infiltration parameters. The reason may also

be associated with the assumption employed in developing the model, which is, the particular solution assumes the depth of flow to be zero. However, in practice this is not true. It should be recalled too that Philip established his equation for infiltration into a uniform homogeneous soil (Philip and Farrell, 1964; Serralheiro, 1995). Therefore, it is not surprising that such an equation type did not perform well in predicting advance distance in heterogeneous soil profile such as the one obtained at this site. Also, theoretically derived equations such as that of Philip are based on assumptions which are often not satisfied in the field (Watson, 1959). Furthermore, Philip's infiltration parameters used in the evaluation of the model were obtained by fitting Philip infiltration equation into data generated from the modified Kostiakov – Lewis equation which could result in some computational errors.

The t - test shows that the table value for 5 degrees of freedom and 5% level of significance (2.571) is higher than the calculated values (0.8292, 2.3107 and 0.7266) for M_1, M_2 and M_3, respectively. It implies that the difference between the means of the calculated values by the models and the observed values is not significant statistically at 5% level of significance. The t - test for significance of the intercept and coefficient of regression (slope) for the regression equations of the various irrigation events show that the values were not significant at 5% level for the regression equations using values predicted by Walker and Skogerboe, and Michael's advance models while that of Philip and Farrell model were all significant at 1% level.

Figures 5.1- 5.3 show plots of observed distances versus predicted distances for the average of irrigation treatments using the different models for predicting advance distance. The data for all the advance distances with the Walker and Skogerboe model

falls on the 1:1 line except for the first point (see Fig 5.1). This shows that there was almost no variation or there was a good agreement with the observed distances. The data for the predicted distances with the Michael's advance model falls very close to the 1:1 line signifying little variation from the observed distances on the field. In Fig 5.2, of the 6 points, 4 points under predicted with 1 over predicting slightly. There was a considerable scatter of data points for the predicted distances with the Philip and Farrell model except for the two data points mid-way of the entire length (Fig 5.3). This shows no agreement between the observed and predicted distances.

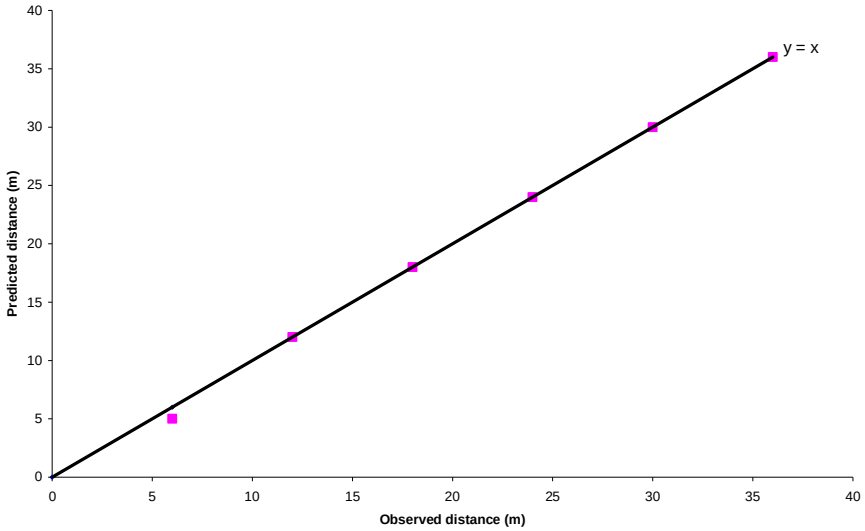


Fig 5.1: Plot of observed distances versus predicted distances by Walker and Skogerboe model

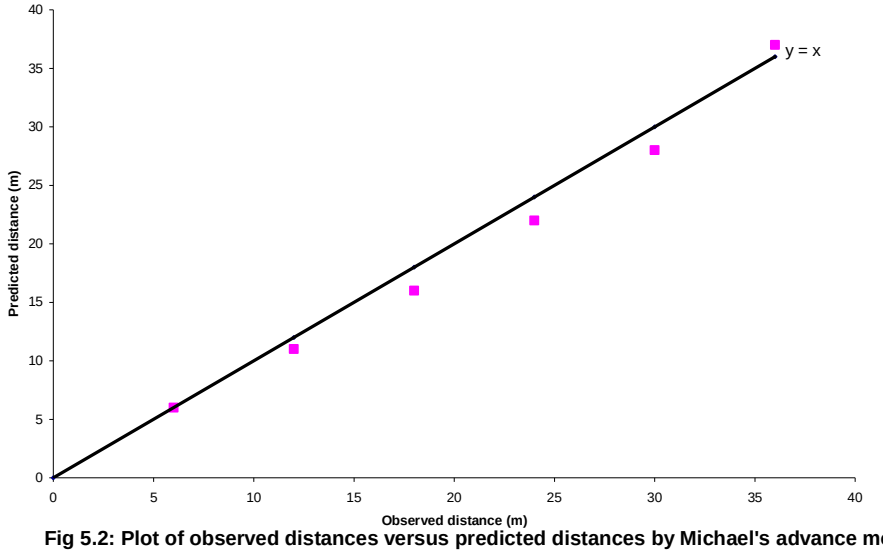


Fig 5.2: Plot of observed distances versus predicted distances by Michael's advance model

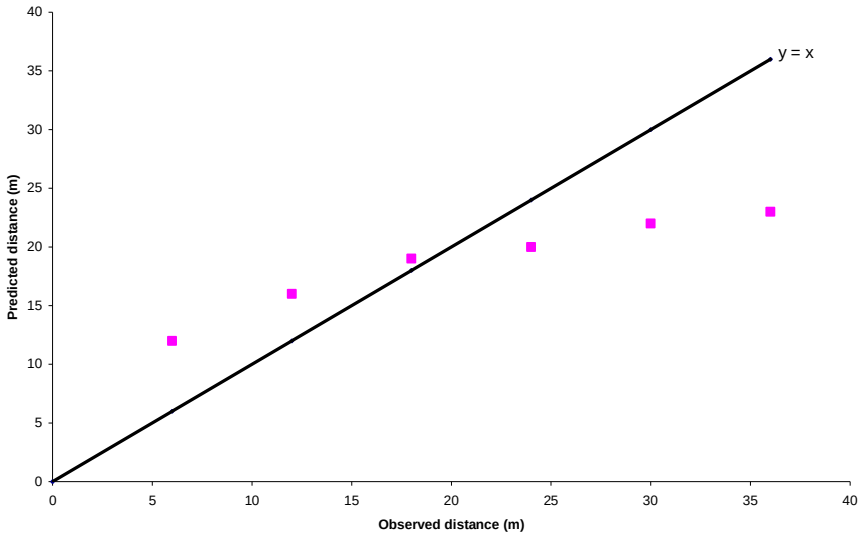


Fig 5.3: Plot of observed distances versus predicted distances by Philip and Farrell model

Comparison Between the Models

In evaluating the performance among the three models, two models were chosen at a time for comparison. The comparison was done between M_1 and M_2, M_1 and M_3, and M_2 and M_3. Their performances were quantified by calculating λ,σ, R^2 and E..

The values of the evaluation indices between the models for the three irrigation treatments at the site and the average values of the irrigation treatments are given in Tables 4.12 and 4.13, respectively. The average values of λ, R^2 and E given in Table 4.13 indicates that the comparison of M_1 and M_2 have the highest accuracy (λ = 0.98, R^2 = 0.98 and E = 10.87%) compared with the other two associations. This shows that the predicted advance distances values by Walker and Skogerboe model and Michael's advance model are very close. This may be related to the similar infiltration parameter used in the model which is the modified Kostiakov- Lewis equation. Also the two models make use of additional variables in the development of the model, that is, the surface storage factor and the exponent of the advance equation for the Walker and Skogerboe model and the average depth of flow along the furrow for Michael's model. There was a considerable poor interaction of M_1 and M_3, and M_2 and M_3 with values (λ = 0.34, R^2 = 0.96 & E = 48.14%) and (λ = 0.33 R^2 = 0.90 & E = 43.85%), respectively. These indicates a high degree of prediction difference between M_1 and M_3, and M_2 and M_3. This basically may be due to the differences in the assumption on which the models were developed and differences in the input parameters to the models.

The test for significance of the intercept and coefficient of regression (slope) for the regression equations comparing the models show that the values were not significant

at 5% level for the regression equation of predicted advance distances by M_1 and M_2 while that of M_1 and M_3, and M_2 and M_3 were all significant at 1% level.

Figures 5.4-5.6 show plots of one model against another model for the average of irrigation treatments. The data for all the advance distances predicted by both Walker and Skogerboe model and Michael's advance model show a very close agreement with the data falling close to the 1:1 line (see Fig 5.4). The reason for this may be that the two models use the modified Kostiakov-Lewis infiltration equation in the particular solution of the models.

The comparison of M_1 and M_3, and M_2 and M_3 show a great variation of the data of M_1 and M_2 from the data of M_3, (Figs 5.5 and 5.6). This may be related to the infiltration equation parameters used in the models which though are of the same form but different assumptions were used in their development as stated previously. Also, there is variation in the number of input parameters into the models which could account for the difference in the predicted advance distances by the models.

5.6 Suitability of the models for field application

The overall suitability of a model from the point of view of accuracy of its predictions can be examined by considering the various evaluation indices; however, as a general rule, the average absolute error, E can be used to indicate the relative performance of the models.

It is pertinent, however, to know that some input parameters, particularly infiltration characteristics and furrow geometry parameters are often subject to estimation

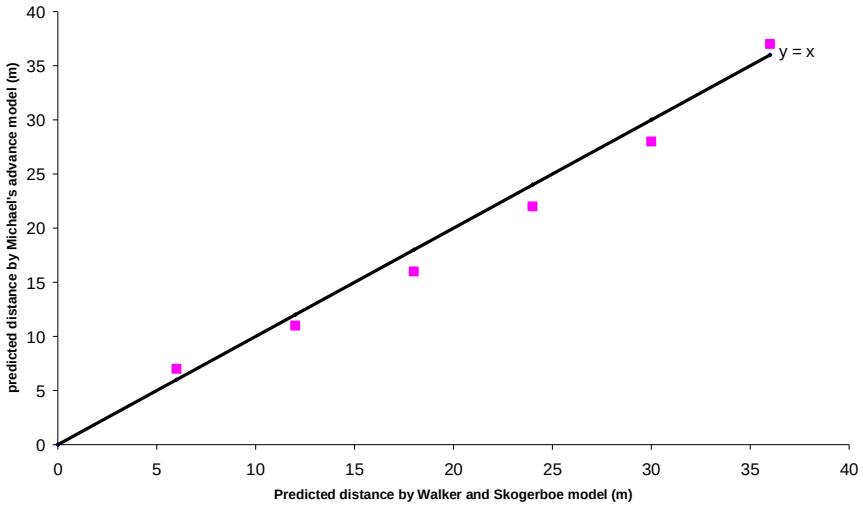


Fig 5.4: Plot of predicted advance distances by Walker and Skogerboe model vs Michael's advance model

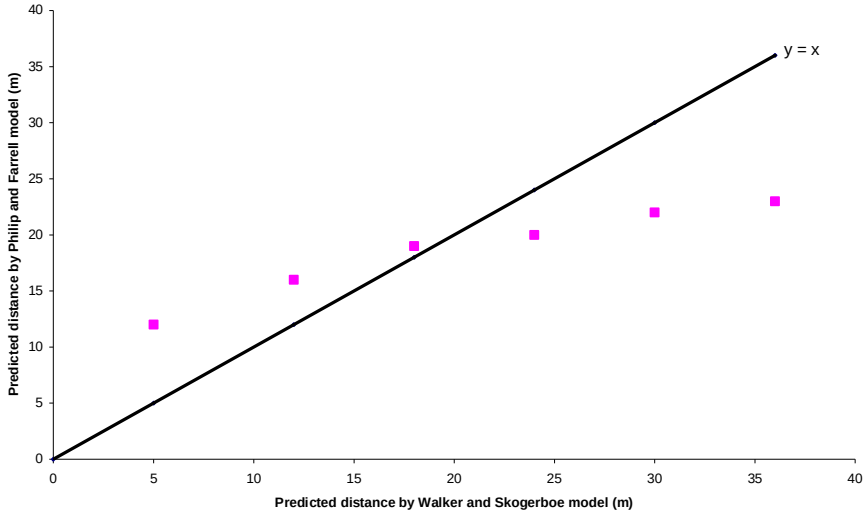


Fig 5.5: Plot of predicted advance distances by Walker and Skogerboe model vs Philip and Farrell model

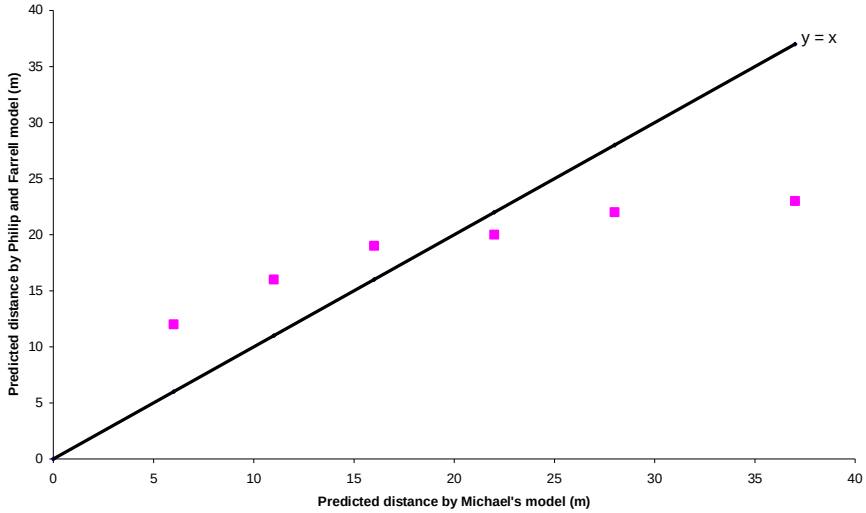


Fig 5.6: Plot of predicted advance distances by Michael's advance model vs Philip and Farrell model

errors and may affect the performance of the models. The above observation suggests that the performance of a given model is affected by site which may be due to the effect of specific field conditions present at the site, the accuracy of the input parameters and assumptions made in developing the models.

In general, considering the values of the various indices for the models, it is felt that the performance of the Walker and Skogerboe model is superior to that of Michael's model which follows closely and the least is that of Philip and Farrell model with average absolute errors of 4.40%, 9.67% and 37.08%, respectively.

CHAPTER SIX

SUMMARY, CONCLUSION AND RECOMMENDATIONS

6.1 Summary

Three different models for predicting water advance distance in continuous flow irrigation under furrow irrigation system were chosen to test their suitability to field condition. These models were developed using different assumptions by the different researchers but employing the same form of infiltration equation parameters. The use of infiltration parameters in the entire model only emphasizes the critical influence of soil infiltration properties on the performance of surface irrigation system. However, this research shows that additional factor such as surface storage factor, depth of flow along the furrow and time exponent of advance equation play vital roles in determining water advance distance under continuous flow conditions.

Five furrows were chosen to monitor the irrigation events. A total of 15 irrigation events were monitored from the three irrigation treatments. The furrow geometry parameters, advance equation parameters and infiltration characteristic were determined and put into the models from which predicted values of advance distances were calculated. The observed advance distances were compared with the predicted advance distances for the three models. Thereafter the predicted advance distances by the different models were compared with each other.

Comparing the observed advance distances with the predicted advance distances the average absolute error, E, slope of the best –fit line, λ, coefficient of determination, R^2 and the standard error of estimate, σ show that the Walker and Skogerboe model is

superior with Michael's advance model following closely while the Philip's models is the least in terms of performance among the models. However, the paired plot analysis indicates that the mean of the observed values and those predicted are at par.

Comparing the predicted advance distances of one model with another, the average absolute error, E, slope of the best-fit line,λ the coefficient of determination, R^2 and the standard error of estimate, σ indicate that the comparison between M_1 and M_2 is superior to the rest. The comparison between M_1 and M_3, and M_2 and M_3 were very poor and had almost the same values for the various indices.

6.2 Conclusion

In conclusion, for prediction of advance distance, the performance of the Walker and Skogerboe model and Michael's advance model were satisfactory though the Walker and Skogerboe model was found to be the best model for simulating furrow irrigation under the field conditions encountered in the present study. The predictions by Philip's model were very poor with respect to the indices used in comparison. This study has also shown that apart from the critical influence of the soil infiltration characteristics on the design and performance of surface irrigation, furrow geometry is also an important parameter for determining advance distance and should be included among the design parameters in installation and maintenance of furrow irrigation system. Therefore, the application of these models under verified field conditions leads to the determination of accurate discharge rate and application time that would optimize irrigation performance, minimize water wastage and allow proper growth of the crop.

6.3 Recommendations.

The following recommendations can be drawn from this research on furrow irrigation system;

1. The Walker and Skogerboe model and Michael's advance model can successfully be applied for design and management purpose at this site and other sites having the same soil properties.
2. Apart from the volume balance models, other types of the solution given to mechanistic model (e.g. hydrodynamic, zero-inertia and kinematic-wave models) should be chosen and applied to a specific field condition to validate and evaluate their suitability.
3. Relatively short furrow length of 40m long was used for this research due to the practice obtainable on this site; therefore this work should be carried out for furrow length of 100m and above to test the suitability of the models to long furrow lengths.
4. This study was carried out on a silt-loam to loam soil, due to the effect of soil type on infiltration, this research should be carried out on different soil types to verify the effect of soil type on these models.

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APPENDIX A

Table A1: Average values of depth from furrow bottom and furrow top width per irrigation treatment.

Depth from furrow bottom (m)	Furrow top width for treatment 1 (m)	Furrow top width for treatment 2 (m)	Furrow top width for treatment 3 (m)
0.01	0.210	0.204	0.232
0.02	0.245	0.228	0.265
0.03	0.285	0.270	0.300
0.04	0.320	0.308	0.330
0.05	0.354	0.340	0.360
0.06	0.389	0.375	0.392
0.07	0.421	0.410	0.418
0.08	0.452	0.441	0.448
0.09	0.483	0.472	0.478
0.1	0.513	0.503	0.509

APPENDIX B

Table B1: Average advance and recession times measured at the field for treatment 1

Observed distance (m)	Advance time (min)	Recession time (min)
0	0.0	10.7
6	1.1	11.6
12	2.5	12.8
18	4.1	14.2
24	5.7	15.7
30	7.2	17.0
36	9.4	18.1

Table B2: Average advance and recession times measured at the field for treatment 2

Observed distance (m)	Advance time (min)	Recession time (min)
0	0.0	12.1
6	1.6	13.5
12	3.3	15.2
18	4.9	17.0
24	6.6	18.3
30	8.3	19.5
36	10.5	21.1

Table B3: Average advance and recession times measured at the field for treatment 3

Observed distance (m)	Advance time (min)	Recession time (min)
0	0.0	11.8
6	2.1	13.6
12	4.0	15.3
18	5.6	17.1
24	7.5	18.4
30	8.9	19.5
36	10.6	20.6

APPENDIX C

Table C1: Average infiltration rate generated using modified Kostiakov – Lewis equation per irrigation treatment.

Time (min)	Infiltration rate for treatment 1 (mm/hr)	Infiltration rate for treatment 2 (mm/hr)	Infiltration rate for treatment 3 (mm/hr)
3	412.36	442.90	392.74
5	286.87	291.47	249.27
8	225.47	220.57	189.24
13	191.06	182.48	160.29
23	170.38	160.62	145.52
33	163.27	153.43	141.17
48	158.67	148.92	138.66
63	156.47	146.83	137.58
93	154.40	144.91	136.66
123	153.44	144.05	136.28
183	152.54	143.27	135.96
243	152.13	142.93	135.83
303	151.19	142.74	135.76

APPENDIX D

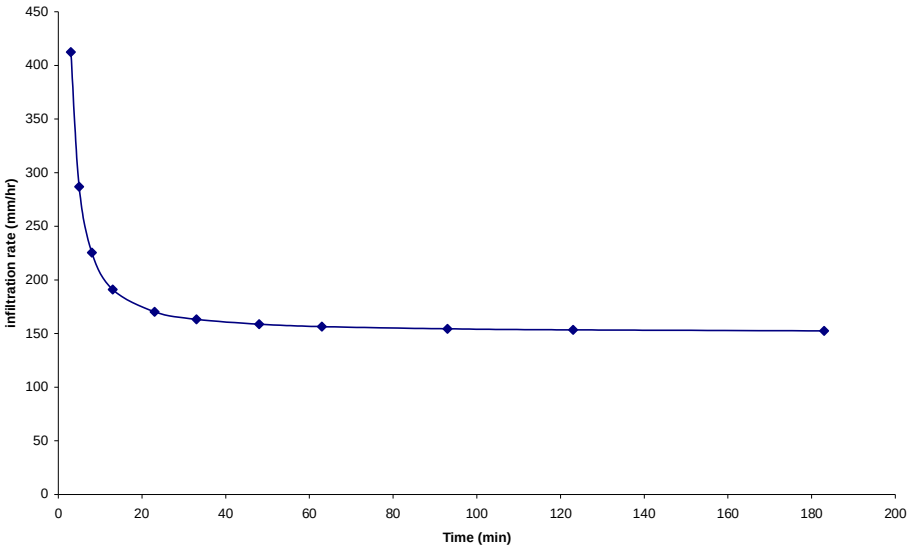


Fig D1: Graph of infiltration rate against time for treatment 1

APPENDIX D

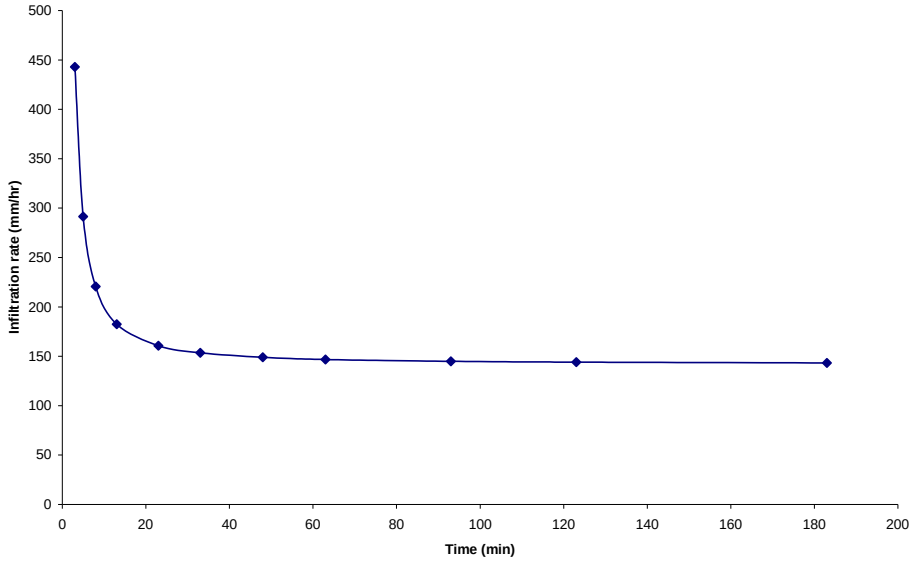


Fig D2: Graph of infiltraion rate against time for treatment 2

APPENDIX D

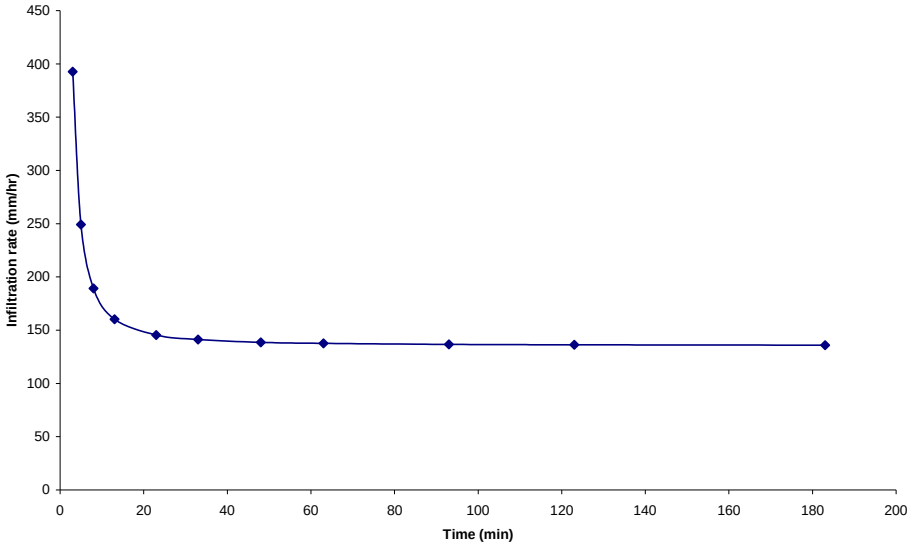


Fig D3: Graph of infiltration rate against time for treatment 3