GROUNDWATER CONTRIBUTION TO CORN WATER USE IN INLAND VALLEY OF BADEGGI, NIGERIA

BY

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(PHD/ENG/4297/91-92)

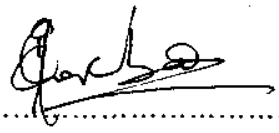
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DECLARATION

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. The sources of information are specifically acknowledged by means of references.



Date: 31:10:2007

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CERTIFICATION

This thesis entitled "**GROUNDWATER CONTRIBUTION TO CORN WATER USE IN INLAND VALLEY OF BADEGGI, NIGERIA**" by EGHAREVBA, NOSA' ANTHONY meets the regulations governing the award of the degree of Doctor of Philosophy (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 loving parents Engr. T. J. Egharevba and Madam V. Obaseki as well as my faithful and patient family, Honey Millicent Olapetan Egharevba (Mrs), Princess Toluwani Erhunmwunse Egharevba and Militant Osayomwanbo Samuel Egharevba; I dedicate this work.

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ABSTRACT

In order to quantify the groundwater contribution to total corn water use, two sets of experiments were conducted. One was in a greenhouse were corn was grown in a cylindrical containers in which the water table depths were maintained at 100, 200, 300, 450, and 600 mm. The second was in an open field along an inland valley where water table depths range of 200 to 500 mm and 600 to 800 mm were used. The sources of water for meeting the water requirement of corn in a greenhouse during the crop growing seasons of 1997 to 1999 were the water table and surface water application. The corn on the field was rainfed in the month of September and partly in October and thereafter, left to obtain water from the groundwater table during the remaining dry period of October to December of each year during the study period.

The maximum yield was 1.3 t/ha at the 450 mm water depth in the greenhouse, which is therefore taken as a suitable water regime for corn grown under the greenhouse culture. The grain yield of 2.9 t/ha in the field plots situated naturally within the water table depth range of 200 to 500 mm along the valley toposequence was higher when compared to the yield of 0.8 t/ha from plots on water table depth range of 600 to 800 mm. It is found that as much as 37% of the total corn evapotranspiration demand was derived from the groundwater. The water table fluctuations along the inland valley during the period of study can be represented by an exponential function of time during the wet season. However, Fourier series curves at weekly time steps gave a better representation of the water table fluctuation for both the wet and dry seasons.

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ABBREVIATIONS, GLOSSARIES AND SYMBOLS

A', A	Proportionality constant
A_1	Empirical constant
A_0, A_i, B_i	Fourier series coefficients
a, b	Régression constants
B_1	Empirical constant
C	Coefficient of proportionality (correction factor)
C_m	Maximum harmonic number in the Fourier series
D, H	Water height or depth to water table (m)
DAP	Days after planting
d	Equivalent depth to the impermeable substratum (m)
d_n	Net irrigation (mm)
D_r	Drainage below the root zone (mm)
E_c , E_{ce}	Electrical conductivity of the groundwater (mmhos/cm; ds/m)
E_0	Free water or pan evaporation (mm)
ET	Evapotranspiration (mm)
ET_{max}	Maximum evapotranspiration (mm)
ET_R	Reference crop evapotranspiration (mm)
ESP	Exchange sodium percent
h	Pressure head (m)
h_1, h_2, ..., h_n	Pressure heads at elevations of various soil layers Z_1, Z_2, ...,Z_n (m)
h_t	Water table head at time t (m)
h_0	Initial water table head at time t_0 (m)

$h(\theta)$	Soil water characterisitcs
hwt	High water Table
$\mathbf{H_c}$	Critical capillary height (m)
K	Soil hydraulic conductivity (cm/day)
K(h)	Hydraulic conductivity as a function of matric potential
$K(\theta)$	Hydraulic conductivity as a function of volumetric moisture content
$\mathbf{K_s}$	Vertical saturated conductivity (cm/day
$\mathbf{K_c}$	Crop coefficient
L	Drain spacing (m)
lwt	Low water table
m	Proportionality constant
N	Soil Nitrogen (kg/m^2)
O	Other minerals (kg/m^2)
P	Net photosynthesis
PAR	Photosynthetically active radiation
P_e	Effective precipitation (mm)
q	Drain discharge rate per unit area
q_t, q_{t-1}	Drain discharge at time t and t-1
R	Groundwater recharge by rainfall (mm)
$R_{\Delta t}$	Mean value of groundwater recharge during the time interval t-1 to t (mm)
R_s	Solar radiation
S_b	Amount of water in the root zone at the beginning of a given period (mm)
S_c	Amount of water in the root zone at the end of a given period (mm)

SAR	Sodium adsorption ratio
t	Time (days)
T	Transpiration (mm)
T_t	Mean daily temperature (°C)
T_{max}	Transpiration corresponding to maximum crop yield (mm)
U_t	Upward soil water flow (mm)
V	Flow velocity (m/s)
W	Crop water-use (mm)
wk	Week
WUE	Water use efficiency
Y	Crop yield (kg/ha or kg/m^2)
$Y_p(t)$	Transformed model parameter at day, t
Y_{max}	Soil separate layer in the soil profile
α	Reaction factor (days^{-1})
β	Dimensionless slope (yield response factor)
μ	Drainable pore space (m^3/m^3)
θ	Potential or energy status of the water in the soil
Δe	Water vapour pressure deficit (mbar)
λ	Hydrologic ratio (degree of dryness /wetness)
Δt	Time interval (days)
r, R	Coefficient of correlation
π	Pi
ρ	Soil bulk density (g/cm^3)

CHAPTER ONE

INTRODUCTION

Water resources management has become one of the most important issues in the world as we experience more cases of drought on the one hand, and several record - breaking floods on the other. Agricultural production utilises enormous portion of limited water resource. Hence, the need to adequately manage the limited water resources without depressing crop yields cannot be overemphasised. The focus therefore is not only to save the limited amount of water during crop production but also to conserve the energy requirement as well as the environment (Yagi et al., 1995).

Local geology (occurrence of an impermeable layer at shallow depths for example) and traditional inefficient surface irrigation practices as well as inadequate drainage facilities in Nigeria combined to create high water tables under much of the irrigated areas. At Kadawa, Kano River Project for example, where a loamy to sandy loam soil overlies a lateritic iron pan, a water table depth of between 0 and 600 mm at the peak of the rains has been reported (Nwa, 1982; Maurya, 1980). A groundwater survey in the area (62,000 ha) before the project construction in 1970 showed that no water table existed within 1.5 m depth even during the rainy season (NEDECO, 1974). This indicates that in a period of eight years (1970 to 1977) the groundwater had risen by over 1.0 m. In Bacita where the sugar cane plantation for Nigeria Sugar Company is located, the problem of high water table had also been identified (Salami, 1990; Nwa, 1997). This

problem of high water table is also present in Nigerian Brewery Limited (NBL) farm near Baddegi, Bida Local Government Area of Niger State. The original plan for NBL farm was to raise maize crops to serve as raw materials for their brewery industry. However, they were later forced to go into rice production due to the shallow water table that developed. Groundwater problem seems to have been unchecked right from the inception of most irrigation projects including River Basin Projects in Nigeria (Nwa, 1980). Unchecked rising water table results in water logging and salinity problems. This problem has long been recognised. As far back as 1876, Commissions were set up in North India to study the aptly named twin menace of water logging and salinity. The solution of the problem involves in principle the restoration of the balance between groundwater recharge and depletion at a safe water table depth (Smedema, 1992).

Most current irrigation scheduling techniques ignore groundwater contribution to crop water requirements. However, under some conditions, upward flow of water from the water table will reduce net irrigation requirements. The long - term effect may be a lowering of the water table. Scheduling provides information, which irrigation managers can use to develop irrigation strategies for each field on the farm (Martin et al., 1990).

In irrigated agriculture, water shortages and increases in water application costs have multiplied crop production costs in recent years. To help alleviate these water shortages and to reduce water costs, a shallow water table existing or imposed in the root zone of a crop, can compensate for water needs not provided by surface irrigation or rainfall. Water uptake from an existing shallow water table

will supply some of the evapotranspiration requirements if that water table is at the proper crop rooting depth. Each crop - soil combination in a given climatic setting has a unique water table depth that provides the soil - water - air combinations needed for maximum or optimum production.

Agricultural crops vary genetically and physiologically and thus require different soil water regimes for optimum production (Williamson and Kriz, 1970). The soil water regime in humid areas where both water deficits and water excess are common is especially difficult to regulate. Drainage engineers are generally concerned with removing excess soil water as rapidly as economically feasible irrespective of the type of crops. The natural variability of soils, the differences in crop drainage requirements plus a lack of information about those needs, and climatic variability all contribute to the complexity of drainage design problems. Past concepts have emphasised the establishment of perfect drainage, that is, easy passage of surface - applied water well below the root zone at all times.

The direct aim of a drainage system is to lower the moisture content of the upper layers of the soil so that air can penetrate into the soil more easily and become available to the roots of the plants. At the same time, it is necessary that carbon dioxide produced by the roots, microorganisms or chemical reactions in the soil diffuse through the air-filled pores to the surface. On the other hand, the water table should not be lowered so far that a severe water deficiency occurs and irrigation has to be practised. Thus, two limiting depths of the water table need to be considered. One is an upper limit dictated by the demand that roots have for some minimum level of aeration. The other is a lower limit that will

supply adequate water to the roots so as to prevent death or depressed crop yields because of water deficiency. Considerations of this type are valuable in deciding whether to use or how to use a constant or a fluctuating water table.

Proper crop drainage should include utilisation of an existing or an imposed shallow water table for crop production. Preferred drainage practices as indicated earlier would allow a water table at a depth which will supply water by capillary action to crops but not so shallow that roots aeration becomes a problem. The optimum water table depth will be different for different climates, different soils, and different crops. Water quality must, however, be good to prevent salinity and other possible soil problems from affecting crop production that depends on water flux from groundwater. When existing shallow water table contributes to crop water use, significant amount of water, energy and consequently, money can be saved in crop production.

1.1 Objectives

This study was conducted to evaluate the contribution of water table to the seasonal water use or demand of corn (*Zea Mays*) and to develop a model for the water table fluctuations which can be applicable beyond the project location. In particular, the research project aims at:

1. Monitoring and modelling groundwater table movement for application to soil water balance studies.
2. Evaluation of corn yield response to fluctuating water table.

3. Determination of the relationship between water use and corn yield under shallow water table condition.
4. Estimation of groundwater use as a percentage of corn seasonal evapotranspiration requirement.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Corn (*Zea Mays*) grows almost everywhere except in extreme climatic conditions. It is a warm temperature crop performing best at optimum soil temperature of 16 to 18° C and air - temperature of 24 - 30 ° C. Corn has deep and extensive root system. The active root system are in the top 900 to 1000 mm (Plaut, 1993). Seminal roots grow directly from the seed while the adventitious roots grow from the first internode of the stem. The adventitious roots are of more importance in terms of water use. Corn is very efficient in transforming radiant energy into dry matter, and it needs plenty of water and fertilizer. The relation between water applied and the crop yield is almost linear (Musick and Dusek, 1980) and the entire growth stages are sensitive to water stress. Feddes (1985), in reporting results from studies at Davis, California; Fort Collins, Colorado and Logan, Utah showed linear evapotranspiration (ET) - yield relationships in which the regression line passed near the origin. Corn is grown under a wide variety of soil and climatic conditions in the world and water tables may considerably influence crop production. Actual crop production under irrigation in Nigeria in the mid-eighties was estimated at 20,968,908 t corresponding to an irrigated area of 9,664 ha (Adeniyi, 1985).

In many parts of the world, corn simply means grains. However, American and Nigerian corn is called maize. In many areas, particularly Mexico and parts of

South America and Africa, various corn products constitute a large percentage of the daily diet for much of the populace. In industry, corn is used in the manufacture of a wide range of non-food products. Industrial grades of corn are used in expensive paints, soap and rubber substitutes. Cornstarch provides a finish on fabrics, leathers, and paper. It is also used in the manufacture of rayon, explosives, pharmaceuticals, and dextrin, which serve as adhesives. The corn kernel consists of 60 - 62% starch, 9 - 10% protein, 3 - 4% oil and 12 - 16% sugar (Friedman, 1981). To sustain the increasing multipurpose use of corn, it is important to put more land under cultivation at minimum costs. The sustainable utilization of inland valley for agricultural production is, conceivably, one way of relieving some of the current pressure on the natural resource base of upland agroecosystems (Carsky and Masojo, 1992).

2.2 Water Table Monitoring and Applications

2.2.1 Water table measurement

Observation wells and piezometers from which water level data are measured may be existing wells or may be specially constructed. Observation wells are constructed according to a chosen network. They are usually cased or uncased depending on soil stability at each location, and on depth to the water table. A piezometer is a small - diameter pipe driven into an aquifer such that there is no leakage around it and water entrance is only through its open lower end. It indicates the hydrostatic pressure of the aquifer at the specific point where the open lower end is located and is used on semi confined and confined

aquifers. Some methods of measuring and monitoring water levels (Mbajiorgu and Napka, 1988) are:

i. Wetted tape method,

ii. Electrical indicator,

iii. Mechanical sounding, and

iv. Floating level recorder.

In the wetted tape method, which is the method adopted for this study, a calibrated tape to which a weight is attached, is lowered to the end of a vertically buried piezometer tube. The length of the wetted part is subtracted from the lowered length for the depth - to - the water level from the reference point.

The type of aquifer under study, the extent and period over which water levels fluctuates, and the nature of the problems under investigation, are some of the factors which determine frequency of the observation. Where mean maximum, mean minimum and mean annual levels are required, such as in drainage projects weekly observations will suffice. Daily observations may be required in areas bordering watercourses. For a time series of groundwater levels used in studies of groundwater and surface water interaction in aquifer systems, monthly observations over many years will be required.

The density of an observation network depends on the required accuracy, which is inversely proportional to the size of land under study (Boonstra, 1984). In areas of flat topography, if the geology is known to be homogenous then observation wells can be spaced far apart than areas of relief features and

heterogeneous geology. Table 2.1 gives a rough guide as proposed by Boonstra (1984).

Table 2.1: Number of observation wells as a function of size of area and accuracy requirement

Size of area under study (ha)	Number of observation points	Number of observation points per 100 ha
100	20	20
1000	40	4
10000	100	1
100000	300	0.3

Source: Boonstra (1984)

2.2.2 Applications of water table data

Water level data consist essentially of depth - to - the water table or piezometric surface observations made during a year or several years (Mbajorgu and Napka, 1988). They (water level data) are applied in assessing drainage problems, groundwater storage, recharge and discharge, aquifer characteristics, and rates and direction of groundwater flow.

Water resource and land use problems are thus related to water level fluctuations and are managed by measures which may involve lowering the water levels, as in land drainage and reclamation, raising the levels, as in recharge and irrigation, or maintaining a constant level, as in control of land subsidence and acidification.

2.3 Modelling Water Table Movement

2.3.1 Falling water table

The Glover - Dumn drainage formula (Smedema and Rycroff, 1988) describes the rate of fall of water table after the latter has risen instantaneously (at t = 0) to a height h_0 above the base (typical of the behaviour of shallow water table in irrigated land which often rise sharply during water application and then recede more sharply). According to Glover - Dumn, the mid - spacing water table head h_t at time t relates to the head h_0 (at t = 0) as:

$$\frac{h_t}{h_0} = 1.16\, e^{-\alpha t}, \text{ and} \quad \text{.....2.1}$$

$$\alpha = \frac{10\, kd}{\mu L^2} \quad \text{..... 2.2}$$

where t = time (days)

h_0 = initial water table head at time = t_o ,(m)

h_t = water table head at time t ,(m)

α = reaction factor ($days^{-1}$)

μ = drainable pore space (m^3/m^3)

L = drain spacing (m)

d = equivalent depth to the impermeable substratum (m)

k = hydraulic conductivity (m/day)

Combining Eqs. (2.1) and (2.2) and making L the subject of the formula gives (Smedema and Rycroff, 1988):

$$L^2 = \frac{10\,k\,dt}{\mu}\left[\ln 1.16\frac{h_0}{h_t}\right]^{-1} \quad \text{.....2.3}$$

In these formulae it is assumed that the shape of the water table conforms to a fourth degree parabola, which explains the use of the factor 1.16 in Eq. 2.1. Radial resistances are taken into account by replacing the depth D to the impermeable substratum by Hooghoudt's equivalent depth d, making the Glover - Dumn formula applicable to pipe drainage.

A rather similar equation was derived by Bouwer and Schiffgaarde (1962) by assuming that in periods during which recharge, R is zero, the discharge, q is related to the rate of fall of water table (dh / dt) as:

$$q = -C\,\mu\,\frac{dh}{dt} \quad \text{..... 2.4}$$

where q = drain discharge rate per unit area

C = correction factor

$\frac{dh}{dt}$ = rate of fall of water table

and μ is as ealier defined.

The coefficient of proportionality is made up of μ (drainable pore space) and C (a correction factor accounting for the fact that during recession the water will not remain horizontal but falls more rapidly nearer to the drains). The value of C is of the order of 0.7 to 0.9 for h at mid - spacing). Combining Eq. 2.4 with Hooghoudt formula given as:

$$q = 8k\,dh/L^2 \quad \text{..... 2.5}$$

gives:

$$dt = -C \frac{\mu L^2}{8k\, dh} dh \qquad \text{.....2.6}$$

Integrating Eq. 2.6 from $t = 0$; $h = h_0$ and $t = t$; $h = h_t$, and assuming $C = 0.8$ (Smedema and Rycroff, 1988) gives:

$$L^2 = \frac{10\, k\, dt}{\mu} \left[\ln \frac{h_0}{h_t} \right]^{-1} \qquad \text{.....2.7}$$

2.3.2 Fluctuating water table

Hooghoudt's simple formula (Eq. 2.5) may be used to show the non - steady response to periodic rainfall or irrigation (Smedems and Rycroff, 1988). In this Hooghoudt's equation the drain discharge (q) is linearly related to the mid - space water table head (h):

$$q = \frac{8kd\, h}{L^2}, \text{ from Eq. 2.5}$$

The variation of the drain discharge with time is thus also linearly related to the variation in time of water table head:

$$\frac{dq}{dt} = \frac{8kd}{L^2} \frac{dh}{dt} \qquad \text{..... 2.8}$$

If the groundwater body is recharged by rainfall or by another source (R) and is depleted by drain discharge (q), it follows that the water table will rise when $(R - q) > 0$ and fall when $(R - q) < 0$. By analogy with Eq. 2.4, De-Zeeuw and Hellinga (1960) proved that the water table fluctuation may be described by:

$$\frac{dh}{dt} = \frac{(R - q)}{C\mu} \qquad \text{..... 2.9}$$

where R = groundwater recharge (mm)

and other symbols are as earlier defined.

Combining Eqs. 2.8 and 2.9 and taking C = 0.8 gives

$$\frac{dq}{dt} = \frac{10\,kd}{\mu L^2}(R - q) = \alpha(R - q) \quad \text{..... 2.10}$$

Thus, the change in drain discharge (dq/dt) is proportional to the excess recharge (R - q).

Integration of Eq. 2.10 between the limits t = t-1, q = q_{t-1} and t = t, q = q_t gives:

$$\int_{q_{t-1}}^{q_t} \frac{dq}{(R-q)} = \int_{t-1}^{t} \alpha\, dt \quad \text{..... 2.11}$$

$$\text{or, } \frac{(R - q)_t}{(R-q)_{t-1}} = e^{-\alpha\Delta t} \quad \text{.....2.12}$$

which may be simplified to:

$$q_t = \frac{q_{t-1}e^{-\alpha\Delta t}}{q_{t-1}} + R_{\Delta t}\left(1 - e^{-\alpha\Delta t}\right) \quad \text{.....2.13}$$

where Δt = time interval (days)

$R_{\Delta t}$,= mean value of groundwater recharge during the time interval t-1 to t, and α and R are as earlier defined in Eq. 2.2

Using the linear relationship between q and h of Eq. 2.5, it also follows that:

$$h_t = h_{t-1}\, e^{-\alpha\Delta t} + \frac{R_{\Delta t}}{0.8\mu\alpha}\left(1 - e^{-\alpha\Delta t}\right) \quad \text{..... 2.14}$$

when R = 0,

$$h_t = h_{t-1}e^{-\alpha\Delta t} \quad \text{..... 2.14a}$$

Equations 2.13 and 2.14, first derived by De - Zeeuw and Hellinga (1960); may be used to model drain discharge and water table fluctuations on the basis of (historical) weather data given the value of the reaction factor α.

$$\text{The reaction factor } \alpha = \frac{10\,kd}{\mu L^2} \qquad \text{(see Eq. 2.2)}$$

is a direct index of the intensity with which the drain discharge rate responds to change in the recharge. Values of α generally vary from 0.1 to 0.3 for land with a slow response to 2.0 to 5.0 for rapidly responsive land (high kd value, low drainable pore space) (Smedems and Rycroff, 1988). The reaction factor α may be calculated according to Eq. 2.2 (from known kd, L and μ values) but since the μ - value is especially difficult to determine, best estimates of α are obtained by observing the actual response of the system in the field. From Eqs. 2.13 and 2.14, it follows that in periods during which there is no recharge (R = 0):

$$\alpha = \frac{\ln q_{t-1} - \ln q_t}{\Delta t} = \frac{2.30\left(\log q_{t-1} - \log q_t\right)}{\Delta t} \qquad \text{..... 2.15}$$

$$\alpha = \frac{\ln h_{t-1} - \ln h_t}{\Delta t} = \frac{2.30\left(\log h_{t-1} - \log h_t\right)}{\Delta t} \qquad \text{..... 2.16}$$

Observations (of q_t or h_t values) are best during periods of low evaporation shortly after the end of a few good rainy days when the recharge to the groundwater has ceased and the water table start receding. The Equation 2.14a was adopted for this study for the prediction of the groundwater table fluctuation, since the model equation is mainly for dynamic water table condition. Equation 2.16 was used to estimate the mean reaction factor (α).

2.3.3 Time series expression

In addition to using equation 2.14a to simulate water table fluctuations, stochastic models can also be adopted. Jimoh (1999) successfully used Fourier series to model daily rainfall events in Nigeria. This involves using the historical rainfall records to estimate the model parameters of an appropriate model, which may then be used to simulate the desired length of rainfall series. An extension of the usefulness of Fourier series applications can be adopted in simulating water table fluctuation especially because the fall and rise of this water table depends on rainfall amount.

The Fourier series for the parameters of a first-order model at daily time step is expressed as (Jimoh, 1999):

$$Y(t) = A_0 + \sum_{i=1}^{Cm} A_i \mathrm{Cos}(i\tau) + B_i \mathrm{Sin}(i\tau) = \sum_{j=0}^{j=k} \beta_j X_{ji} \quad \text{.....2.17}$$

Where I is the harmonic, C_m the maximum harmonic required for the series, A_i and B_i (or β_j) are the coefficients of the series, X_{ji} the Cosine or Sine of ($i\tau$) for a given harmonic I, $Y_p(t)$ is the transformed model parameter at day t, and

$$k=2C_m + 1.$$

In order to fit the Fourier series at a weekly time step, τ is modified to become (Jimoh, 1999):

$$\tau = \frac{\pi(WK_{day} - 3.5) - 182.5}{182.5} \quad \text{.....2.18}$$

where WK_{day} is the Julian day at the end of the week.

The Fourier series for the parameters of a first order model at a daily/weekly time step may be expressed as:

$$Y(t) = \log_e\left(\frac{H(t)}{1-H(t)}\right) \quad \text{.....2.19}$$

or

$$H(t) = \frac{\exp(Y(t))}{1+\exp(Y(t))} \quad \text{.....2.20}$$

where H denotes the value of the water table depth. Equation 2.19 holds for values of H(t) of less or equal to 1(m).

2.4 Modelling Crop Yield.

Crop simulation models are a combination of mathematical equations and logic used to conceptually represent a simplified crop production system. Crop models are a principal tool needed to bring agronomic sciences into the information age. Ritchie (1991) reported that research results abound regarding site specific crop yield models and factors that affect them. He added that such site specific models cannot easily be used for predicting crop performances for other sites and years .

An ideal generic model should at least take certain basic factors into consideration for estmation of crop yields. These factors according to Ritchie (1999) should include growth and development. For growth, the mass accumulation deals with the adsorption of photosynthetically active radiation (PAR) for the assimilation of carbon. Thus, mass growth is dependent on the

amount of PAR received from the sun and the amount of the leave surface available for the adsorption of PAR for photosynthesis. Environmental factors and stresses affecting the cell expansion are different form those that affect mass growth. The duration of plant growth also has two distinctly different features; namely phasic and morphological development. Phasic development involving changes in stages of growth is associated with major changes in biomass partitioning patterns. This feature is of major importance in the analysis of risk associated with crop production. Morphological development refers to the beginning and ending of plant organ development within the whole plant cycle. Modelling of morphological is attempted in more mechanistic model to provide an estimate of the number of leaves, tillers, and grains that will be produced by a plant. The genotypic characteristic affecting plant response to photoperiod are also an important determinant of the duration of growth in addition to the temperature influence.

De-Vries and Spitters (1991) argued that crop yield simulation should be discussed by crop production level rather than by discipline. They distinguished four levels of crop production. These are: potential yield (limited by solar radiation and temperature); nitrogen-limited yield (controlled by soil nitrogen and soil water); and minerals-limited yield (controlled by phosphorous and other minerals).

A list of crop simulation models for maize include (Ritchie, 1991):

CERES – Maize V I; CERES-Maize V.2.0; CORNF; VT-Maize, GAPS; and CUPID. A model for research on a crop system is complex, but for application, we

need models that are easy to use. Simplicity in use can be obtained in at least three ways: through (i) regression equation from results of comprehensive models; (ii) summary models made from large models; and (iii) simulation with comprehensive models utilising a user-friendly interface (De-Vries and Spitters, 1991). The advantage of this procedure would be that many targeted summary models could be derived from one comprehensive model, while the old fashion way of developing simple models by regression from trial data is slow and expensive. Several simple models for prediction purposes combine simulation and regression equations. This may be a step towards simple model fully derived from larger ones. For empirical models, calibration of key parameters is the only way to progress. The accuracy of yield simulation depends on the degree to which the model structure is adequate, parameters are precise, and environmental data are accurate. Thus crop yield Y can be expressed as:

$$Y = f(R_s, T_t, R, \rho, N, O) \quad \text{.....2.21}$$

Where: R_s = Solar radiation (MJ/m^2)

T_t = Mean daily temp (^oC)

R = rainfall or irrigation (mm)

ρ = Bulk density of soil (g/cm^3)

N = Nitrogen (soil or applied) (kg/m^2)

O = Other minerals (kg/m^2)

The development of the actual expression for Eq 2.21 is complicated and time consuming. The solution of Eq 2.21 is usually obtained by keeping some of the

variables constant and varying one or two of interest. Consequently, some investigators (Hanks, 1974; Feddes, 1982; Feddes, 1985) tried to solve Eq 2.21 by considering water supply to the crop as the limiting factor. In spite of the above simplification, the result of such analysis has been very satisfactory.

2.5 Yield Response to Water Table Depth

Water movement by capillary rise from a water table into an active plant root zone is recognised as an important water resource in agriculture (Campel et al., 1960; Chaudhary, et al., 1974 and Wallender, et al., 1979). Numerous field and lysimeter experiments (Chaudhury et al., 1975; Williamson and Kriz, 1970) have been conducted to determine crop response to water table depths, and the effect of long - term flooding on crop response. Effects of shallow water tables on crop yields have been determined for example by Hooghoudt (1952) who showed that sugar beet yields in the Netherlands were less when the water table was 0.4 to 0.6 m deep than when it was 0.9 to 1.5 m deep. Tovey (1964) stated that the optimum water table depth for alfalfa production in Nevada, United States of America, was 0.6 m while Williamson and Van Schilfgearde (1965) as cited by Benz et al. (1985a) found that the optimum water table in North Carolina ranged from 0.76 to 0.86 m for corn and from 0.46 to 0.76 m for soya bean. In studies with corn and sugar beet on sandy soil, Benz et al. (1981) found that relatively small increases in water table depths beyond the optimum range increased the surface irrigation requirement for maximum crop production.

Most of the earlier work in determining the relationships between crop yields and depth to water table was conducted in field experiments where the elements of nature could not be controlled. Thus, conflicting results were obtained in successive years. Goins et al. (1966) in a green house experiment with combination watering, found that corn stalk yields increased significantly by increasing the water table depth from 15 to 80 cm. Investigation with corn in field lysimeters at Raleigh, North Carolina showed that combination watering caused yields to increase as the depth to the water table increased.

Novak (1993) reported that shallow water table with depth less than or equal to 1.5 m below the soil surface strongly influenced the water regime of soil and plants during dry and average seasons. During the wet year the contribution of shallow groundwater table on soil water regime was found to be negligible. Hanks and Hill (1980), however, gave a range of 1.5 to 1.8 m as the critical depth for groundwater table and concluded that dropping the value below those depths can decrease evapotranspiration and subsequently, maize yields, will decrease too. These studies have clearly demonstrated that species differ in their response to imposed root soil environments. Varietal and genotype differences within species are expected also (Williamson and Kriz, 1970).

Numerous laboratory and field experiments on the effect of water table depth on crop yields have been conducted at various locations, but it is difficult to transfer the results from one location to another because of different soil types, watering procedures, and climatic conditions. In order to specify an optimum water table depth, it is necessary to know at least the crop species, soil

characteristics and watering procedure. The discussion above shows that plant response to the soil physical environment imposed by maintenance of water tables at specific depths requires further study (Williamson and Kriz, 1970; Omotowoju, 1992).

2.6 Yield Response to Water Use

Doorenbos et al. (1980) reported that many complex processes of biological, physical, physiological and chemical nature are involved in the relationships encountered between crop and water, and that this complexity has rendered the level of success attained in studies too low to justify the magnitude of efforts that have been put in over the years. Hanks and Hill (1980) further observed that these complex processes are only partially understood. Other researchers (Hanks and Hills, 1980; Doorenbos et al., 1980; Vaux and Pruitt, 1983; Omotowoju, 1992) agreed that further research into these complex processes are required as the present available literature are full of contradictions and lacking in basic information.

Miguel et al. (1988) advanced the development of a method that simultaneously simulates the transport of water through a root and soil system that would provide a more realistic approach for simulating the transient water content in the root zone of a soil. However, such method could easily become too cumbersome for practical use. Additional research is therefore, required, such that, the resulting simulation model (yield - water use relations) will be of practical use in a large variety of agricultural studies.

2.6.1 Modelling Yield Response to Water Use

When considering production - water use relationships one should in fact not consider the water use by soil plus crop, that is evapotranspiration, but the water used by the crop itself only, that is, transpiration (Feddes, 1985). This is because dry matter production / photosynthesis and transpiration are directly related through the processes of diffusion of carbon dioxide and water vapour through the stomata of the leaves. In practice, partitioning of evapotranspiration between transpiration and soil evaporation is often difficult, especially for conditions of partial soil cover. With the aid of computer simulation of the soil water balance, however, one might be able to separate transpiration and soil evaporation reasonably well.

At constant atmospheric carbon dioxide (CO_2) concentration, and assuming that water use efficiency for dry matter production of a crop, Y/T (yield to transpiration ratio), is proportional to the water use efficiency for net photosynthesis of individual leaves, P/T (net photosynthesis to transpiration ratio), according to Bierhuizen and Slatyer (1965).

$$\frac{P}{T} = \frac{Y}{T} = \frac{A}{\Delta e} \qquad \text{.....} \qquad 2.22$$

where the proportionality constant A has dimensions of mbar (Y in kg, T in kg), or kg. $ha^{-1}mm^{-1}$ mbar when expressing Y in kg. ha^{-1} $(day)^{-1}$, T in mm $(day)^{-1}$ and Δe,the water vapour pressure deficit from the difference in the leaf and air water vapour pressures being functions of the leaf and air temperatures, respectively in mbar. Equation 2.22 implies that for a specific crop, variation in Y/T from one

climatic region to another can mainly be explained by differences in Δe. De - Wit (1958) as reported by Feddes (1985) had earlier suggested that under high solar radiation conditions not restricting transpiration, Y/T is proportional to the level of solar radiation, expressed as free water or pan evaporation, E_o (assumed to be equal to potential transpiration). That is,

$$\frac{Y}{T} = \frac{M}{E_o^x} \qquad \text{..... 2.23}$$

where x = 1 for semi -arid zones and x = 0 for temperate zones, and M is the proportionality constant. De - Wit (1958) as given by Feddes(1985) further indicated that generally Y/T relationship are hardly affected by small variations in water and nutrient availability.

It has been shown (Feddes, 1985) for a number of field crop data that the use of Eq. 2.22 is superior to that of Eq. 2.23. Apparently, E_o in Eq. 2.23 does not reflect the vapour pressure deficit, Δe well enough, and hence it is a poor parameter to normalise climatic differences.

From Eqs. such as 2.22 and 2.23 one can easily derive relative dry matter yield - transpiration relationships. Assuming that maximum yield, Y_{max}, is reached at maximum transpiration, T_{mx} for a crop growing in a well watered soil, one can give an expression analogous to Eq. 2.23.

$$\frac{Y_{max}}{T_{max}} = \frac{A'}{\Delta c} \qquad \text{..... 2.24}$$

If the slopes of the linear relationships of Eqs. 2.23 and 2.24 are the same, that is A = A', one may write, dividing Eq. 2.22 by Eq. 2.24..

$$\frac{Y}{Y_{max}} = \frac{T}{T_{max}} \quad \text{..... 2.25}$$

which is also referred to as the model of Hanks (1974). Feddes (1985) applied Eq. 2.25 for dry matter yield of sorghum and dry matter and grain yields of maize with satisfactory results. As Hanks (1983) correctly remarked, Eq. 2.25 is most suitable for comparing treatments within one year, because Y_{max} may vary from year to year. The attractiveness of the use of Eq. 2.25 is that instead of slope A, maximum yield Y_{max} has to be determined.

The models discussed in the Eqs. 222 to 2.25 are linear, that is, dry matter production increases linearly with transpiration until potential transpiration is reached. Feddes et al (1978) and Feddes (1982) have given a mathematical derivation of the growth rate of a crop as a hyperbolic function of the growth factor (water) with the maximum growth rate as the upper limit and the efficiency of utilisation of this factor as the initial slope of the hyperbola.

In order to obtain a better generalisation of Y - ET relationships for different years and regions Shalhevet et al. (1981) as reported by Feddes (1985) applied a normalised relationship analogous to Eq. 2.25 yielding,

$$\frac{Y}{Y_{max}} = \frac{a\,ET}{ET_{max}} - b \ , \quad \text{..... 2.26}$$

in which ET_{max} is the maximum evapotranspiration and a and b are the constants of regression.

Feddes (1985) also reported the development of a Y - ET relationship starting with the assumption of a maximum yield level at each evapotranspiration

level, varying from $Y = Y_{max}$ at $ET = ET_{max}$ (the origin of the function) and linearly increasing for $ET < ET_{max}$, according to (see Fig. 2.1):

$$\left(1 - \frac{Y}{Y_{max}}\right) = \beta\left(1 - \frac{ET}{ET_{max}}\right) \quad \text{..... 2.27}$$

where β is the dimensionless slope to be determined from field experiments, for which the quantities Y_{max}, ET_{max}, Y and ET have to be calculated or measured.

Since the 1960s, crop growth simulation models and soil water balance models have been developed with large variation in complexity. In general, it is preferred to have a crop growth - soil water model that is as simple as possible, having parameters few enough to be measured directly or indirectly (Passioura, 1973), and where the crop and soil system have a clear interaction with each other.

After a crop growth - soil water simulation model has been tested carefully with field experiments and the proper crop and soil parameters have been evaluated, it is possible to carry out numerical experiments on the computer. Ideally the crop - soil system on computer should react upon making changes in the environmental conditions the same way as in the field. Only the numerical experiments will go much faster than the field experiments. Such models can be a helpful tool to predict influences of irrigation regimes on crop yield (Feddes, 1985).

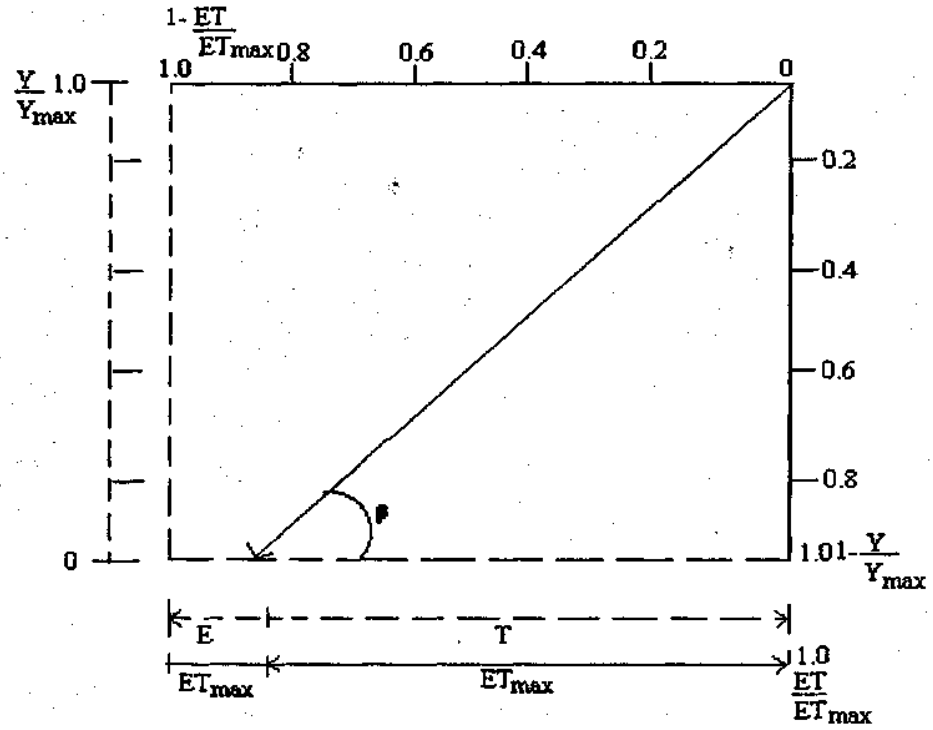


Fig. 2.1: Relative yield decrease versus relative evapotranspiration decrease according to equation 2.27 with origin at the upper hand corner (Feddes, 1985)

2.7 Groundwater Flux

The flow of water in the soil may be described by Darcy's law (Wesseling, 1968):

$$V = -k \text{ grad } \theta \qquad 2.28$$

where V = flow velocity

k = hydraulic conductivity

θ = potential or energy status of the water in the soil.

Darcy's law applies also to the movement of soil moisture (unsaturated flow). The difference between the unsaturated zone and the saturated zone is that in the latter one, k may be considered as a constant. In unsaturated zone, k is a function of the moisture content or the suction of the soil moisture.

When rather shallow water tables are present and the soil is covered by plant the water supply to the roots, except for precipitation, depends on the flux from the groundwater table, that is, on the height of capillary rise (Brandyk and Wesseling, 1985; Brandyk et al., 1993).

One dimensional steady state flow can, according to Darcy's, law be written as:

$$q = -k(h)\left(\frac{dh}{dz} + 1\right) \qquad 2.29$$

where: q is the groundwater flow or discharge (mm/day),

k is the hydraulic conductivity (mm/day),

h is pressure head (negative in unsaturated soil) (mm),

z is vertical co-ordinate, positively upward and zero at the phreatic surface

Equation 2.29 can be solved for any region of z by separating the variables and integrating yielding:

$$\int_{z_1}^{z_2} dz = \int_{h_1}^{h_2} \frac{-1}{1 + \frac{q}{k(h)}} dh \qquad \text{..... 2.30}$$

For a flow in a layered soil profile, Eq 2.29 can be applied for each separate layer. Hence:

$$z = -\int_{0}^{h_1} \frac{dh}{1 + \frac{q}{k_1(h)}} - \int_{h_1}^{h_2} \frac{dh}{1 + \frac{q}{k_2(h)}} \text{.....} - \int_{h_{n-1}}^{h_n} \frac{dh}{1 + \frac{q}{k_n(h)}} \qquad \text{..... 2.31}$$

where: h_1, h_2, ..., h_n are the pressure heads at elevations of various layers, z_1, z_2,...., z_n. In this way the integration may proceed until the last value h_n is reached or until capillary rise reaches the soil surface. During integration care must be taken to use the hydraulic conductivity for the layer at that moment under consideration.

For several functions k(h), as exponential, power functions and constant values, Eq. 2.31 can be solved analytically. A practical application of the steady state calculation is computing the groundwater table depth that yields the optimum production for a soil profile covered by field crops. The depth of water table and the allowable limits within which it should be maintained are soil - dependent. The k(h) function can be evaluated directly from measurements or approximated from soil water characteristics, h(0) and vertical saturated hydraulic conductivity k_s, using for example, methods proposed by Millington and Quirk (1961), Kunz et al. (1968), Van Genuchten (1980) and Adeoye and Maurya (1981).

Using tensiometers placed at various depths in the soil, in a circular lysimeter (56 cm internal diameter) for constant water table depths, Adeoye and Maurya (1981) were able to measure dh/dz in Eq. 2.29, and from field data, the hydraulic conductivity of the soil as a function of suction was computed from Eqs. 2.29 and 2.30. Two simple functions of the form:

$$k(h) = A_1 h^{B_1} \quad \text{.....2.32}$$

and $$k(h) = A_1 \exp(B_1 h) \quad \text{.....2.33}$$

where :A_1 and B_1 are empirical constants whose values depend on climate, crop covered and soil type, were tried using the hydraulic conductivity data generated from the field data. The fit gave a correlation coefficient of -0.76 for the power function (Eq. 2.32) and -0.91 for the exponential function (Eq. 2.33) which was used to determine the maximum water flux for a given water table depth.

Higher groundwater table depths are generally permitted in sandy soils than in loam and clay soils since the latter have very limited air - filled pores in the capillary fringe above the groundwater table. This effect of soil type has been expressed as minimum depth of groundwater table required for maximum yields for most crops as follows (Doorenbos and Pruitt, 1977):

Sand, rooting depth + 200 mm

Clay, rooting depth + 400 mm

Loam, rooting depth + 800 mm.

2.8 Soil Water Balance

For developing an efficient and economic irrigation schedule, the knowledge of groundwater table contribution and irrigation requirement of the crop, together with its production functions under different soil water regimes is of practical importance. Doering (1963) reported a flow rate of 0.91 ± 0.061 mm/day from a groundwater table located at a depth of 1.52 m in a bare soil and the flow rate at the same water table depth and for the soil type covered by plant, increased to 3.71 ± 0.089 mm/day due to evapotranspiration. This suggests that an upward flow of water from the groundwater was equal to evaporation in bare soil and equal to evapotranspiration in cropped fields.

All aspects of irrigation management, and especially irrigation scheduling, require an understanding of the soil water balance. Using a soil water balance to manage irrigation involves estimating the amount of water in the crop root zone at any time. The major components of soil water balance are illustrated in Fig. 2.2. In order to describe the change in the amount of water in a crop root zone over a period of time, the soil water balance equation is used (Martin et al., 1990; Iwata et al., 1995):

$$S_e - S_b = d_n + P_e + U_f - ET - D_r \quad \text{.....} \quad 2.34$$

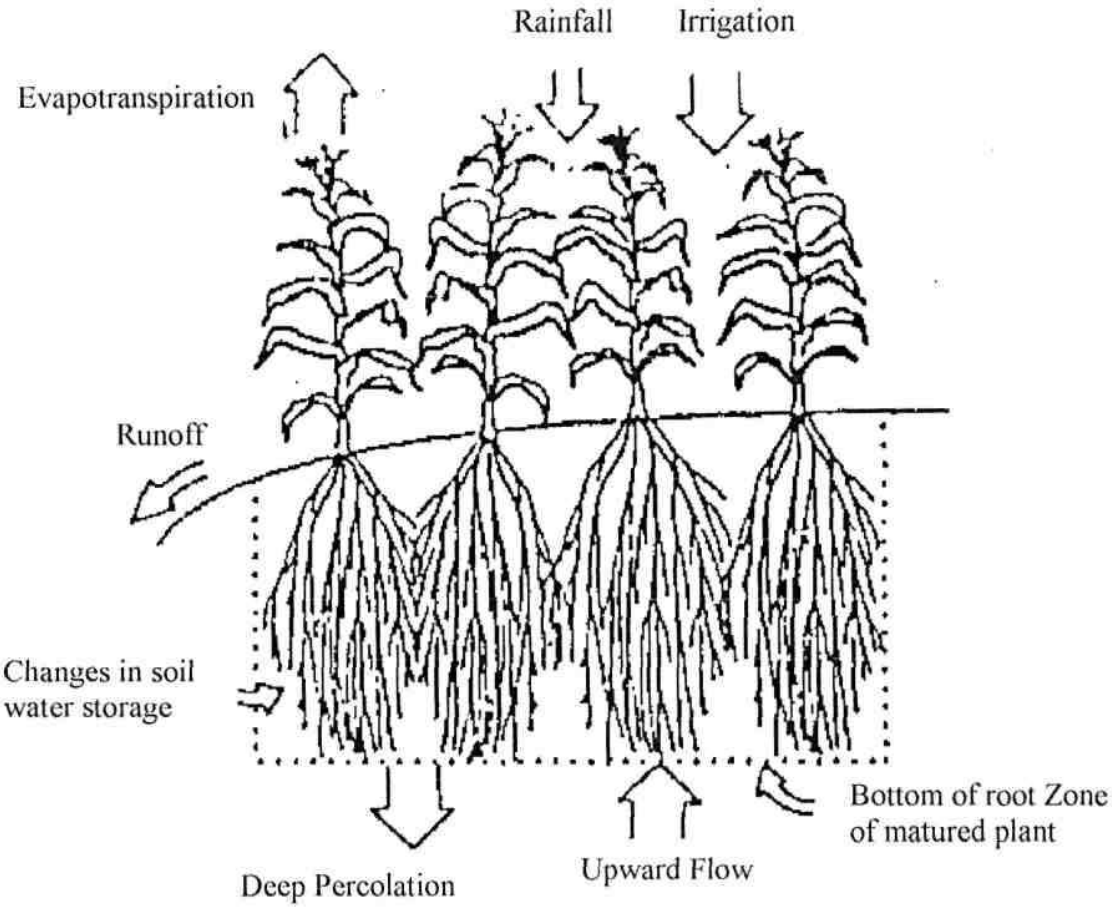


Fig. 2.2: The major components of soil water balance (adapted from Martin et al., 1990.)

where S_e and S_b are the amounts of water in the root zone in mm at the end and beginning of the period. Additions to the soil water balance include the net irrigation (d_n) in mm, effective precipitation (P_e) in mm, and any upward flow (U_f) in mm from a shallow water table. The losses of water from the root zone are drainage below the root zone (D_r) in mm and evapotranspiration in mm. The evapotranspiration ET can alternatively be calculated from (Abdulmumuni and Misari, 1990; Di – Stefano and Ferro, 1997):

$$ET = kc \, . \, ET_R \qquad \text{.....} \qquad 2.35$$

where ET_R is the grass reference crop evapotranspiration and kc is the crop coefficient.

2.9 Groundwater Quality

In many parts of the world the soil is not suitable for successful agriculture. Some of these areas are unproductive because the salt content of the soil is too high. World-wide, 100 million ha of irrigated land is at risk from salinization or waterlogging. The challenge is to keep this land in production (Hisgen, 1993).

There are two main causes of high soil salinity (Waite, 1981):

(i) Naturally occurring salts in the soil either because the land has only recently been reclaimed from the sea or because the ancient rocks which have formed the soil had a high salt content.

(ii) Secondary salinization occurs in areas which have received large quantities of water (either through flooding or irrigation) sufficient to raise the water table close to the soil surface. These can result in high rates of evaporation from

the groundwater (in areas of high potential evaporation) and salts are rapidly deposited in the upper layers of the soil.

Salt concentration is normally expressed in mg/l. Soil salinity concentrations are also commonly expressed in yet another indirect form using the electrical conductivity (Ec - value) of the soil solution. The system developed by the United States - Salinity Laboratory (United States Department of Agriculture(USDA), 1954) is most commonly used for the classification of salty soils (Table 2.2). The diagnostic parameters in this system are the Electrical conductivity, Ece (indicative of the osmotic problems) and the Exchangeable Sodium Percent, ESP - value (indicative of the dispersion problems).

Table 2.2: The US Laboratory Classification System for Salty Soils

	Ece≤ 4 mS/cm	Ece>4 mS/cm
ESP ≤ 15%	non - saline soil non - sodic soil	saline soils
ESP > 15%	Sodic soils	saline soils sodic soils

Source: USDA (1954)

The PH - value of salty soils often fits the following (USDA, 1954):

Saline soils PH < 8.5)

Saline sodic PH ≈ 8.5) determined in the saturation extracts

Sodic soil PH = 8.5 - 10)

2.9.1 Salinization From Groundwater (Capillary Salinization)

The groundwater may evaporate directly from the water table when the latter occurs within the evaporation zone, or it may be drawn from deeper down as the evaporation itself will create a gradient for upward capillary flow from the water table into the evaporation zone. As the water evaporates the salts remain behind in the evaporation zone. Thus, for this type of salinization to take place, saline groundwater must occur within such a depth that upward flow is able to reach the evaporation zone (Smedema and Rycroff, 1988). When net upward water movement occurs from the salty water table the result is the accumulation of salt within the root zone. However, the yearly water and salt balance is a function of groundwater depth. The groundwater table depth above which salt accumulation occurs in the overlying soil profile is called the critical depth (Toth, 1993).

2.9.2 Critical water table depth

Capillary flow upwards from a water table can reach great heights but the rate of flow generally decreases with increasing height above the water table. Since the rate of upward salt movement is proportional to the rate of upward flow, the rate of upward salt movement also decreases as the distance between the evaporation zone and the water table increases (Smedema and Rycroff, 1988). The distance at which the upward capillary flow becomes too small for any significant upward salt movement is called the critical capillary height (Hc). Its value depends on:

(i) Soil type: soils with a large proportion of their pores of a small size such as fine sandy laom, silty loam, have large Hc values. Coarse sand has a small Hc value whereas well structured medium to fine soils have intermediate values.

(ii) Salt concentration of the groundwater: upward salt movement is the product of the flow rate and salt concentration. Hence Hc values will increase with increasing groundwater salinity. In general, very little capillary salinization will occur provided the salt concentration in the upper groundwater layer remains < 1,000 mg/l (EC $\leq$ 1.5 mS/cm).

Crop evaportranspiration can be affected by soil salinity which is partly caused by reduction in water availability due to salinity, reduced growth due to nutritional imbalances and toxic effects of specific ions in soil water solution. In addition uptake of soil water by plant can be drastically reduced due to the higher osmotic pressure of the saline soil water (Doorenbos and Pruitt, 1977).

Shallow water table of satisfactory quality can be used as a resource to minimise irrigation and drainage but requires close observation of potential salinity or specific ion toxicity hazards (Wallender et al., 1979). Details of crop tolerance with respect to soil salinity are tabulated by Food and Agricultural Organisation,FAO (1976).

Several studies (Ayers and Shoneman, 1984; Grimes and Herderson, 1984; Namken, et al., 1969) as cited by Ayers and McWhorter (1985) have shown that many salt tolerant crops such as corn, cotton, alfalfa, barley, are capable of extracting significant quantities of water from a saline water table. Wallender et

al. (1979) found that cotton extracted up to 60% evapotranspiration (ET) from a saline (6 dS/m) water table. Ayers and Shoneman (1984) found that cotton extracted up to 49% of its ET from a saline (10 dS/m) water table depending on the irrigation treatment. In order to effectively utilize saline and non saline water tables as a water supply, future drainage system designs will have to include water extraction by plants. Effective water management in the future will require that the irrigation and drainage for irrigated areas be operated as a single system (Ayers and McWhorter, 1985).

By pooling all the data for seasonal uptake from studies of alfalfa, cotton and barley, Grimes and Henderson (1984) were able to develop a regression equation (accuracy of fit, not stated) for the percent of season ET as a function of water table, salinity and depth. The resultant equation is:

$$WT\% = 43.3 + 46.93D - 18.5D^2 - 7.542\ Ec + 0.128\ Ec^2 + 1.678D\ Ec \quad .....2.36$$

Where: WT% = percent of season ET

Ec = electrical conductivity of the groundwater (dS/m)

D = depth to the water table in meters.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Research Project Location

An Inland Valley located in Badeggi, Bida Local Government Area of Niger State, Nigeria, near the National Cereal Research Institute (Lat. 9° 45′ N, Long. 6° 07′ E) was selected as representing both high and low water table conditions. The soil texture varied slightly from sandy soil in the inland valley fringes to sandy clay loam in the valley bottom (Dirisu, 1997). The additional physical characteristics of the soils are given in Table 3.1. The sodium absorption ratio (SAR) range was 0.3 to 0.7, the pH of the saturation extract, 8.3 to 8.5 (Table 3.2). Preliminary survey of the project location showed that the groundwater table from May to October was usually within 0 to 600 mm below the ground surface. In the remaining part of the hydrologic year (November to April), the water table dropped to as far as 1 m below the ground surface at the valley fringes. The major crops raised in these farms during the rainy season include maize, guinea corn, rice and soya bean.

Table 3.1: Some Physical Soil Properties of the Project Site

(a) Dry Season

	Soil Layers (cm)							
	0 - 20		20 - 40		40 - 60		60 – 80	
	HWT	LWT	HWT	LWT	HWT	LWT	HWT	LWT
Wet bulk density (g/cm^3)	2.07	1.84	2.0	2.0	2.44	1.90	2.14	2.09
Dry bulk density (g/cm^3)	1.90	1.79	1.8	1.94	1.84	1.84	1.92	1.88
Porosity (%)	8.21	3.72	9.0	3.03	9.80	4.12	10.28	10.04
Hydraulic Conductivity (m/hr)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12

(b) Wet Season

	Soil Layers (cm)							
	0 - 20		20 - 40		40 - 60		60 – 80	
	HWT	LWT	HWT	LWT	HWT	LWT	HWT	LWT
Wet bulk density (g/cm^3)	2.25	2.08	2.02	2.22	2.04	2.03	2.15	2.11
Dry bulk density (g/cm^3)	1.89	1.79	1.82	1.94	1.83	1.84	1.91	1.88
Porosity (%)	16.0	13.94	9.90	12.61	10.29	9.06	11.16	10.90
Hydraulic Conductivity (m/hr)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12

[1]HWT = High water table plot (≤ 500 mm);

[2]LWT = Low water table plot (≥ 600 mm)

Table 3.2: Groundwater Quality of the Study Location

						Major constituents (mg/l)					
Depth to water	Ec	ESP	pH	SAR[b]	Na^+	Ca^{2+} + Mg^{2+}	K^+	SO_4^{2-}	CO_3	Cl^-	HCO_3^-
(cm)		[a]									
0 – 30	0.4	0.5	8.3	0.3	0.8	11	0.3	1.0	Nil	0.4	0.01
30 – 60	0.3	1.0	8.4	0.7	1.6	12	0.3	1.1	Nil	0.4	0.01
60 – 90	0.5	0.6	8.5	0.4	0.9	11	0.3	0.3	Nil	0.2	0.01

$$^1\mathbf{ESP} = \frac{100\,(0.015\ \mathrm{SAR})}{1 + 0.015\ \mathrm{SAR}}$$

$$^2\mathrm{SAR} = \frac{Na^+}{\sqrt{\frac{(Ca + Mg)^{2+}}{2}}}$$

3.1.1 Geological Features

The geology of Niger State is divided into two distinct geological zones, the basement complex and Nupe sandstone. Each geological formation exhibits different topographical and soil features which are highly influential in determining existing settlement.

The study area is within the Nupe sandstone. The Nupe sandstone consist of weakly cemented fine to coarse grained clays, silt stones and sandstones with locally interbedded thin beds of carbonaceous shales. Lenses of conglomerate and pebbly sandstone also occur particularly near the contact with the underlying basement rocks (Maxlock, 1980). Considering the structural and hydrogeological land form and major aquifer units, the study location belongs to both semi-confined and confined aquifers (Federal University of Technology, Minna Consultancy - FUTMIN, 1991).

3.1.2 Meteorological Characteristics

The project location falls within the southern Guinea zone (Keary, 1959). This agro - ecological zone consists of open, savannah wood land. The rainfall distribution is unimodal. The average annual rainfall amounts to 1000 - 1200 mm and most of the rains fall in August / September. The mean rainfall during the month of maximum rainfall is 200 - 300 mm/month. The hydrologic ratio, λ,defined as the ratio of degree of dryness to wetness is 0.40 to 0.60. The sunshine hours and solar radiation can be described as of moderate drying power. The effective

temperature factor is within cool / warm zone (Federal University of Technology, Minna Consultancy - FUTMIN, 1991). Tables 3.3 to 3.6 give the average long term values of the major climatic parameters of the study area.

Table 3.3 Rainfall amount (mm) for 1996 - 1999 at study location

Month	1996	1997	1998	1999	Average(1965-1995)
Jan.	0	0	0	0	1.0
Feb.	0	0	0	0	2.2
Mar.	0	64.9	0	0.8	21.0
Apr.	12.6	53.4	67.1	112.1	57.0
May	199.9	129.3	213.2	135.4	130.2
Jun.	190.7	279.2	75.5	196.8	173.5
Jul.	201.8	216.0	239.7	264.1	214.7
Aug.	326.1	227.2	145.5	194.5	228.4
Sep.	107.5	145.7	153.7	153.7	205.5
Oct.	41.3	135.4	103.0	98.0	85.8
Nov.	0	7.3	0	0	1.5
Dec.	0	0	0	0	0.5
Total	1079.9	1258	997.7	1158.2	1121.3

Source: National Cereal Research Institute's (NCRI) Meteorological Station.

Table 3.4: Relative humidity (%) for 1996 - 1999 at study location

Month	1996	1997	1998	1999	Average (1965-1995)
Jan.	67.0	57.1	52.0	54	59.1
Feb.	65.0	29.6	43.0	57	52.9
Mar.	65.0	54.2	33.0	68	61.6
Apr.	65.0	70.2	68.0	70	70.6
May	78.0	77.0	82.0	79	77.4
Jun.	83.0	82.0	82.0	85	81.7
Jul.	86.0	84.0	85.0	87	84.5
Aug.	88.0	82.0	84.0	86	85.6
Sep.	87.0	83.0	85.0	86	84.7
Oct.	77.0	82.0	82.0	85	79.2
Nov.	65.0	72.0	80.0	72	73.3
Dec.	68.0	57.0	70.0	63	64.0

Source: National Cereal Research Institute's (NCRI) Meteorological Station.

Table 3.5: Mean air temperature (°C) for 1996 - 1999 at study location

Month	1996	1997	1998	1999	Average(1965-1995)
Jan.	25.0	28.3	26.0	26.0	25.0
Feb.	26.0	28.3	30.0	28.5	26.7
Mar.	31.0	30.7	31.5	31.5	30.9
Apr.	32.0	30.1	33.0	31.0	30.2
May	28.5	28.7	29.5	29.0	27.8
Jun.	27.0	27.2	28.5	27.5	27.4
Jul.	27.0	27.0	28.0	27.0	27.4
Aug.	26.0	27.6	27.0	26.5	26.4
Sep.	26.0	27.4	27.0	27.0	25.6
Oct.	27.0	28.1	25.5	28.0	25.2
Nov.	25.5	27.0	25.4	28.0	25.7
Dec.	26.0	26.5	25.5	25.5	25.2

Source: National Cereal Research Institute's Meteorological Station.

Table 3.6: Wind speed (km/d) for 1996 - 1997 at study location

Month	1996	1997	Mean (1996-1997)
Jan.	32.9	21.8	27.4
Feb.	65.4	48.7	57.1
Mar.	89.2	69.3	79.3
Apr.	143.0	107.7	125.4
May	109.4	83.6	96.5
Jun.	85.9	80.5	83.2
Jul.	75.4	83.4	79.4
Aug.	59.4	75.3	67.4
Sep.	82.6	88.1	85.4
Oct.	51.6	73.4	62.5
Nov.	23.3	30.4	26.9
Dec.	14.4	20.3	17.4

Source: National Cereal Research Institute's Meteorological Station.

3.2 Design Of Experiment

3.2.1 Preliminary Investigation

Observation tubes (piezometers) 50 mm in diameter were installed 30 m apart and 1 m below the ground surface across the valley in the project sites. Figure 3.1 shows the main sections of the inland valley with relative positions of piezometer tubes while Plate 1 indicates a pictorial view of the inland valley of the project area. The water levels in the seven piezometer points were monitored weekly using the wetted tape method. The observation of the groundwater fluctuations commenced in May 1996. The groundwater table was monitored for three years (1996 to 1998), while planting of the maize seeds on the field plots commenced in 1998.

The reaction factor (α) for each of the piezometer tubes was determined from observed water table heads (h_t) by plotting observed h_t values versus time. The observed h_t values – time expression can be represented by a straight line for some selected time interval and with a slope equal to α.

Experiment 1: Greenhouse culture: Three initial water table depths viz.: 100 mm, 200 mm and 300 mm (Acevedo, 1994) were used in three replicates in plastic containers, 35 cm internal diameter x 40 cm depth, in a greenhouse environment at the National Cereal Research Institute premises, Badeggi, Niger State. One additional set of the containers had perforated bottom to represent free drainage, that is, no water table influence on the crop. Four sets of the containers at the same water table level formed a plot to give 48 containers in all that is 4 plots, 4 treatments and 3 replications. The water levels were maintained at the same level

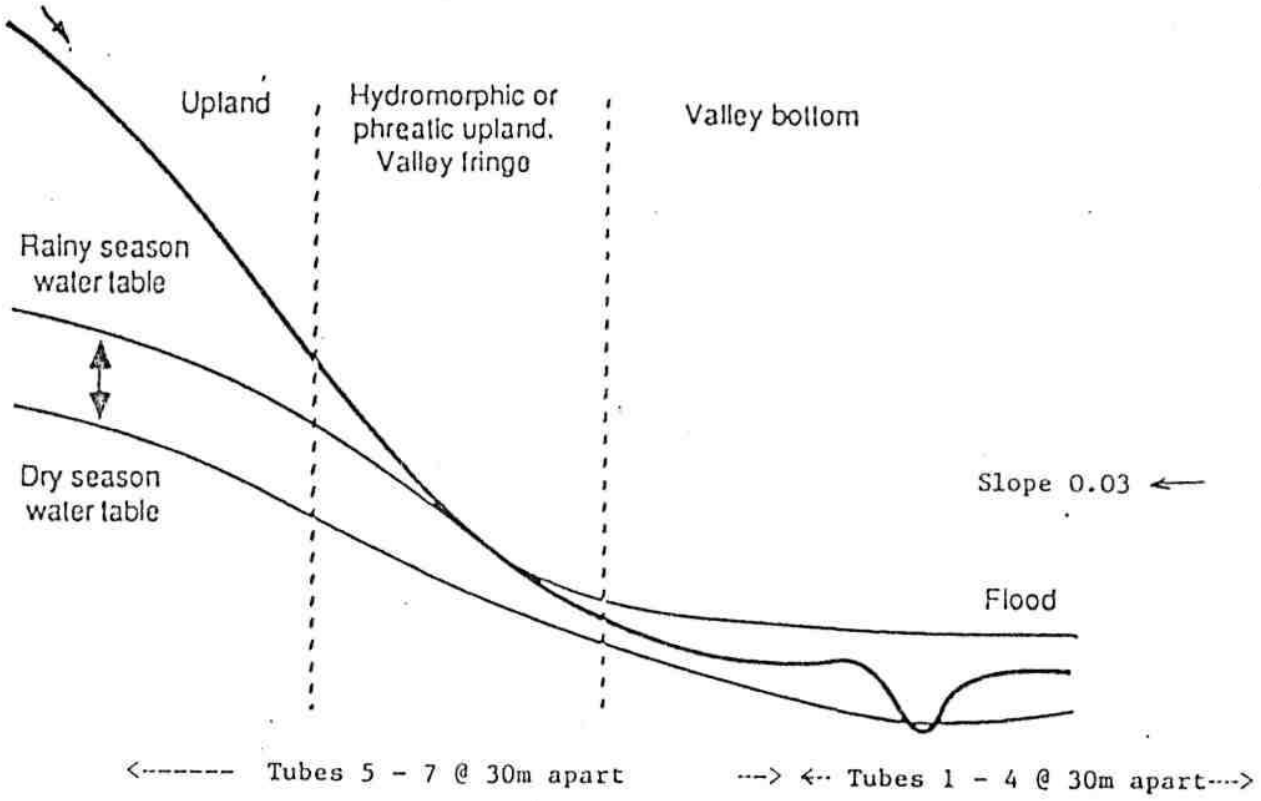


Fig. 3.1 : Inland valley slope with approximate demarcation of valley fringe and valley bottom in relation to seasonally fluctuating groundwater table.



Plate I: Pictorial view of the Inland Valley

at 2 - week intervals through surface watering. The perforations at the required levels served as spillways for excess water application.

All treatments received the same amount of fertiliser (NPK) application at the same time, 21 days after planting (DAP) and 42 DAP according to the prevailing practice.

The early maturing corn variety (Zea mays) was planted (two seeds per container) on July 10th, 1997. The soil moisture deficit was determined by weighing balance at 2 - week intervals while the growth indices of leaf area (leaf length multiplied by leaf width) and plant height, were measured using steel tape at 14 - day intervals until maturity stage and harvest. The harvested grains were dried and yields are reported at 12.5% moisture content (Musick and Dusek, 1980). The main characteristics of the green house are summarised in Table 3.7 (plate II).

Table 3.7: The main dimensions of the greenhouse

Length	13.2 m
Width	6.3 m
Wall height	1.3 m
Wire mesh height	1.8 m



Plate II: Pictorial view of the greenhouse

3.2.2 Experiment 2: Greenhouse and open field environment

In 1998, additional experiments were carried out in the green house environment and the open field. For the greenhouse experiment, three water table depths of 300 mm, 450 mm and 600 mm were maintained in metallic containers, 400 mm internal diameter and 720 mm depth. One set of the containers with perforated bottom represented negligible effect of groundwater table on crop growth. Four containers were at the same water table depth in three replicates. In all, there were 12 containers made up of four treatments and three replicates.

The seeds (early maturing corn variety) were planted in June, 1998. The mini - climate (except for direct precipitation) in the greenhouse closely simulated the open environment because of the design and construction of the structure (Boulard et al., 1997). In the open field, seed beds were raised to 500 mm height (Ayotamuno and Idike, 1997) at two field locations (plot sizes 2.5 m by 5.25 m) at different water table levels, 0 - 0.5 m and 0.6 -1.0 m, respectively). Although the two water tables were replicated thrice (to make a total of 6 plots), they were separated from each other without being randomly placed in the landscape. Therefore, data was analysed separately for the two water table depths. At the beginning of the crop growing season, pre - planting irrigation was applied to each field bed to compensate for residual differences in profile moisture content. Fertiliser (NPK) application was the same for all the treatments at 21 DAP and 42 DAP.

In order to reduce surface runoff effects from higher grounds on the field plots, the seed beds were enclosed by ridges (Cavazza and Pisa, 1988). The mean

water table depth at the field plots was calculated from the readings of the water levels per piezometer during the cropping season.

The soil in the containers in the greenhouse obtained from the top 0.6 m of the study area were subjected to three wetting - drying cycles to permit settling of the materials and hence simulated the natural soil profile (Musick and Dusek, 1980).

The water use of the crops in the greenhouse was obtained by determining the difference in weight before and after surface water application. In addition, crop growth indices of plant height and leaf area were monitored throughout the growing season at 10-day intervals. The climatic / meteorological data required for the potential evapotranspiration computation were obtained from the NCRI meteorological station.

3.2.3 Experiment 3: Greenhouse culture and field plots

In 1999, final experiments were carried out in both the greenhouse and field plots at NCRI, Badeggi; to validate the previous years results (Experiments 1 and 2). Under the greenhouse culture, four water table depths of 300 mm, 450 mm, and 600 mm were maintained in metallic containers (400 mm internal diameter, 720 mm depth). One set of the containers had perforated bottom to serve as experimental control (free drainage). In all, there were 12 cylindrical containers made up of four treatments and three replicates.

The corn (Zea mays) crop was raised each year between, (1998-1999) between September and December. This was to allow for sufficient rain for crop establishment in September and October and thereafter subject the crop to water

uptake from the shallow water table as the water source during the dry spell of November and December. That is, the water supply to the roots in the absence of rain relied on the flux from groundwater table. One of the plots 2.5m x 5.2m, was located at a water depth range of 0 to 500 mm, called high water table (hwt), while the other was sited at 600 mm to 1000 mm depth range, called low water table (lwt). On the field plots, seed beds were raised to about 0.5 m height at two field locations as done during 1998 experimental set up.

The water use of the crops under the greenhouse culture as well as the crop growth indices of plant height and leaf area for both the field crops and green house crops were monitored throughout the growing season at 10 - day intervals. The grain yield was obtained after maturity and harvest period.

Equation 2.26 (which is a generalisation of yield - evapotranspiration relation with the advantage of being used for different years and regions) was adopted to estimate the field crop evapotranspiration and hence the percentage contribution of groundwater use to total corn water use. In this way, the climatic variability for the different years of study was taken into account by applying the ratio of actual water use to potential evapotranspiration (Duru, 1984). Thus, the information from this study could in fact be extended beyond the restricted region in which they were obtained. Moreover, relative yield (Eq. 2.26) was used to allow the presentation of data from different years on a common basis.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

Crop growth is affected by fluctuations in the groundwater table. A better understanding of its response will help us to optimize drainage and irrigation for a given field condition, through determination of the optimum depth to water table range for corn (Zea mays) production.

The discussion in this chapter is focused on corn yield response as affected by depth to water table for both the greenhouse (controlled environment) and the open field conditions. The trend of the groundwater table fluctuations in the project location, the relative yield and relative evapotranspiration values, the percentage contribution of ground water to corn water use as well as corn yield - water use expression obtained from the study are also discussed.

4.2 Climate

The monthly rainfall data at the project location (Badeggi, Niger State) during the study period of 1996 to 1999 is given in Table 3.3. The maximum amount of rainfall occurred in the months of August in 1996, June, 1997, July, 1998, and July, 1999. The monthly long term average for the period 1965-1995 occurred in August (Table 3.3).

The relatively high amount of annual rainfall for the period from 1996 to 1999 was an indication of an increase in the quantity of water going into surface runoff, stream flow and ground water recharge. The relative humidity values for the 4 years of study were approximately the same for each of the months in the consecutive years (Table 3.4) and to the long term average (Table 3.4). The maximum temperature during the rainy season (May to October) occurred in the month of May (Table 3.5) from 1996 to 1999. The mean maximum wind speed for 1996 to 1997 occurred in April (Table 3.6).

4.3 Water Table Fluctuation

The trend of the water table movement and the predicted fluctuation of each of the piezometers (tubes) during the rainy season are given in Figs. 4.1 to 4.3 and Figs. A.1 to A.3 while the corresponding dry season trend and predicted values are shown Figs. 4.4 to 4.6 and Figs. A.4 to A.7. The modified Zeeuw - Hellinga equation (Eqs. 2.14 and 2.16) was used for modelling the ground watertable vertical movement. During the wet season, except for piezometer tubes at points 1 and 2, the other observed values intercepted with predicted values at four distinct points. The graph for Tube 5 (rainy season) was not shown because the groundwater level remained at the surface for most of the period. For tube 4, the water level remained at the surface from the month of May to the early part of September (Fig. A.2).

On the other hand the water level at tube 6 rose to the surface by July and remained stable till September before it fell to 50 cm below the ground surface within 4 weeks (Fig. A.3). The trend observed in tubes 4 and 5 where water level

remained at the surface for considerable time can be attributed to the fact that these portion of land was close to the valley bottom of the inland valley. The water level at tube 3 came to the peak (surface) at the end of July, and then fell to 20 cm below the ground surface by the beginning of September and thereafter fell steadily to below 60 cm within 4 weeks. The water level at tube 1 gradually increased from the month of May to the peak at the soil surface, at the beginning of September and thereafter fell to 42 cm below the ground surface within 1 week. The trend equations describing the fluctuating water table levels for both wet and dry seasons are also given in Figs. 4.1 to 4.6 and Figs. A.1 to A.7.

During the dry season (November to March), the water table steadily moved downward in most points at the project location (Fig. 4.4 to 4.6, and Figs. A.4 to A.7). At the Piezometer (tube) 1, the maximum rate of falling occurred in the month of February (50 mm/wk). Tube 2 also had its maximum falling rate in February (40 mm/wk). For tube 3, the water level remained constant at between 60 to 65 cm below the ground surface and thereafter fell at the rates of 32.5 mm/wk, 30 mm/wk and 100 mm/wk for the months of December, January and February, respectively.

At tube 4, the rate of downward movement increased from 12.5 mm/wk to a maximum of 35 mm/wk in December and remained constant between 71 to 79 cm below the ground surface in March. Tube 5 gave 96.7 mm/wk in November which reduced to 15 mm/wk and 3.75 mm/wk in the months of December and February, respectively. At tube 6 location, the rate of falling water table was 25 mm/wk in November and 50 mm/wk in January and then reduced to 27.5 mm/wk in February and thereafter remained constant at about 1 m below the ground surface. For tube

7, the average rate of falling water table was 40 mm/wk for the months of December, January and February, and thereafter remained at about 1 m in March.

It is interesting to point out that except at the first three piezometer locations, the individual correlation factor, r, for the dry season trend were higher than the corresponding wet season trend.

The Zeeuw-Hellinga equation (with $\alpha \cong 0.02$) used to predict the water table movement need further modification so as to model the dry and wet periods adequately. Separate prediction for the two seasons (dry and wet) may be required. The trend equations however, took care of this anomaly (Figs. 4. 1 to 4.6).

Equation 2.17 (Section 2.3.3) was solved by using the following steps:

1. Determine the log-transformed value of observed water table level from Eq. 2.19
2. Compute the Sine and Cosine values of the Fourier series.
3. Repeat step (2) until there is no justification for increasing the harmonic (*i*) and generate the predicted values and Fourier coefficients from Eqs. 2.17 to 2.19
4. Use Chi-Square test to verify the deviance of the observed and predicted water table depths.

The Fourier series coefficient obtained at weekly time steps are given in Appendix B. The Fourier fitting curves are given in Figs 4.7 and 4.8. It can be seen that the Fourier fitting curves gave better predictions than those obtained from the use of the Zeeuw – Hellinga's modelling equation.

The mean ground water levels at the field plots were also monitored during the 1998/99 cropping period. The rate of fall of the water table depth especially during the dry months (November and December) was 1.2 mm/day and 0.7 mm/day on the average for the high water table and low water table depths respectively (Table 4.1).

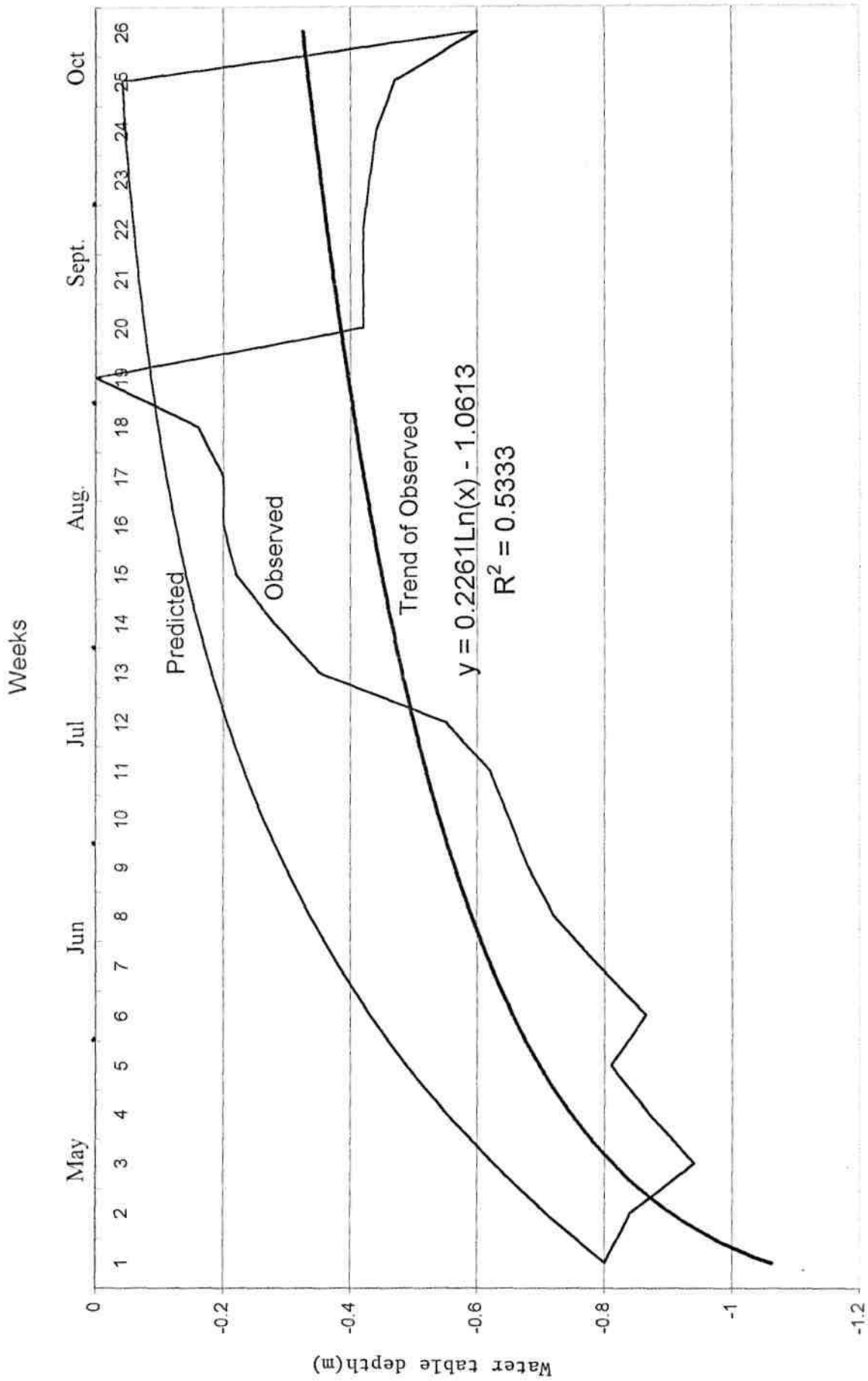


Fig 4.1: Water table hydrograph during wet season at piezometer 1

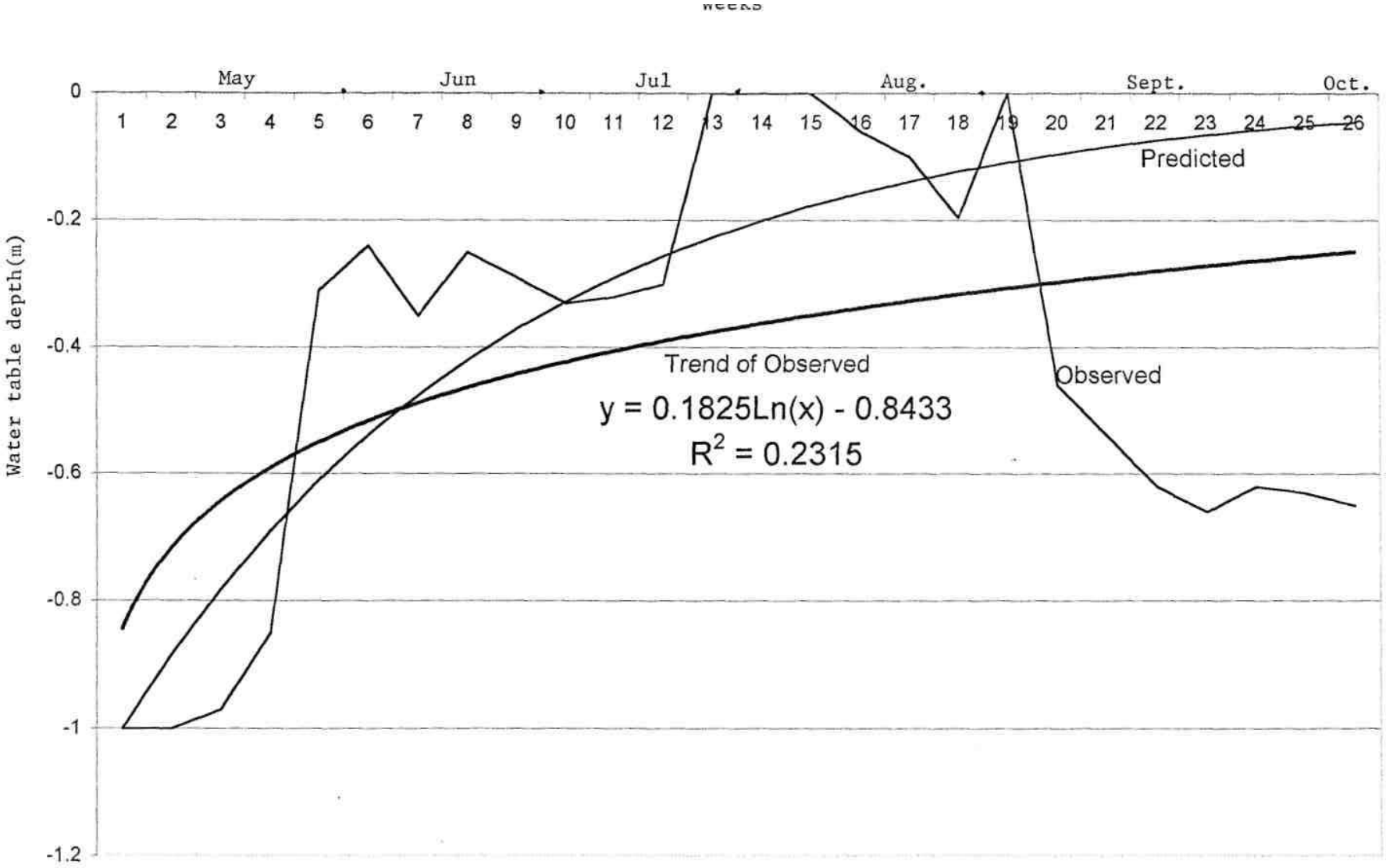


Fig. 4.2: Water table hydrograph during wet season at piezometer 3

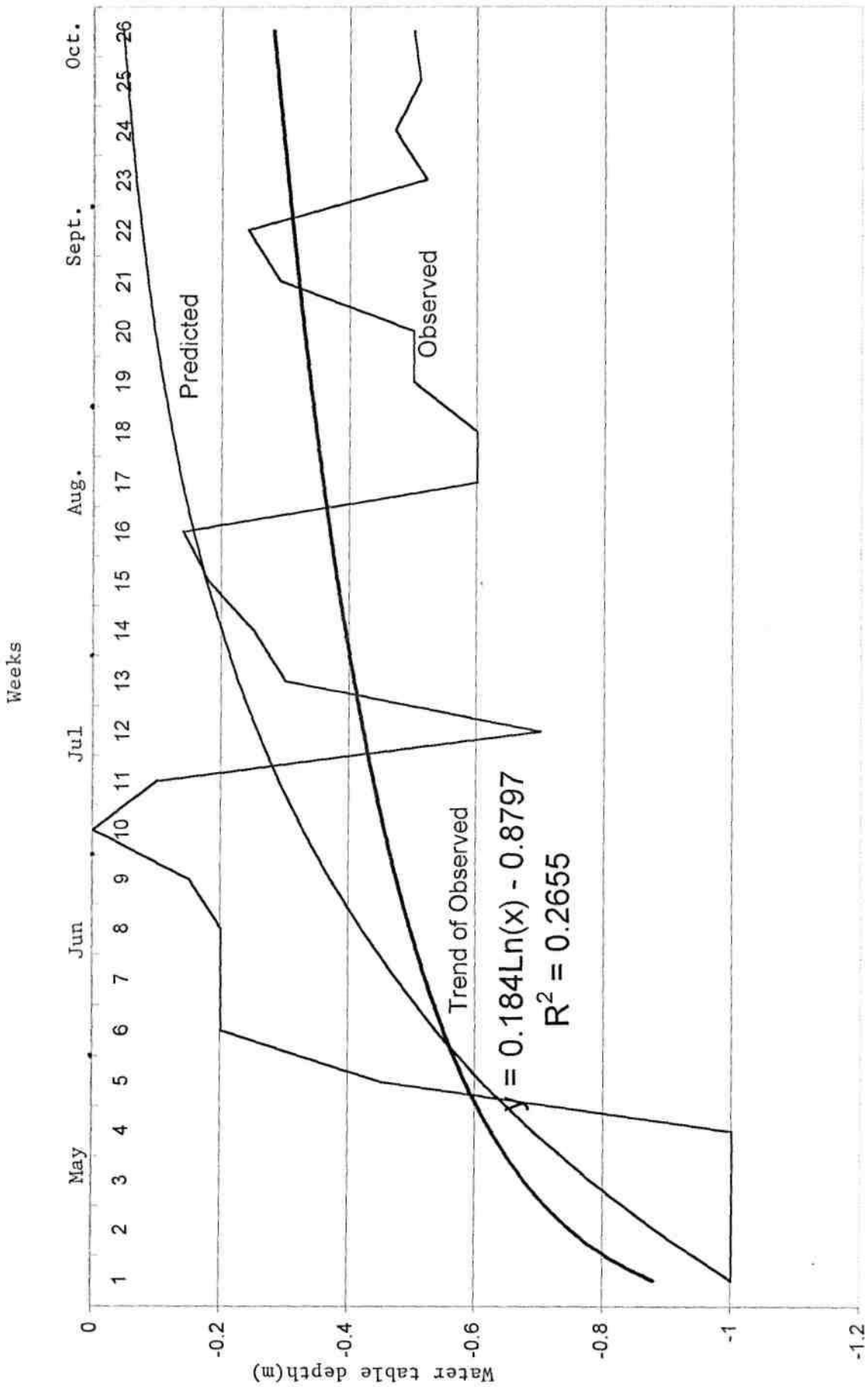


Fig. 4.3: Water table hydrograph during wet season at piezometer 7.

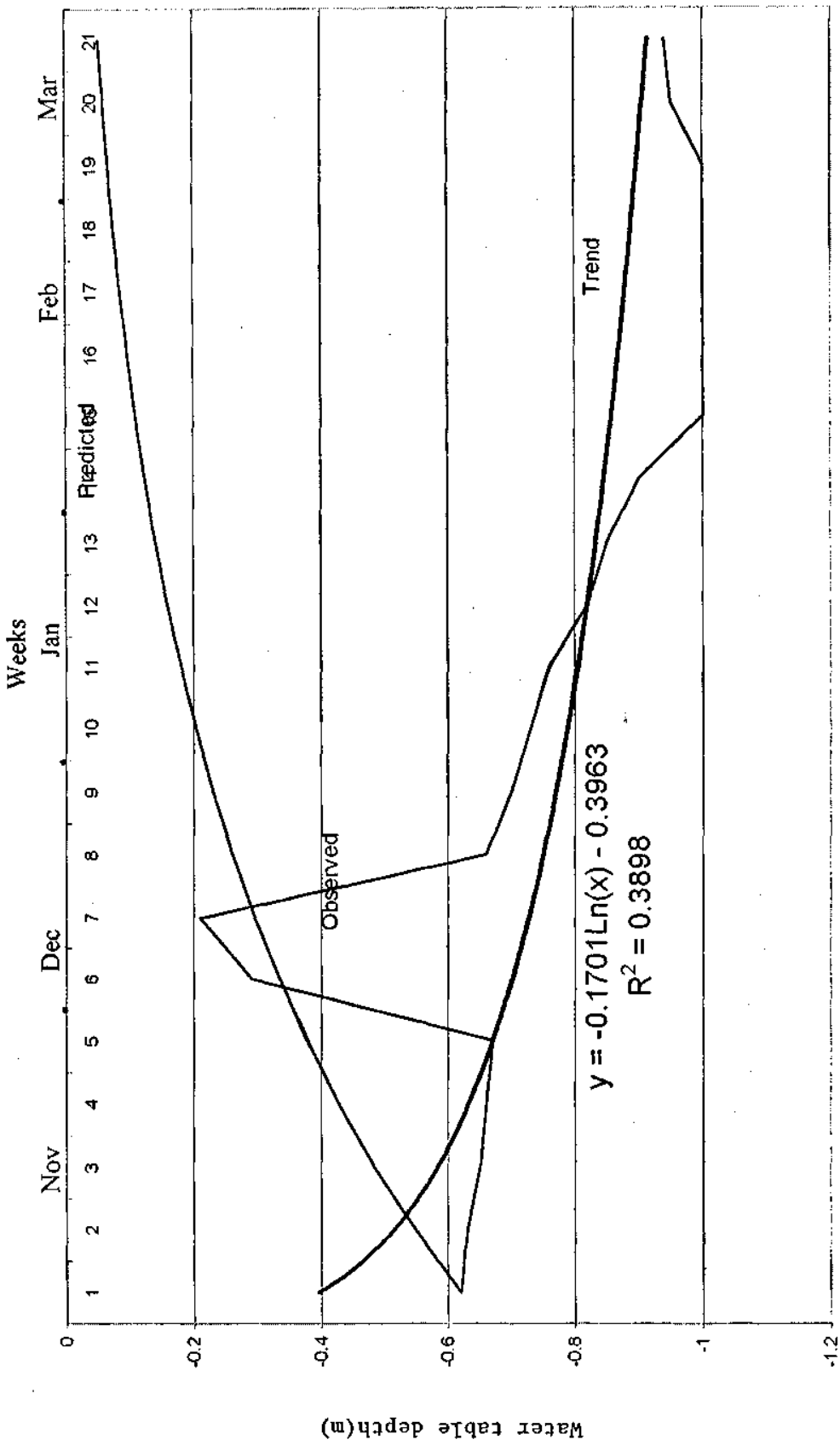


Fig. 4.4: Predicted, trend and observed water table depth during dry season-piezometer 1

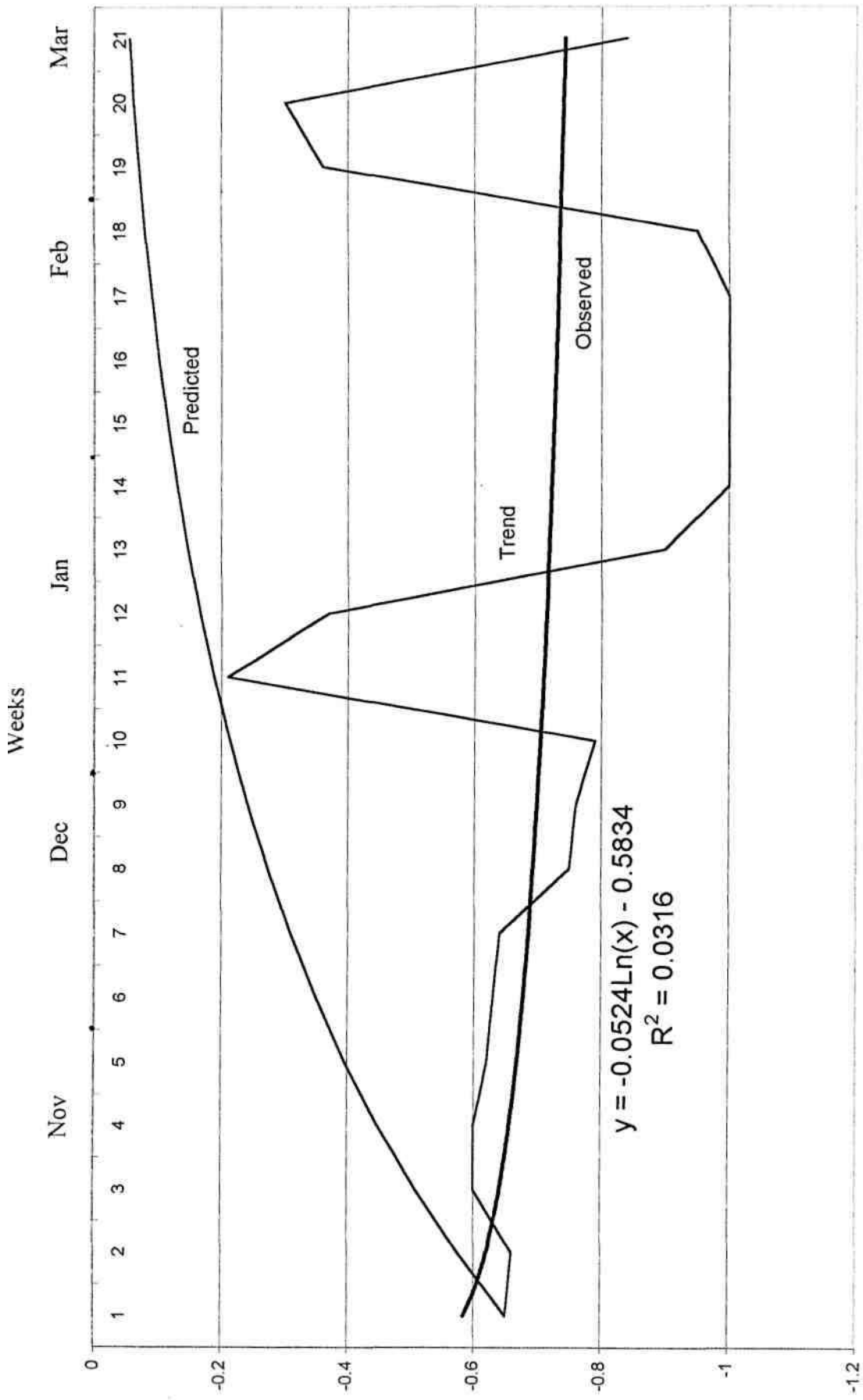
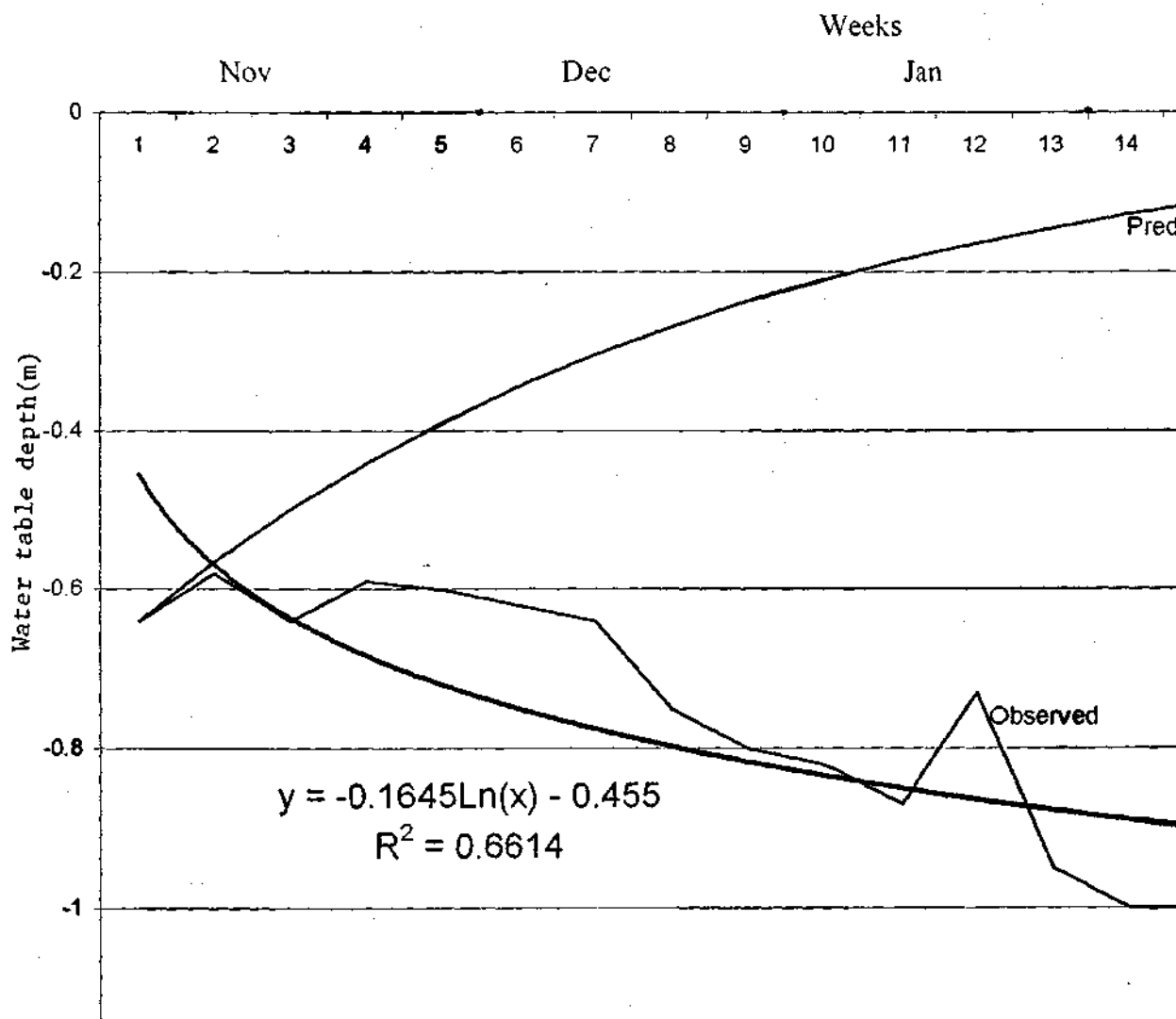


Fig 4.5: Predicted, trend water table depth during dry season piezometer 3


Weeks
Nov
Dec
Jan
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0
-0.2
-0.4
-0.6
-0.8
-1
Water table depth(m)
Pred
Observed
y = -0.1645Ln(x) - 0.455
R2 = 0.6614

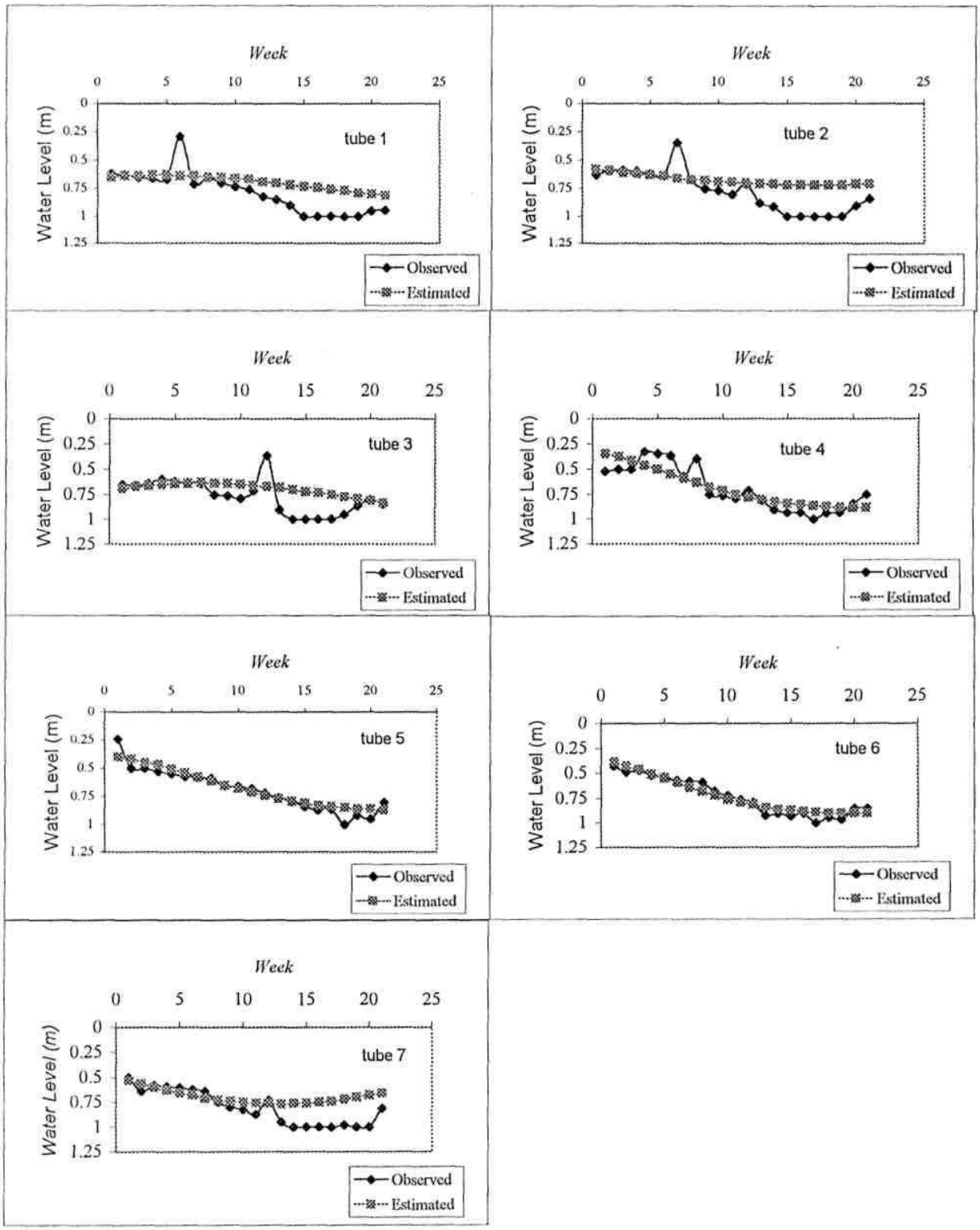


Fig. 4.7: Observed water table levels and fourier fitted curves for dry season

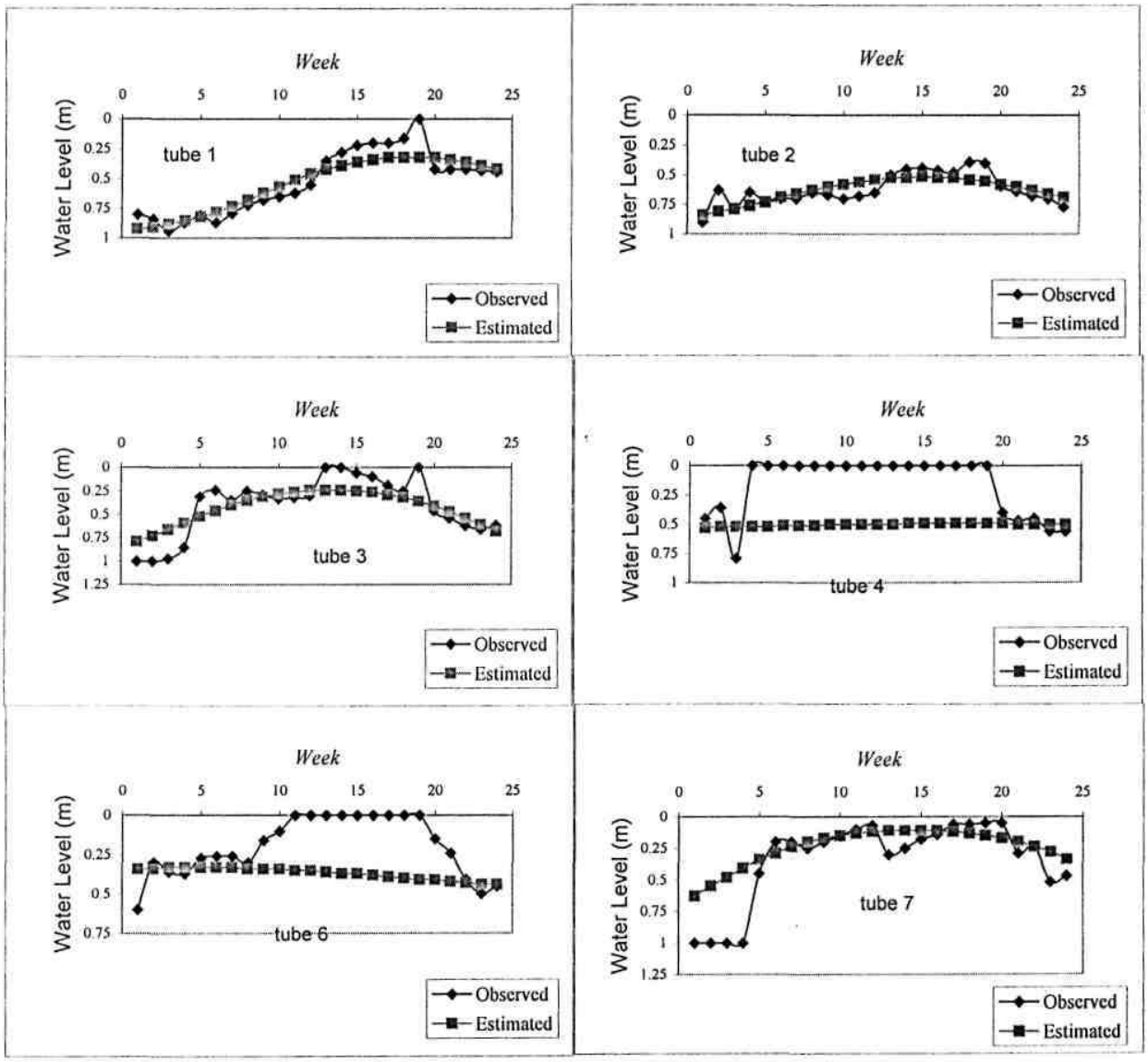


Fig. 4.8: Observed water table levels and Fourier fitted curves for wet season

Table 4.1: Field water table position during 1998/99 cropping season.

DAP[1]	High water table depth (m)	Low water table depth (m)
10	0.20	0.63
20	0.2	0.63
30	0.20	0.60
40	0.28	0.62
50	0.28	0.68
60	0.34	0.73
70	0.38	0.79
80	0.50	0.80
90	0.50	0.81
mean	0.30	0.71

[1] DAP = days after planting

[2] High water table range = 0.2 to 0.5 m

[3] Low water table range = 0.6 to 0.8 m

4.4 Corn Yield and Growth Indices

4.4.1 Greenhouse culture

The grain yield under the greenhouse culture during the preliminary investigation (1997) increased gradually from 0.30 kg/m^2 in the 100 mm water table height to a maximum value of 0.06 kg/m^2 in the 300 mm water table depth (Table 4.2). Examination of this data showed that the yield at 300 mm water depth was twice that obtained at 100 mm water table depth. In addition, the yield increased averagely at the rate of 0.02 kg/m^2 per 100 mm water depth, for the water depth range under consideration (100 mm to 300 mm).

In 1998, the water table depths were maintained at depths of 300 mm, 450 mm, 600 mm and free drainage. The grain yield at 450 mm water depth gave a value of 0.13kg/m^2. At 600 mm water table depth, the grain yield value was 0.1 kg/m2 (Table 4.3). pooling the data from 1997 and 1998, the grain yield at the 100 mm, 200 mm and 300 mm water depths were depressed and were 23.1%, 37.7% and 45.4% of the maximum (at 450 mm water depth), respectively (Table 4.4). the depressed yield can be attributed to excessive soil water in the root zone resulting from the very shallow water table depths.

In 1999, additional data on the grain yield as influenced by the water table depths were obtained to validate the 1997 to 1998 observations. The grain yield trend for 1999 growing season was similar to that earlier obtained in 1997 and 1998 seasons. The relative grain yield for 1999 cropping season increased from 71.6% at 300 mm water depth to a maximum (100%) at 450 mm water depth. Thereafter, the relative grain yield dropped to 76.5% at 600 mm water depth (Fig. 4.9).

Pooling data from 1997 to 1999, it can be concluded that the best moisture regime for crop production under the greenhouse culture was at 450 mm water table mm (Table 4.4). The yield were significantly different at 5% level of significance.

Table 4.2: Corn Yield as influenced by water table depth (100-300 mm) under greenhouse culture.

Water table depth (mm)	Yield (t/ha)	Cumulative water use (mm)
100	0.3	333
200	0.5	300
300	0.6	400

Table 4.3: Corn Yield as influenced by water table depth (300-600 mm) under greenhouse culture.

Water table depth (mm)	Yield (t/ha)	Cumulative water use (mm)
300	0.6	410
450	1.3	795
600	1.0	975
Free Drainage	0.9	1002

Table 4.4: Corn relative yield, under greenhouse culture (1997/98).

Water table depth (mm)	Relative yield (t/ha)
100	23.1
200	37.7
300	45.4
450	100
600	80
Free Drainage	50.8

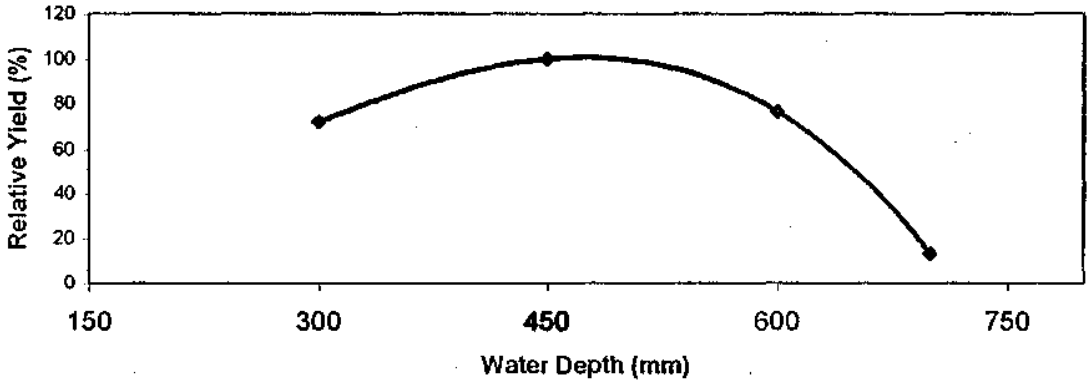


Fig. 4.9: Relative yield versus water table depth during corn growing season (Greenhouse culture).

The corn growth indices of plant height and leaf area increased with the number of days after planting and had the maximum growth rate between 40 to 60 DAP for each of the water table depths. The plant height and the leaf area in relation to the number of days after planting for all the water table depths were S-curves (Figs. 4.10-4.15). However, at 70 to 80 DAP, a plateau was formed and this continued until grain maturity and harvesting period (100 DAP). The maximum plant height and leaf area in 1999 was observed to be 1.14 m and 0.1m^2, respectively at 600 mm water table depth (Table 4.5)

The trend equation (Fig. 4.16) for the corn yield with respect to water table depth for 1999 under the green house culture was obtained as:

$Y = 0.0017\ D^3 - 0.03\ D^2 + 0.1043\ D - 0.017$ 4.1

where Y = yield in kg/m^2

and D = water table height in m.

when the first term of Eq. 4.1 ($0.0017D^3$) is neglected, the corn yield trend assumes a second order (parabolic) equation. The trend equation gives the mathematical model that describes the observed value in the relationship between the corn yield and water table.

The trend equation can be a useful guide for further study on crop performance/crop water use modelling in inland valleys especially for those within the same agroecological zone as the experimental area (Guinea Savannah).

Relating the green house corn yield to the water use for the water table depths under consideration, the following regression equation was obtained:

$Y = 0.09\ w + 0.02$ 4.2

with coefficient of correlation $r = 0.81$

where Y = yield in kg/m^2, and W = Water use in m

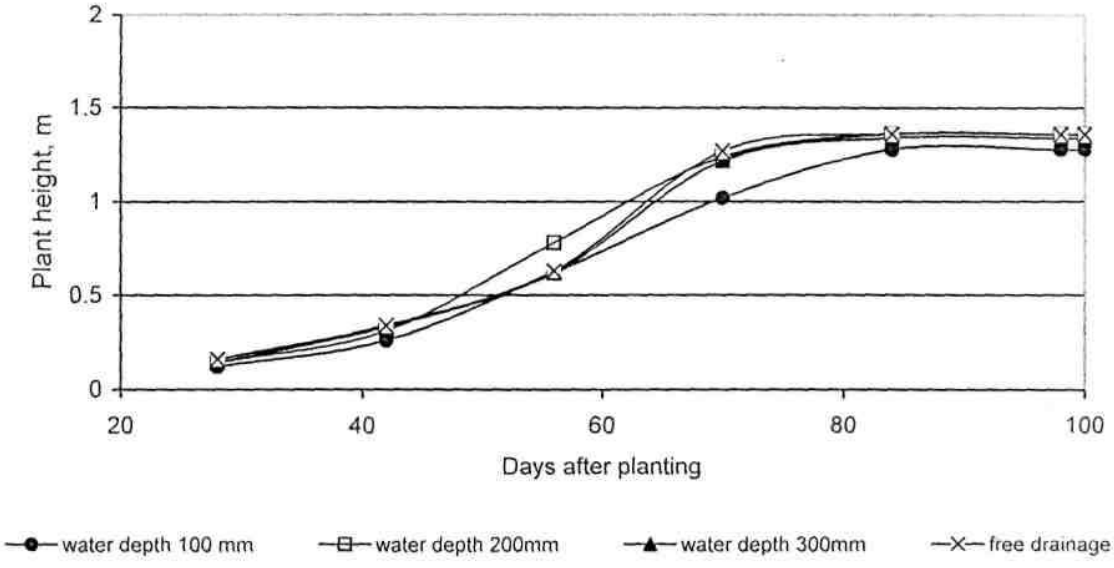


Fig. 4.10: Plant height at different water table depths (100 - 300 mm)

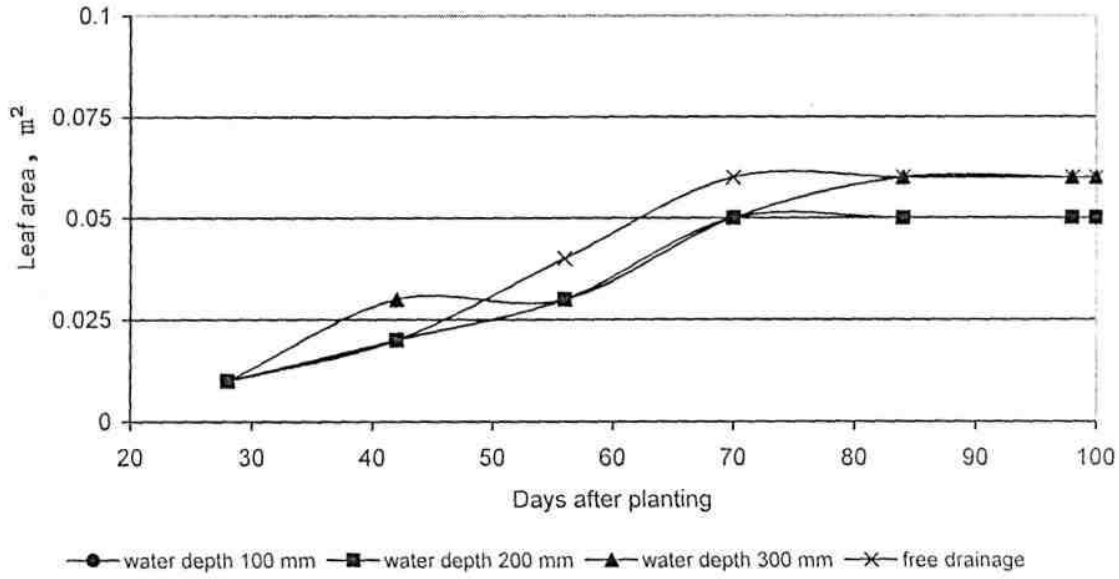


Fig. 4.11: Leaf area at different water table depths (100 - 300 mm)

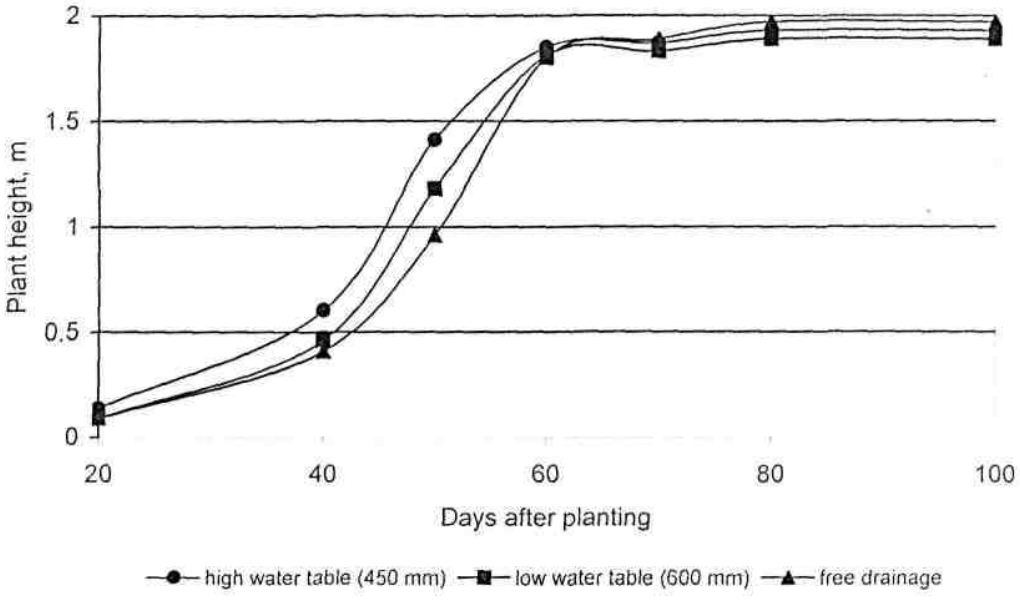


Fig. 4.12: Plant height at different water table depths (450 - 600mm)

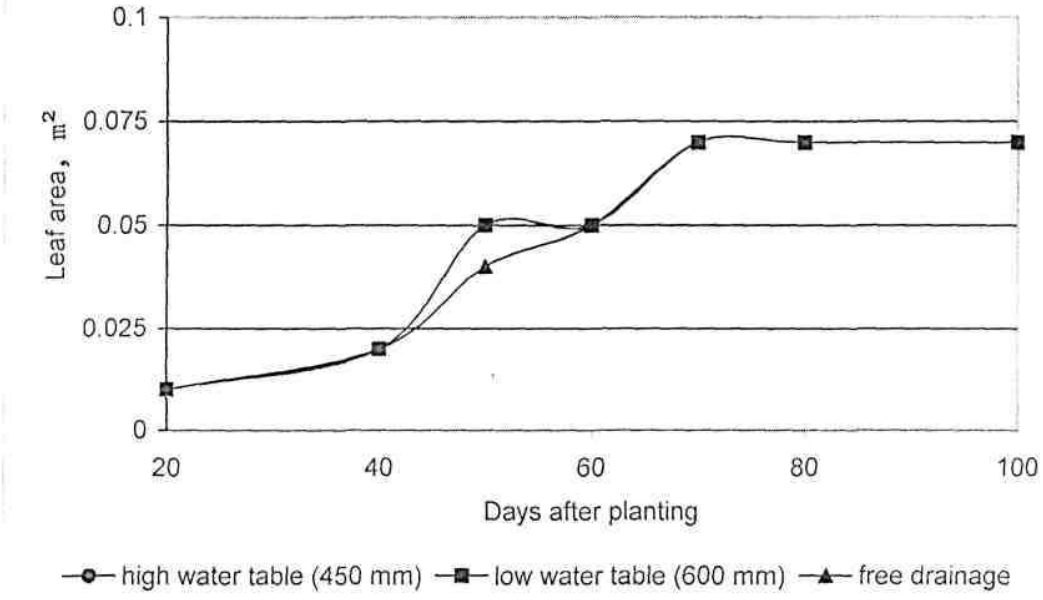


Fig. 4.13: Leaf area at different water table depths (450 - 600mm)

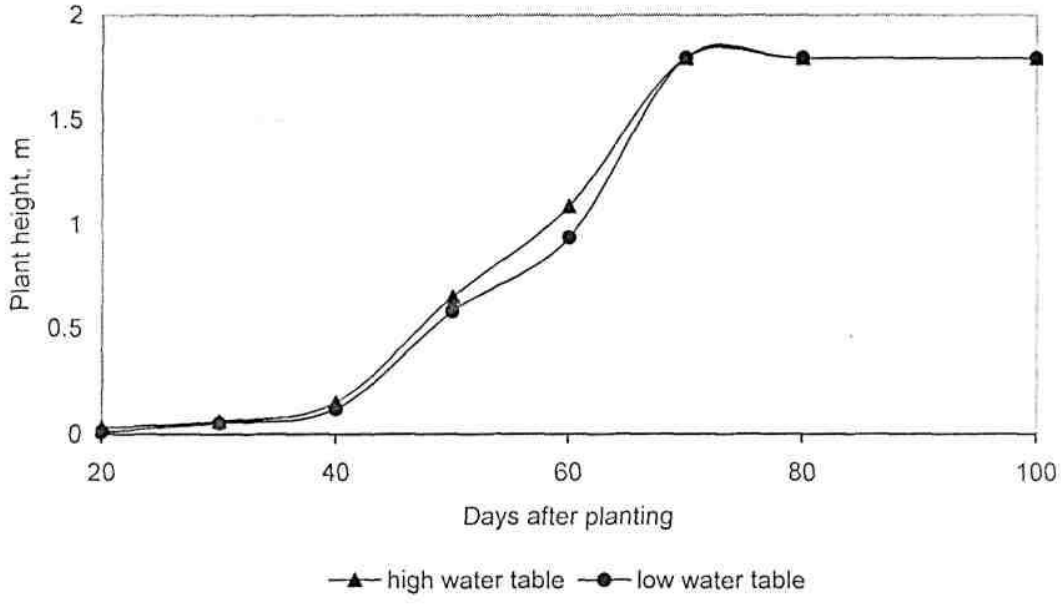


Fig. 4.14: Plant height at different water table depths

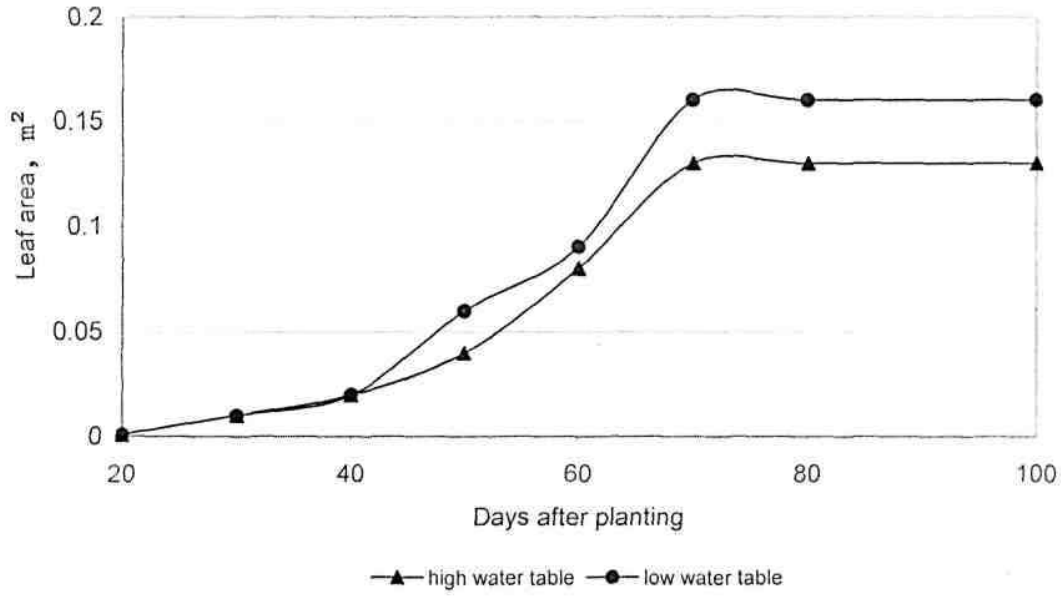


Fig. 4.15: Leaf area at different water table depths

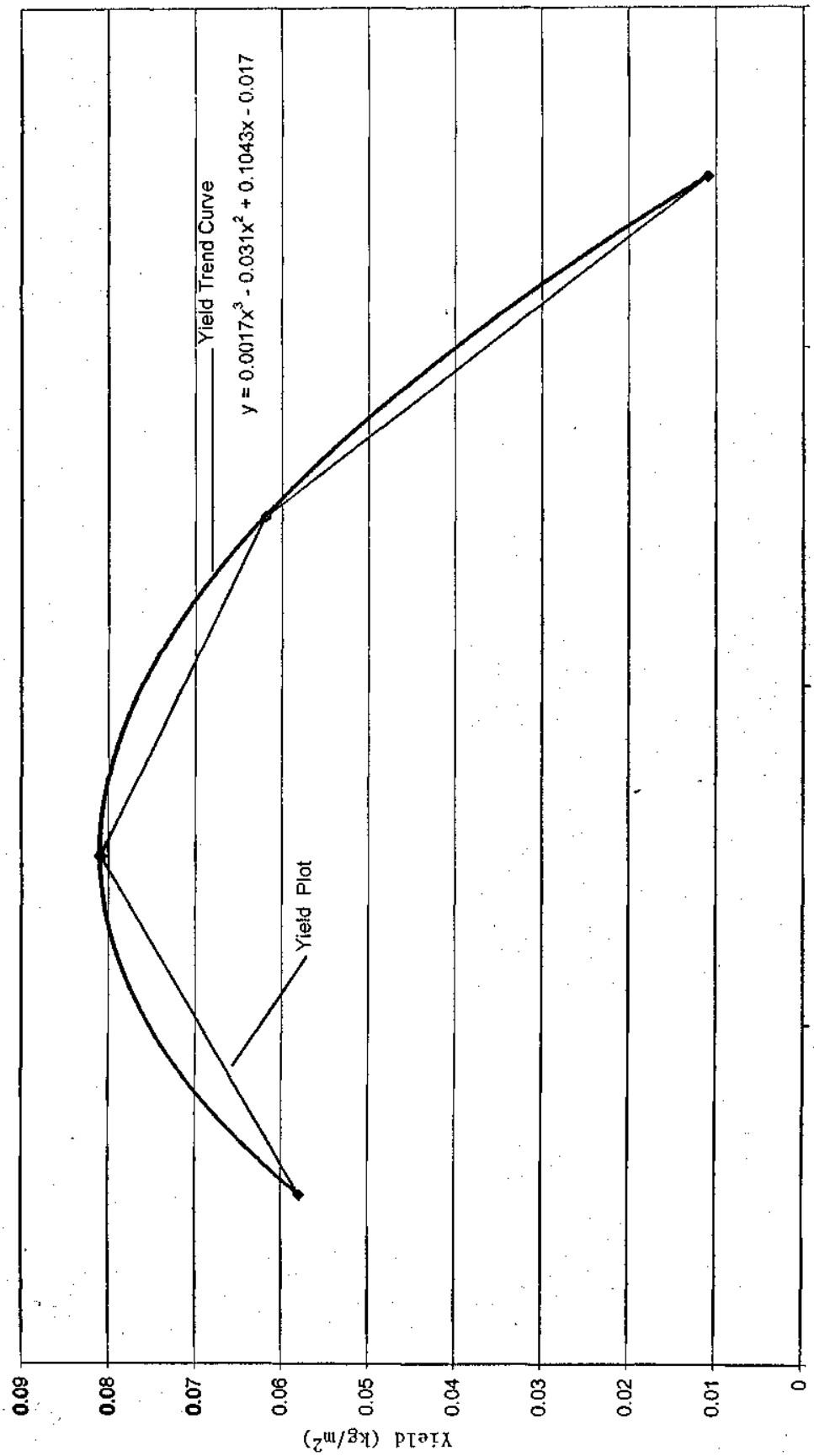


Fig. 4.16 : Corn Yield Trend in 1999 Growing Season (Green House Culture)

Table 4.5: Corn growth indices of plant height and leaf area during 1999 growing season (greenhouse) at 300 – 650 mm water table depth.

[1]DAP	300 mm		450 mm		650 mm		Free drainage	
	Height (m)	Area (m^2)	Height (m)	Area (m^2)	Height (m)	Area (m^2)	Height (m)	Area (m^2)
30	0.2	0.01	0.2	0.02	0.17	0.01	0.2	0.01
40	0.36	0.03	0.36	0.03	0.5	0.04	0.45	0.04
50	0.73	0.06	0.74	0.05	0.59	0.05	0.6	0.05
60	0.92	0.06	0.94	0.06	1.1	0.05	0.98	0.1
70	1.04	0.1	0.96	0.01	1.1	0.01	1.05	0.1
80	1.04	0.1	1.1	0.01	1.14	0.1	1.1	0.1
90	1.04	0.1	1.1	0.01	1.14	0.1	1.1	0.1

[1]DAP = Days After Planting.

4.4.2 Open field condition

In 1998, the mean grain yield of 2.0 t/ha at the high water table was a higher value when compared to that at the low water table of 0.4 t/ha (Table 4. 6). Similarly, in 1999, the mean grain yields in the field plots (Table 4.6) were 3.7 t/ha and 1.1 t/ha at the high water table (hwt) and low water table (lwt), respectively. This means that the yield at the low water table was about 28% of that from high water table plot within the inland valley toposequence positions.

Table 4.6: Corn yield in open field for different water table heights

	grain yield (t/ha)					
	1998			1999		
Plot	R_1	R_2	R_3	R_1	R_2	R_3
High water table (≤ 0.5m)	2.0	1.91	1.81	3.0	4.5	3.7
Low water table (≥ 0.6m)	0.4	0.4	0.35	0.07	1.9	1.0

R_1, R_2, R_3 = replicates 1, 2 and 3 respectively.

The reason for the difference in yield between the hwt and lwt positions can be mainly attributed to the dry spell that began in the month of October. Since there was no rain, the plant could only satisfy its water use requirement from the groundwater accessible to the root zone. The hwt plot situation (≤ 500 mm water depth) seems more favourable to the plant than the lwt (≥ 600 mm water depth) during the cropping period. The soil moisture content values (Table 4.7) which increased with depth especially at the hwt condition confirms this explanation.

during the cropping period. The soil moisture content values (Table 4.7) which increased with depth especially at the hwt condition confirms this explanation.

The field plot at the 200 mm to 500 mm water depth range along the valley toposequence may be considered as the optimum water table depth for corn production for the inland valley studied. This means that the water table was effectively at 700 mm to 1000 mm range considering the seed bed height of 500 mm. The result is consistent with the findings of Reichman et al (1983) and Doering et al (1977) that the water table requirement for highest yields of sugar beet and corn grown on sandy soils was about 1m deep. The ground water quality had been proved to be good (Table 3.2) and so had no detrimental effects on the crop performance. The maximum plant height and leaf area were 1.1 m and 0.1 m^2, respectively during the 1999 corn growing season in the field plots (Table 4.8).

Table 4.7: Soil moisture values during dry season for high water table and low water Table plots

	Gravimetric Moisture content	
Soil depth (mm)	High water table	Low water table
	≤ 500 mm	≥ 600 mm
0 - 200	8.8	2.8
200 - 400	9.9	2.8
400 - 600	11.0	4.4
600 - 800	11.5	11.3

Table 4.8: Corn growth indices of plant height and leaf area during 1999 growing season (field plots)

DAP[1]	High water table		Low water table	
	Height (m)	Area (m^2)	Height (m)	Area (m^2)
30	0.33	0.05	0.3	0.03
40	0.46	0.05	0.37	0.05
50	0.57	0.06	0.53	0.06
60	1.07	0.06	0.98	0.06
70	1.1	0.1	1.0	0.1
80	1.1	0.1	1.0	0.1
90	1.1	0.1	1.0	0.1

[1]DAP = Days After Planting.

4.5 Corn Water Use And Water Use Efficiency

The cumulative water use and water use efficiency during the corn growing period for the green house culture at the various water table depths in 1999 are given in Table 4.9. The water use (605 mm) at 600 mm water table depth was more than that at 300 mm. The additional water use of 205 mm at 600 mm water depth did not result in increase in grain yield. This has clearly indicated that when a crop is allowed to rely on water supply from a shallow water table condition, it is important to determine the optimum water table range for a given soil- crop - climate condition. In each case (greenhouse and field plots), the peak water use occurred between 70 to 80 DAP for the maize crop.

The yield trend as well as the water use trend with respect to the water table heights under the greenhouse culture (1977 – 1998) are given in Fig. 4 .17

Table 4.9: Corn water use and water use efficiency during 1999 growing season under greenhouse culture

Water table depth (mm)	Cumulative water use (mm)	Water use efficiency
300	400	1.4
450	545	1.5
600	605	1.0
Free drainage	628	0.7

The water use efficiency which is the ratio of the yield to water use ranged from 0.7 kg/ha - mm (at free drainage) to a maximum of 1.5 kg/ha - mm (at 450 mm water depth), under the green house culture (Table 4.9).

It was not practically possible to measure the water use for the crop in the field due to lack of instruments. The generalised yield - evapotranspiration model discussed in section 2.6.1 was used (Eq.2.26) to estimate the crop water use and hence the percentage contribution of groundwater use to corn evapotranspiration (ETc) requirement. The discussion on the percentage contribution of groundwater use to ETc demand is given in section 4.6.

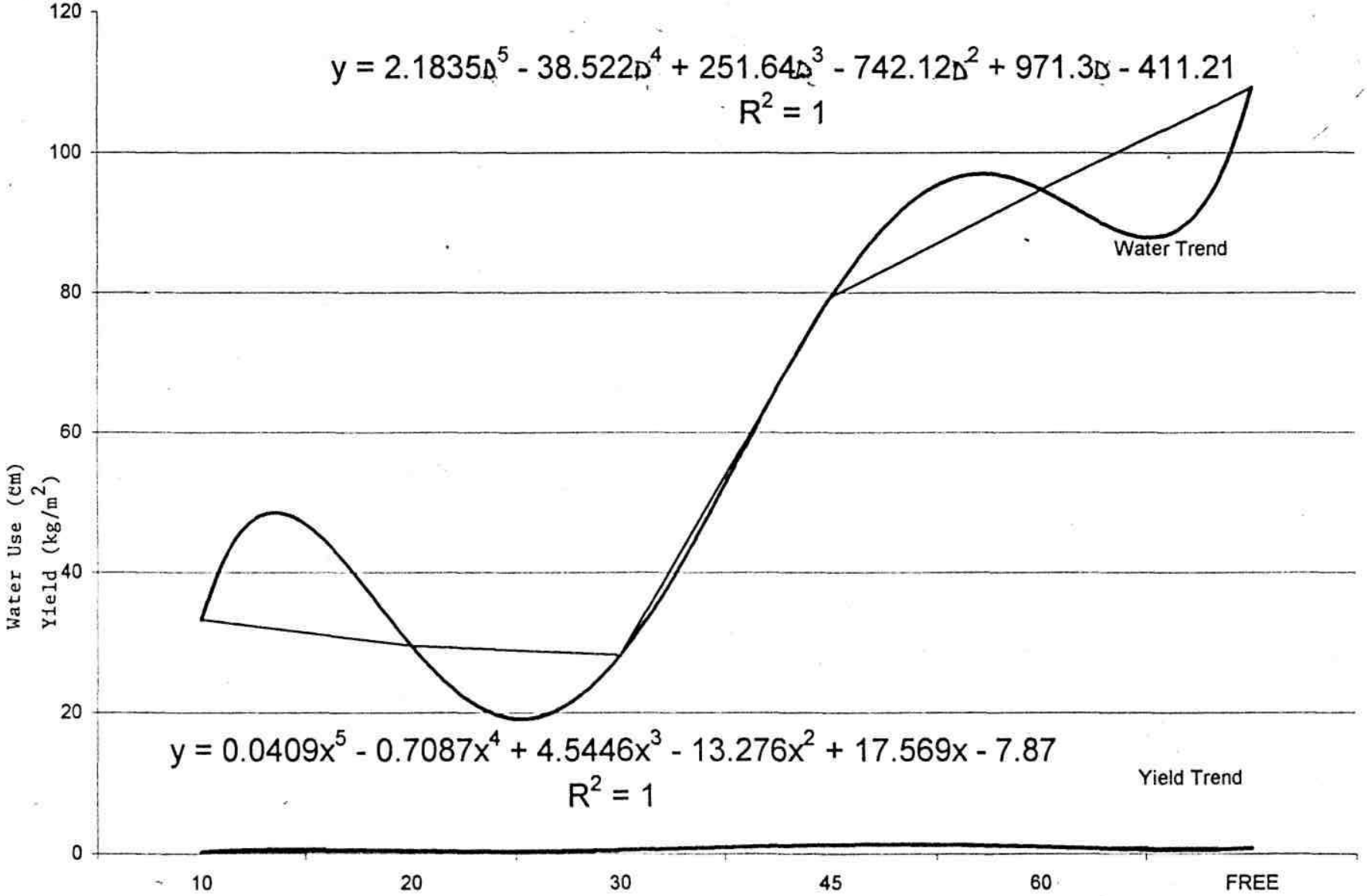


Fig. 4.17 : Trend of water use and grain yield at different water table depths (1997 - 1998).

4.6 Percentage Contribution of Groundwater Use to Total Corn Water Use

Equation 4.3 was used to estimate the percentage contribution of groundwater to corn water use. The equation is a generalization of yield-evapotranspiration relations and have the advantage of being used for different years and regions. In estimating the groundwater use, the rainfall amount during the growing period was considered while the effect of surface runoff from the upland was reduced by means of bunds made around the plots. The use of Relative yield (Y/Y_{max}) (Eq. 2.26 and Table 4.10) for the estimation of groundwater use contribution to the corn water use allowed the presentation of data from different years on a common basis. Hence, differences in climatic period were eliminated. The highest yield (Y_{max}) obtained in each year of an experiment was taken as 100 percent for that experiment and given year (Shalhevet et al., 1981). The data would then be of much greater value and have more substantial impact when its usefulness is extended beyond the restricted region in which they were obtained.

Various factors such as experimental technique, varietal differences, cultural practices and human errors, may limit the transferability of the experimental information from one location to another. The most important element, however, is the difference in environmental factors, namely, climate and soil. It was thus of interest to normalize the data obtained from the various years (1997-1999) by use of relative evapotranspiration values.

Recall, $$\frac{Y}{Y_{max}} = a\frac{ET}{ET_{max}} - b \qquad \text{..... 2.26}$$

From the yield (Y) and water use (ET) values obtained earlier (summarized in Table 4.14), the constants of regression a and b were obtained to be 1 and 0.2 respectively, given:

$$\frac{Y}{Y_{max}} = \frac{ET}{ET_{max}} - 0.2 \quad \text{..... 4.3}$$

Table 4.10: Relative yield and relative evapotranspiration values under green house culture (1998/99 season)

water table depth	Y^1 t/ha	Y^2_{max} t/ha	$\frac{Y}{Y_{max}}$	ET^3 mm/day	$ET_{max}{}^4$ mm/day	$\frac{ET}{ET_{max}}$
300	0.58	0.59	1.0	4.0	4.1	0.98
450	0.81	1.3	0.62	5.5	8.0	0.69
600	0.62	1.04	0.57	6.1	9.8	0.62
Free drainage	0.41	0.9	0.46	6.3	10.0	0.63

^1Y = yield, and $^2Y_{max}$ = corresponding maximum yield

^3ET = evapotranspiration, and $^4ET_{max}$ = corresponding maximum ET

Equation 4.3 was then used to estimate the field crop (corn) evapotranspiration rate, ET, where $Y/Y_{max} = 0.54$ (Table 4.11) and $ET_{max} = ET_p$ (potential ET = 5 mm/day, obtained from (Duru, 1984)). Hence crop evapotranspiration in the field plot $\approx$ 4 mm/day or 400 mm over the 100 days growing period. Since the rainfall amount during the growing season = 251 mm, and assuming this value to be effective rainfall, the percentage contribution of groundwater use to corn total water use (water table range $\leq$ 500 mm)

$$= \frac{400 - 251}{400} \text{ X } 100\% = 37.3\%$$

Similarly, the percentage contribution of ground water use to corn total water use (water table depth range of ≥ 600 mm) = $\frac{300 - 251}{300}$ X 100% = 16.3%

The estimated water use requirement (400 mm) for the field crop (corn) were within the range of values quoted (400 mm to 750 mm) by FAO (Doorenbos and Pruitt, 1977). However, the average corn water use obtained under the green house culture was 625 mm.

Table 4.11: Field plot relative yield values for 1998/99 cropping season

water table depth range (mm)	Y^1 t/ha	$Y_{max}{}^2$ t/ha	$\frac{Y}{Y_{max}}$
≤ 500	2.0	3.7	0.54
≥ 600	**0.4**	1.1	0.4

[1]Y = yield values (1998 growing season)

[2]Y_{max} = maximum yield values (1999 growing season)

4.7 Economics of Sub-irrigation System Along Inland Valley Toposequence

The well – watered, well distributed inland valleys appear to offer a potential impact on food production even without irrigation backup. When this same maize crop is grown in a plot (upland) of negligible water table influence on the root zone, the cost of lift irrigation (dry season farming) for 2 m suction head and lift height of 1.5 m will amount to a total irrigation cost of:

₦10/m^3 x 0.4 m x 10^4 m^2 = ₦40,000.00

assuming unit water cost of ₦10/m^3 (Egharevba, 1996) and considering 1 ha farm plot.

However, with a suitable shallow water table in position along the inland valley toposequence, this irrigation cost could be saved. From this study, it is found that corn crop planted by September, that is, after harvesting the rainfed crops, can still produce reasonable yields. The September and October rains that established the crop contributed 62% of the corn water requirement while the remaining 38% (required for maturation and grain filling) were supplied from the gradient of water available along the toposequence. This indeed confirm that water, energy, and monetary savings are possible when existing shallow water tables are utilised for supplying crop water demand.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS.

5.1 Summary

This investigation had the four-fold goals of modelling the ground water table fluctuations, determination of corn yield response to water table heights, estimation of the percentage contribution of groundwater use to corn total water use and to obtain an expression for corn water use and corn yield under shallow water table conditions. The study began in 1996 with ground water level monitoring at the project location of Badeggi, Niger State, Nigeria.

Corn (Zea mays) were grown under greenhouse culture for three cropping seasons of 1997 to 1999 to determine the corn water use and corn yield in relation to water table depths. In 1998 and 1999, corn were also grown along two toposequence positions of the inland valley of plot size 2.5m x 5.2m each with three replicates. The seed beds in each plot were raised to 0.5m height.

The study showed that depressed yield occurred at very shallow water table depths of 100 mm to 300 mm. The optimum water table depth which resulted in maximum grain yield was at 450 mm water depth under the green house culture. The regression equation relating the corn water use (W) to the grain yield (Y) was linear ($Y = 0.09W + 0.02$; $r = 0.81$).

The corn growth indices of plant height and leaf area increased with increment in number of days after planting (DAP) until it got to between 70 to 80

DAP where it remained constant up to maturity and harvesting period for both the green house and field conditions.

The water table fluctuation in the inland valley can be described by both logarithmic expression and Fourier fitting curves. Corn yield in the field plot showed that the low water table plot of 600 mm to 800 mm resulted in lower grain yield for each year of cropping for 1998 and 1999 when compared with that at the high water table condition (200 mm to 500 mm). The grain yield at the low water table depth was 21% and 30% of that at high water table depths in 1998 and 1999, respectively.

The percentage groundwater use contribution to corn water use obtained from Eqs. 2.21 and 4.4 gave 37.3% and 16.3% for water table depths range of $\leq$ 500 mm and $\geq$ 600 mm, respectively. The cost saving on irrigation water (low lift irrigation system) under high water table condition, assuming unit water cost of ₦10/m^3 amounted to ₦40,000/ha.

5.2 Conclusions

From the results of this study, the following conclusions can be made:

1. The water table fluctuation in the project location (inland valley) can be better described by Fourier fitting curves. The upward movement of the groundwater level peaks at between August and September corresponding to the period of maximum rainfall amount.
2. Very shallow water table depth (100 mm to 300 mm) depressed yield due to reduced aeration associated with restricted growth and soil volume available for mineral nutrient. The best soil moisture regime for corn grown in controlled

(greenhouse) environment was found to be at 450 mm water depth. In addition, on the open field, results of this study have shown that a water table depth at 700 mm to 1000 mm can be a valuable natural water resources for corn production in a relatively dry year, considering the seed bed height (500 mm).

3. The expression relating the grain yield (Y, in kg/m^2) as a function of the corn water use (W, in m) was obtained as : $Y = 0.09W + 0.02$, while the trend equation under the green house culture for the corn yield (Y, in kg/m^2) with respect to water table depth (D, in m) was: $Y = 0.0017D^3 - 0.03D^2 + 0.1043D - 0.017$.
4. Water energy and monetary savings are possible when existing shallow water table are utilised for supplying crop water requirements. The groundwater contribution to corn water use from this investigation (along the inland valley toposequence position) was obtained to be greater than or equal to 37% for water table depths range of 200 to 500 mm (below the ground surface). Moreover, for unit cost of water at ₦10/m^3, a cost saving on irrigation (lift irrigation at 1.5m) amounting to ₦40,000/ ha can be achieved in crop (corn) production within an inland valley ecosystem (Southern Guinea Savannah). Thus, in developing an efficient schedule, the knowledge of groundwater contribution to crop water use together with its production functions under different soil water regimes is of practical importance.

5.3 Recommendations

The following recommendations will be helpful for further study on this research project.

1. Daily monitoring of groundwater fluctuations for crop water use, yield, and yield indices with adequate instruments will result in more generation of data/ data bank and make crop performance modelling more accurate.
2. The entire inland valley ecosystem should be studied as an integrated research and the results adopted and made available to farmers in the communities so as to improve their socio-economic status. The parameters of focus should include the topography, soils

   map, water quality, rainfall - runoff simulation, soil erosion pattern as well as the socio- economic impact. The results may then be adopted in other regions with similar climatic characteristics (Guinea Savannah).
3. Finally, it is recommended that in planning management scheme affected by water level fluctuations, all the factors that cause fluctuations as well as their interactions should be modelled with emphasis on local conditions in order to take advantage of optimisation in achieving set objectives at minimum cost.

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APPENDICES

Appendix A:

Predicted water table fluctuations using modified Zeeuw-Hellinga's modelling equation.

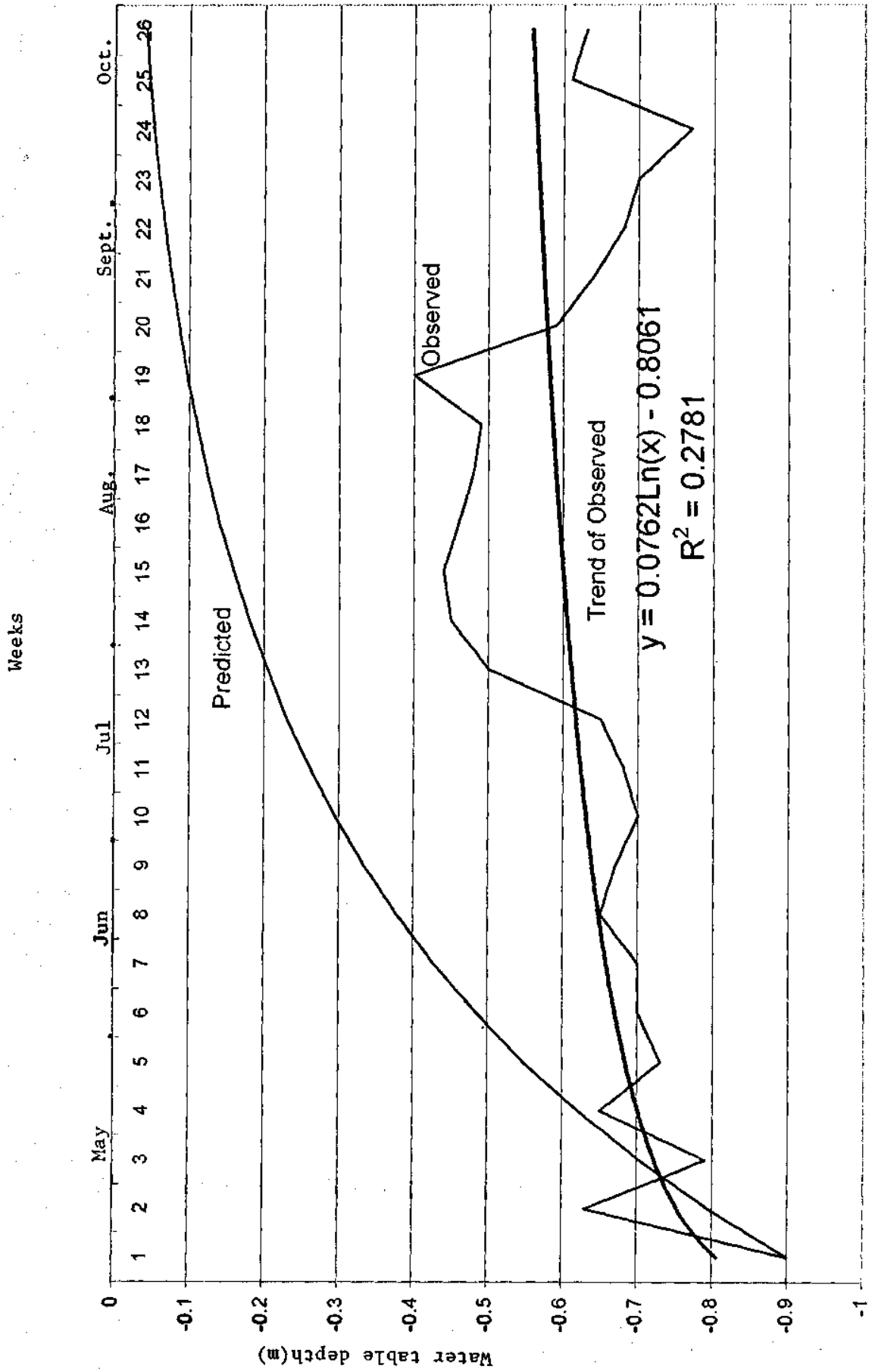


Fig. A.1: Water table hydrograph during wet season at piezometer 2.

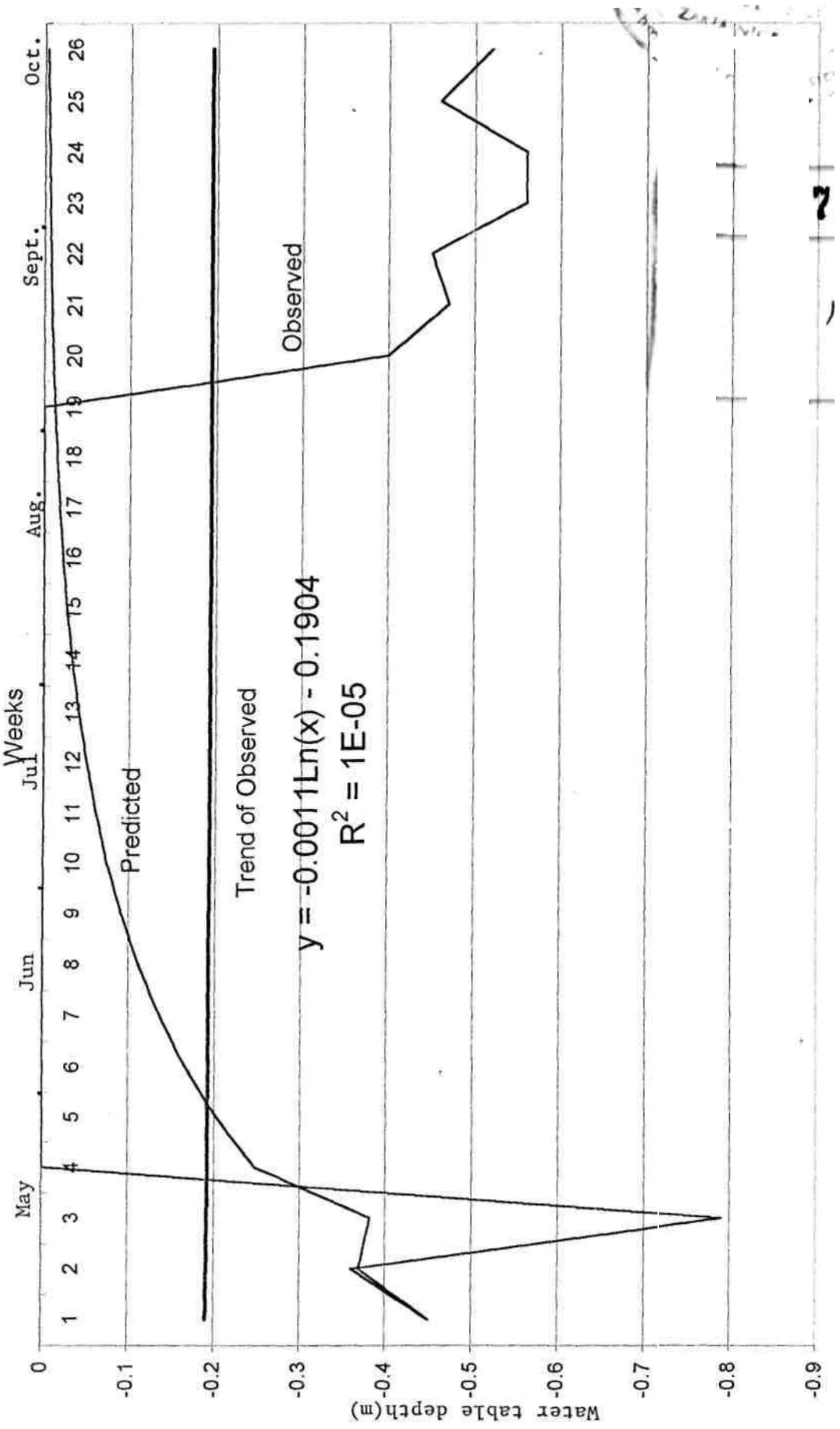
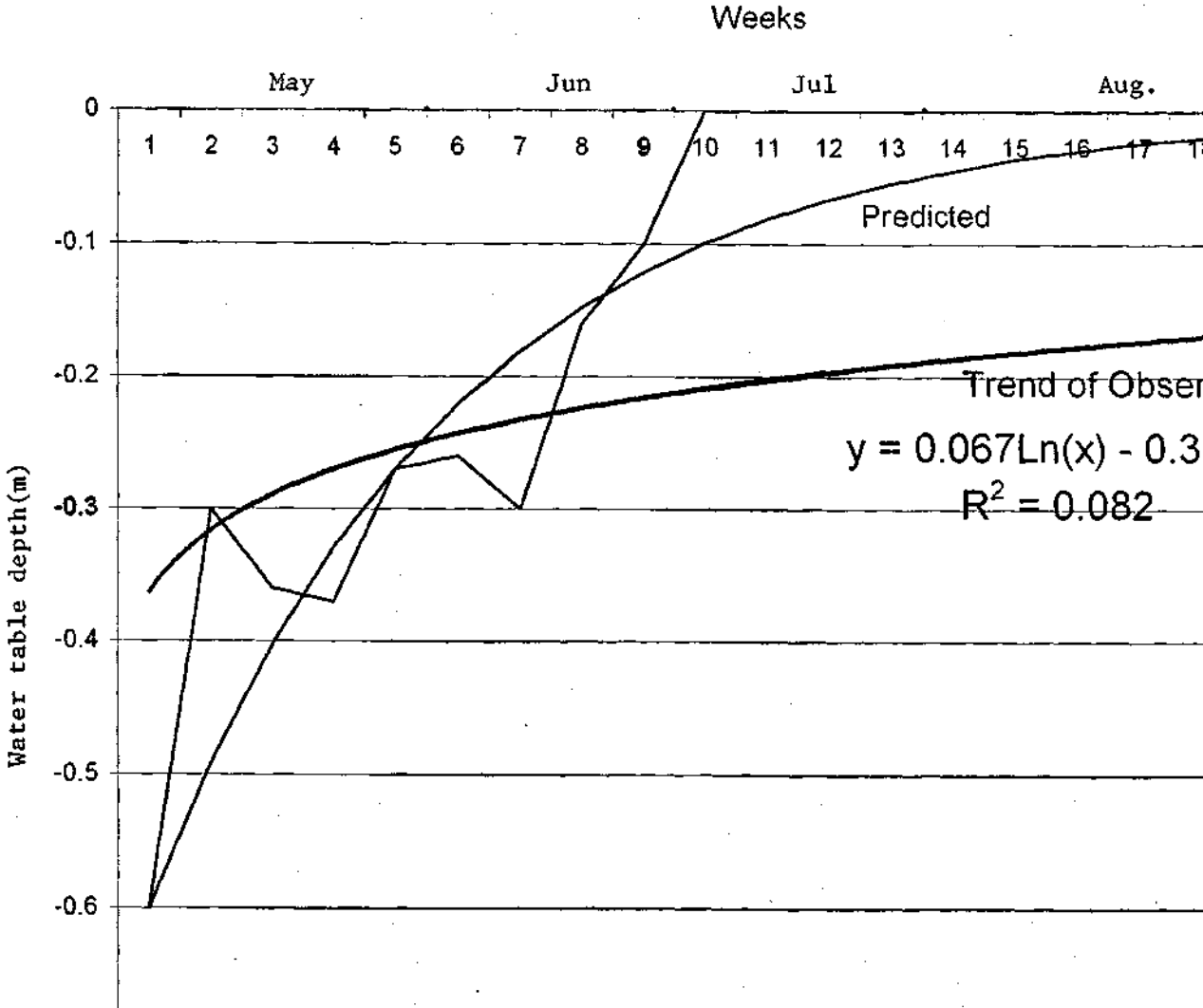
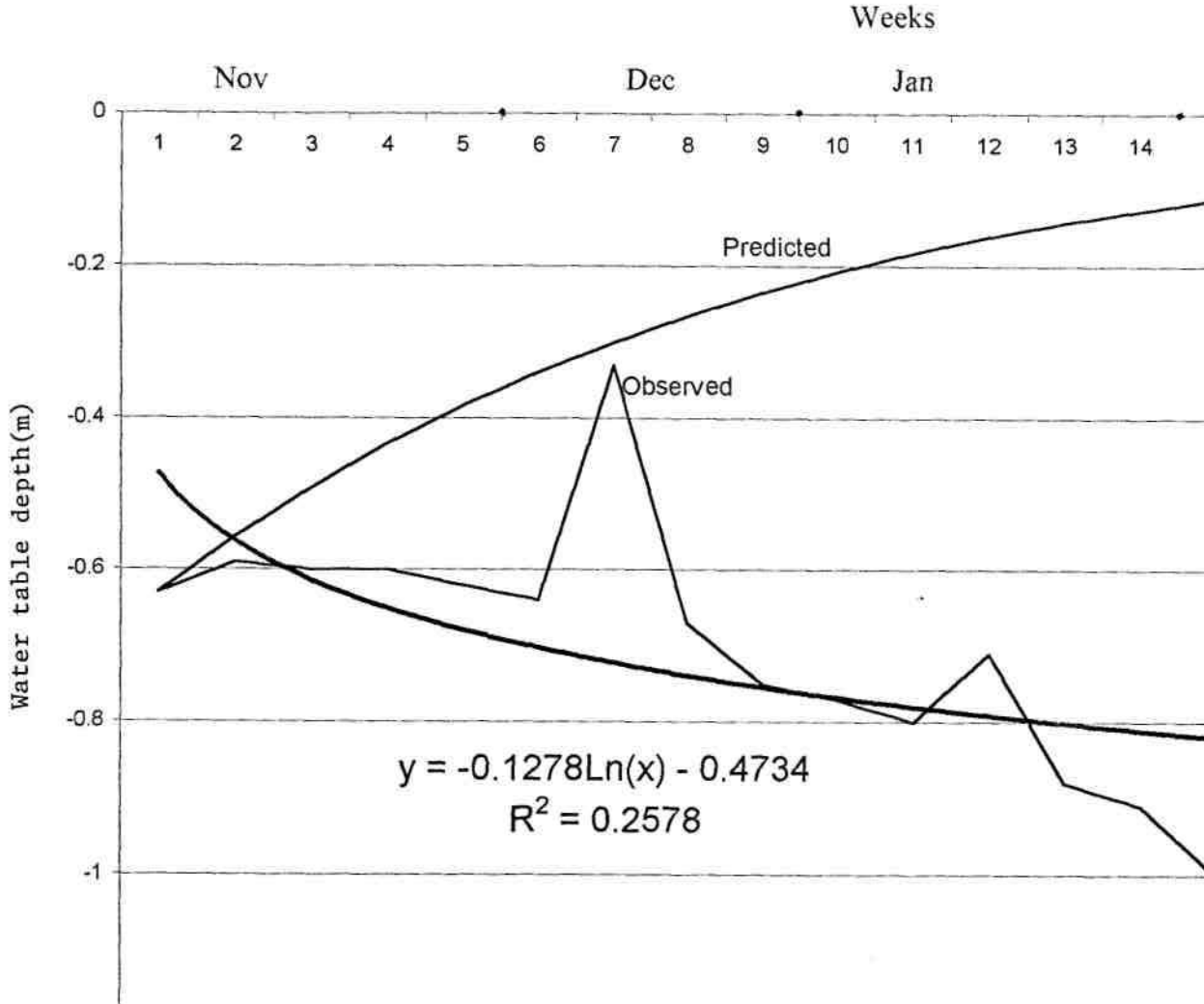


Fig. A.2: Water table hydrograph during wet season at piezometer 4.


Weeks
May
Jun
Jul
Aug.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Predicted
Trend of Obser
y = 0.067Ln(x) - 0.3
R2 = 0.082
Water table depth(m)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6


Weeks
Nov
Dec
Jan
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0
-0.2
-0.4
-0.6
-0.8
-1
Water table depth(m)
Predicted
Observed
y = -0.1278Ln(x) - 0.4734
R2 = 0.2578

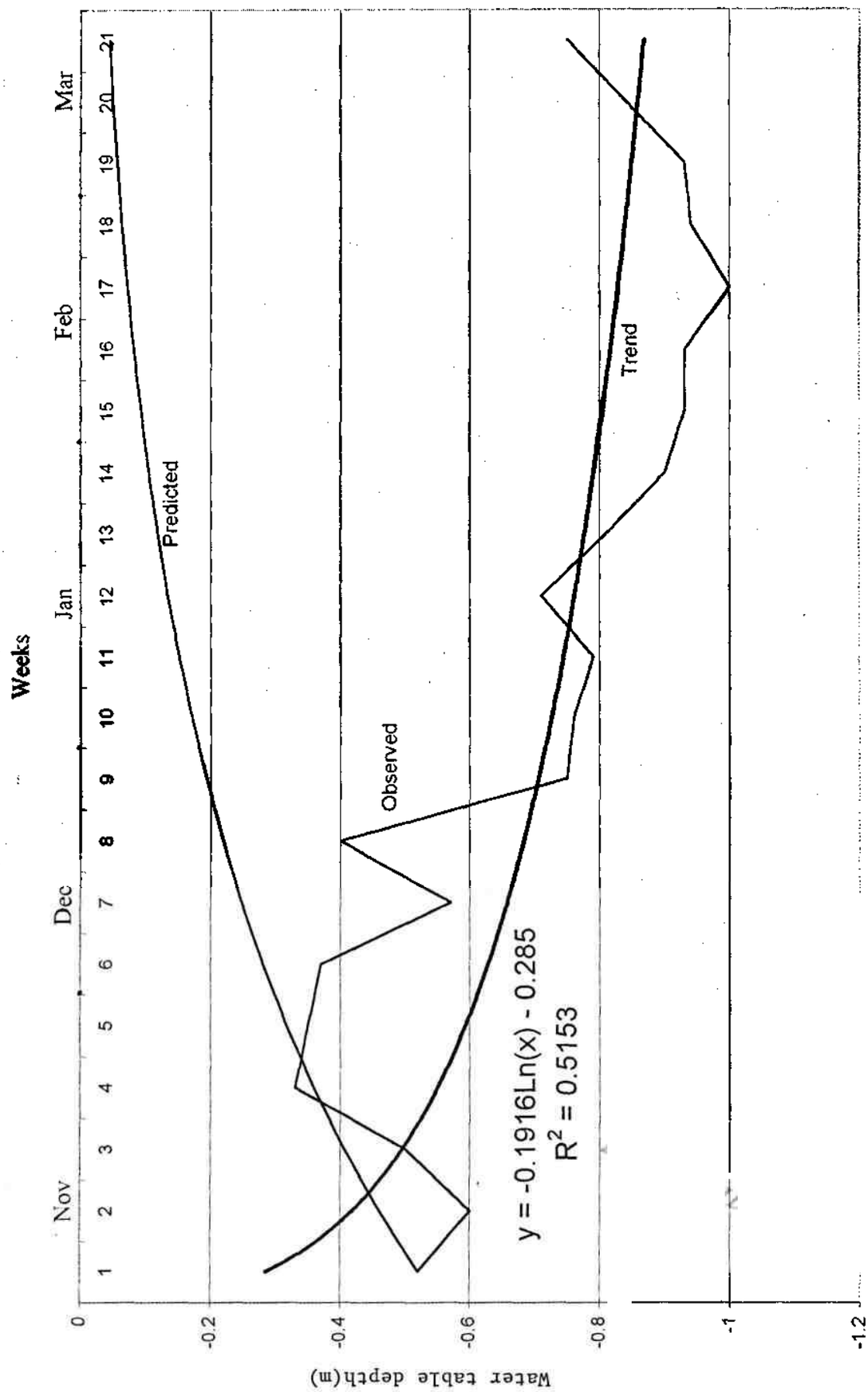


Fig. A.5: Predicted, trend and observed water table depth during dry season - piezometer 4

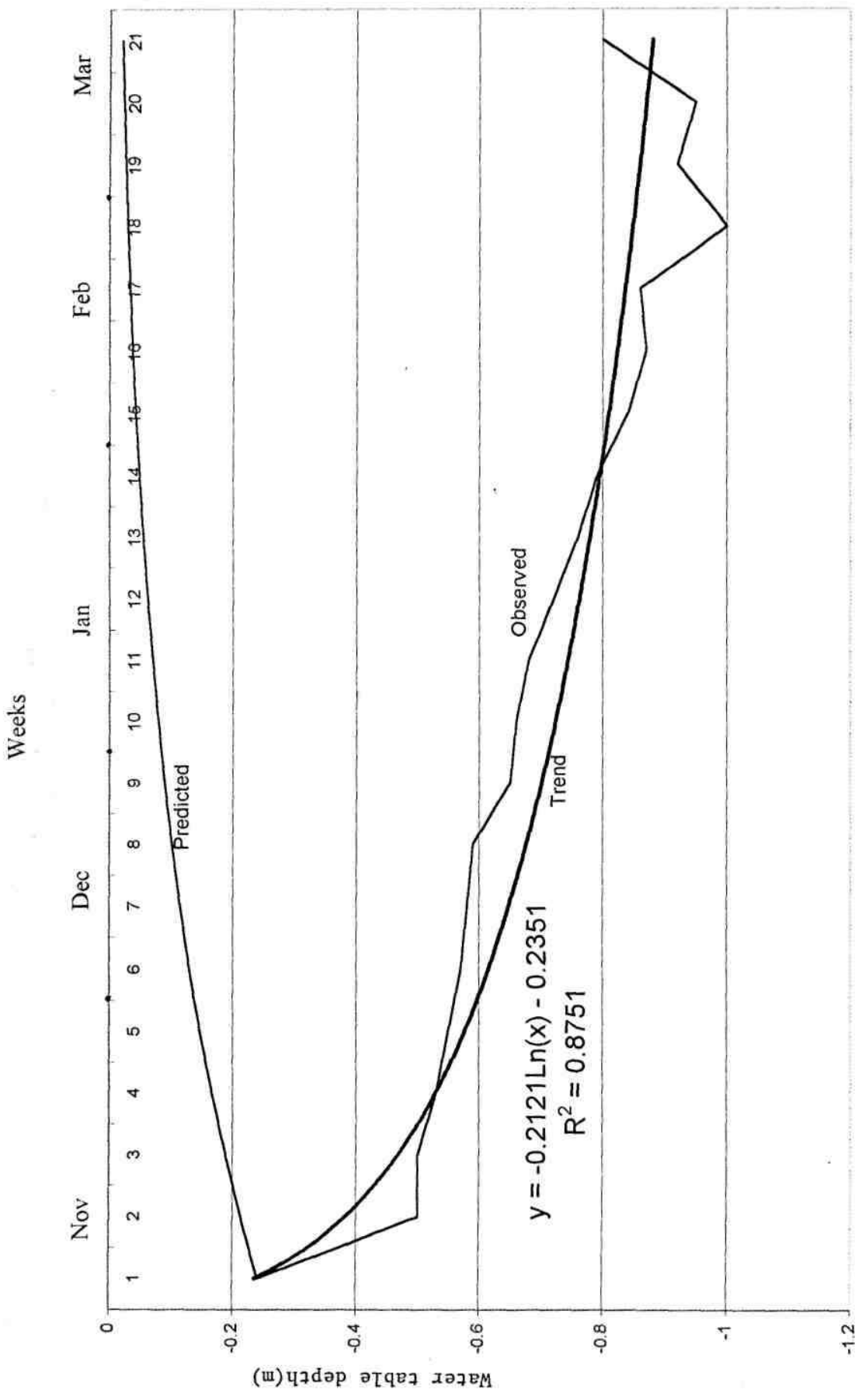


Fig. A.6: Predicted, trend and observed water table depth during dry season - piezometer5

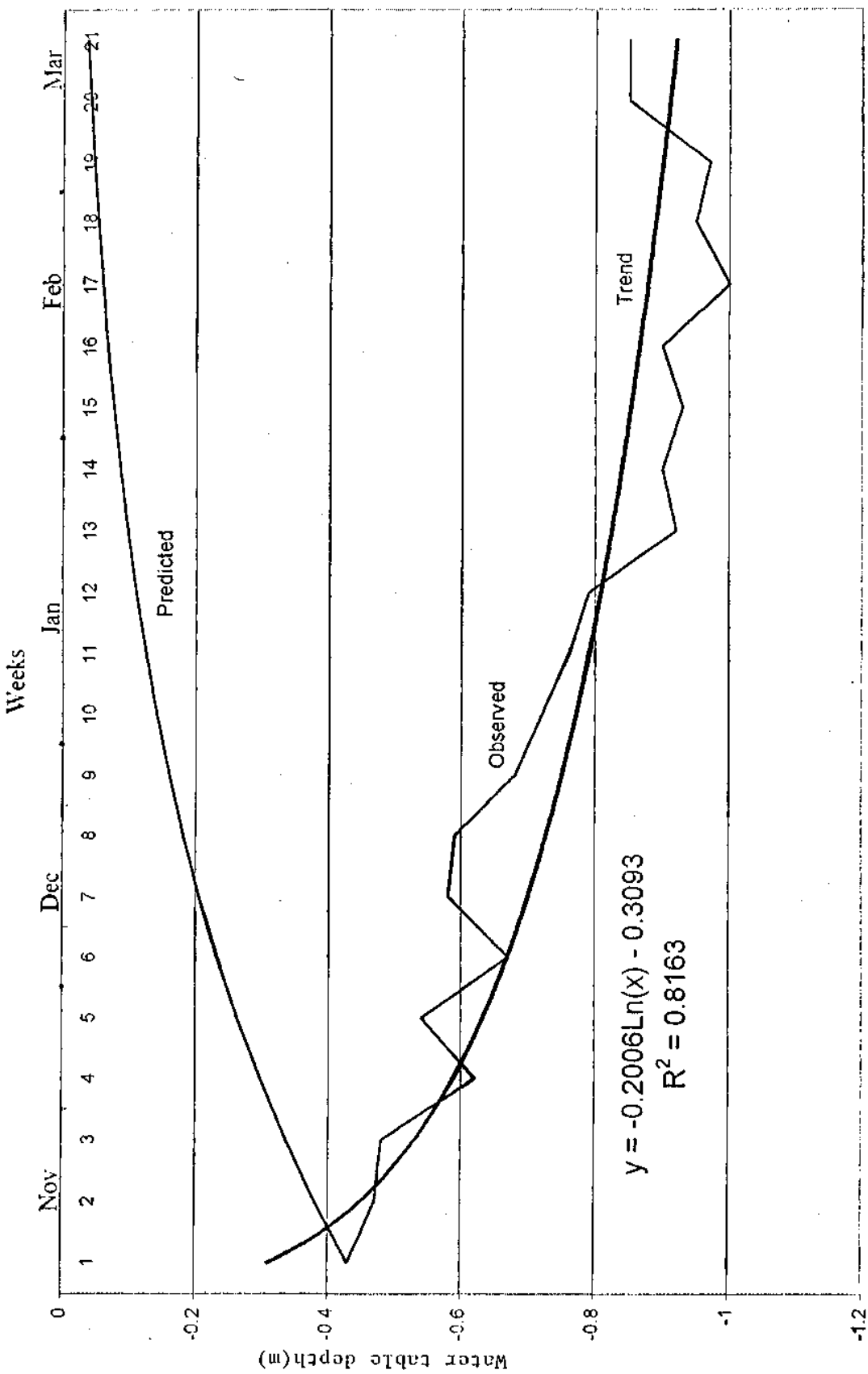


Fig A.7. Predicted, trend and observed water table depth during dry season - piezometer 6

Appendix B:

Fourier series coefficients at weekly time steps.

Table B1: Fourier series[1] coefficients

(a) Wet Season.

Piezometer	A_0	A_i	B_i
Tube 1	1.3794	-0.9854	-1.9151
Tube 2	1.4748	-1.10694	-0.8845
Tube 3	1.5213	-2.389	-1.2253
Tube 4	0.0732	-0.0625	-0.0827
Tube 6	-0.4168	-0.2383	0.1463
Tube 7	0.3637	-2.0153	-1.4286

(b) Dry Season.

Piezometer	A_0	A_i	B_i
Tube 1	1.2069	-0.5556	0.3573
Tube 2	0.4929	0.2668	0.3586
Tube 3	1.4757	-0.8939	0.2389
Tube 4	0.4360	0.3774	1.4958
Tube 5	0.6317	0.0457	1.2630
Tube 6	0.6844	0.3422	1.530
Tube 7	-0.0541	1.1277	0.5078

[1]The Fourier series for the parameters of a first order model at daily time step is expressed as

$$Y(t) = A_0 + \sum_{i=1}^{Cm} A_i \cos(i\tau) + B_i \, Sin(i\tau) = \sum_{j=0}^{j=k} \beta_j X_{jt} \qquad \text{from Eq. 2.17,}$$

for a weekly time steps, τ is modified to become:

$$\tau = \frac{\pi\ ((wk_{day}-3.5) - 182.5)}{182.5} \qquad \text{from Eq. 2.18}$$

where Wk_{day} is the Julian day at the end of the week, and the other symbols are as earlier defined.

Table B.2.: Chi-Square (x^2) Test[2] of observed water table levels and Fourier predicted values.

Piezometer Tube	Wet-Period	Dry-Period
1	0.7667	0.7702
2	0.2754	0.9017
3	1.8502	0.7579
4	8.2492[1]	0.4575
5	-	0.1497
6	4.1525	0.787
7	3.1877	0.8385

1. Other observed values were not significantly different from predicted values at 1% and 5% level of significance except tube 4 (wet-period).
2. Chi square (x^2) test: to test the significance of the difference between the observed (0b) and predicted (pr) frequencies, the following formula was used (Rasheed,1992):

$$x^2 = \sum \frac{(0b - \mathrm{Pr})^2}{\mathrm{Pr}}$$

The value obtained from computation are acceptable (i.e. Ob and Pr values are not significantly different) if and only if it is lower than the corresponding Table values at the given number of degrees of freedom and levels of significance.