ESTIMATION OF DIRECT RECHARGE IN THE SOKOTO-RIMA RIVER BASIN, NIGERIA

BY

OLUREMI EYITAYO AYOOLU OLU

A THESIS SUBMITTED TO THE POSTGRADUATE
SCHOOL, AHMADU BELLO UNIVERSITY, IN
PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF ENGINEERING
IN WATER RESOURCES AND ENVIRONMENTAL
ENGINEERING

DEPARTMENT OF WATER RESOURCES AND ENVIRONMENTAL ENGINEERING .
FACULTY OF ENGINEERING
AHMADU BELLO UNIVERSITY
ZARIA, NIGERIA.

AUGUST, 1985

DECLARATION

The work reported in this thesis was carried out by me under the supervision of Dr. L.I. Odigie. The work has not been previously published or accepted elsewhere for the award of any degree.

All works, opinions and ideas, other than mine have been fully acknowledged.

Oluremi Eyitayo Ayoolu Olu

August, 1985.

DEDICATION

for

jimoh bolaji, funke, bunmi,

bola, yinka and shayo Olu

in sincere appreciation.

CERTIFICATION

This thesis entitled "Estimation of Direct Recharge In The Sokoto-Rima River Basin,Nigeria" by Oluremi Eyitayo Ayoolu Olu meets the regulations governing the award of the degree of Master of Engineering (Water Resources and Environmental Engineering) of Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

Dr. L.I. Odigie
Chairman, Supervisory Committee

Date 20/9/85

Dr. S. Mustafa
Member, Supervisory Committee

2/9/85
Date

Dr. A. Kuzniar
Member, Supervisory Committee

Date

Prof. J.A. Ogunrombi
Head of Department

Date

Prof. G.E. Osuide
Dean, Post-Graduate School

4/XI/85
Date

ACKNOWLEDGEMENTS

I am very grateful to my supervisor for his able guidance, suggestions and kind efforts throughout the period of this work.

Very special thanks to my parents, both at Ilorin and Zaria, for their encouragement and financial support during the period of this work. I highly appreciate your efforts despite your individual difficulties.

My thanks to the departmental postgraduate Coordinator and members of staff of the Computer Centre for their kind suggestions and assistance.

Finally, I will like to put on record the love, care, encouragement and financial assistance I received from friends in Zaria, Ilorin, Kaduna, Bagauda, Jos, Kano, Sokoto, Maiduguri and Lagos in the course of this work. You are all too numerous to be mentioned, but all the same, it is full marks to you all for a job well done. Thanks and God bless.

ABSTRACT

This study was carried out to estimate direct recharge in the Sokoto-Rima river basin, Nigeria, using a soil moisture deficit model. Thereafter, the sensitivity of the model to input and model parameters was investigated. The mean annual recharge for the study period was found to be 255.0mm. The incidence of recharge was validated by comparison of the recharge estimates with well hydrographs obtained in the region. Further studies would be required before the amount of recharge can be fully validated.

The results of the sensitivity analysis show that variations in rainfall and potential evapotranspiration values significantly affect the direct recharge values. From the experience gained in this study, one would call for a more efficient system for data collection, storage and retrieval.

TABLE OF CONTENTS

Chapter		Page
	Declaration	i
	Dedication	ii
	Certification	iii
	Acknowledgements	iv
	Abstract	v
	Table of Content	vi
	List of Tables	x
	List of Figures	xii
	List of Appendices	xiv
1	INTRODUCTION	1
1.1	Objective	1
1.2	General	1
1.2.1	Justification of the study ...	2
1.3	Outline of Work	2
2.	LITERATURE REVIEW	6
2.1	Water Balance Method... ...	6
2.2	Lysimeter Method	8
2.3	Tracer Method	10
2.3.1	Natural tracers	10
2.3.2	Artificial tracers	11
2.4	The Soil Moisture Deficit Model	12
2.5	Conclusion	22

Chapter		Page
3	THE SOIL MOISTURE DEFICIT MODEL	23
3.1	Available Moisture	23
3.2	Availability of Soil Water ...	23
3.2.1	Equal availability	24
3.2.2	Gradually decreasing availability	24
3.2.3	Equal availability followed by decreasing availability ...	26
3.3	Description of the Soil Moisture Deficit Model	26
3.4	Conclusion	32
4	THE STUDY AREA AND ESTIMATION OF MODEL PARAMETERS ...	33
4.1	Description of the Study Area	33
4.1.1	Location and extent	33
4.1.2	Topography	33
4.1.3	Geology	35
4.1.4	Hydrogeology	37
4.1.5	Drainage	37
4.1.6	Climate	39
	Rainfall	40
	Potential evapotranspiration	40
	Temperature and humidity ...	43
4.1.7	Vegetation and soils... ...	43
4.1.8	Land use	44

Chapter		Page
4.2	Sources of Input Data.. ...	44
4.2.1	Water level records	46
4.3	Model Parameters	46
4.3.1	Areally weighted maximum soil moisture deficit (WD) ...	46
4.3.2	Areally weighted root constant (WC)	47
4.3.3	Runoff coefficient	48
4.3.4	Correction factor	52
4.3.5	Weighting factors	52
4.4	Basin Recharge	53
4.5	Description of The Structure of The Computer Program... ...	54
4.6	Sensitivity Analysis... ...	55
4.7	Problems Encountered... ...	57
5	RESULTS AND DISCUSSIONS ...	58
5.1	General	58
5.2	Direct Recharge Estimates ...	58
5.2.1	Sokoto-Rima river basin ...	59
5.2.2	Gwadabawa station polygon ...	66
5.2.3	Koko station polygon ...	74
5.2.4	Yabo station polygon ...	81
5.3	Sensitivity Analysis ...	86
5.3.1	Zonal rainfall (ZNRAIN) ...	87
5.3.2	Potential evapotranspiration (PET)	87
5.3.3	Runoff coefficient	92
5.3.4	Root constant (C) and maximum soil moisture deficit (D)... ...	92

Chapter		Page
5.3.5	Slope of drying curve.. ...	93
5.3.6	Effect of parameter variation on number of days of recharge (NDR)	94
5.3.7	Amount and incidence of recharge	94
5.4	Isorecharge Map	96
5.5	Validation of Incidence of Recharge	96
5.6	Conclusion	109
6	RECOMMENDATIONS AND CONCLUSION	111
6.1	Objectives Achieved	111
6.1.1	Sensitivity of recharge estimates	113
6.1.2	Validation of recharge estimates	114
6.1.3	Variation of basin recharge ...	114
6.2	Recommendation and Suggestion for Further Studies	114
6.2.1	Recommendations based on the results of the study...	114
6.2.2	Suggestion for further studies	116
6.3	Conclusion	117
	REFERENCES	119
	APPENDIX	126

LIST OF TABLES

Table		Page
4.1	Description of some water bearing formations in the Sokoto-Rima river basin	38
4.2	Monthly values of crop root constant and maximum soil moisture deficit (for 1963) in Argungu station polygon	49
4.3	Areally weighted C and D (mm) (Koko station polygon)	50
5.1	Monthly and annual recharge estimates in Sokoto-Rima river basin ...	60
5.2	Analysis of estimated annual recharge in Sokoto-Rima river basin ...	65
5.3	Estimated monthly and annual recharge (mm) in Gwadabawa station polygon	67
5.4	Analysis of estimated annual recharge in Gwadabawa station polygon ...	73
5.5	Estimated monthly and annual recharge (mm) in Koko station polygon ...	76
5.6	Analysis of estimated annual recharge in Koko station polygon ...	80
5.7	Estimated monthly and annual recharge (mm) in Yabo station polygon ...	83
5.8	Sensitivity analysis using weighted monthly, weighted annual and weighted grand totals (Sokoto-Rima river basin)	88

Table		Page
5.9	Sensitivity analysis using average monthly, average annual and grand totals (Gwadabawa station polygon)	89
5.10	Sensitivity analysis using average monthly, average annual and grand totals (Koko station polygon) ...	90

LIST OF FIGURES

Figure		Page
1	Drying curve for a vegetated soil	25
2	Flow chart of the subprogram (subroutine)	27
3	Map of study area	34
4	Geological map of study area ...	36
5	Rainfall isohyets, rainfall stations and polygons in the study area ...	41
6	Monthly rainfall and potential evapotranspiration in Sokoto-Rima river basin	42
10	Comparison of monthly recharge, rainfall and actual evapotranspiration in Sokoto-Rima river basin ...	63
11	Comparison of monthly recharge, rainfall and actual evapotranspiration in Gwadabawa station polygon ...	71
12	Comparison of monthly recharge, rainfall and actual evapotranspiration in Koko station polygon ...	78
13	Comparison of monthly recharge, rainfall and actual evapotranspiration in Yabo station polygon... ...	85
14	Sensitivity of model to variation of ZNRAIN (Sokoto-Rima river basin)..	91
15	Sensitivity of model to variation of ZNRAIN (Gwadabawa station polygon)	91

Figure		Page
16	Sensitivity of model to variation of ZNRAIN (Koko station polygon)	91
17	Sensitivity of model to variation of PET (Sokoto-Rima river basin) ...	91
18	Sensitivity of model to variation of PET (Gwadabawa station polygon)...	91
19	Sensitivity of model to variation of PET (Koko station polygon) ...	91
20	Variation of recharge across the Sokoto-Rima river basin (1962) ...	97
21	Variation of recharge across the Sokoto-Rima river basin (1963) ...	98
22	Average annual recharge across the Sokoto-Rima river basin (1960-1965)	99
23	Comparison of monthly recharge (1962-1964) in two polygons with well hydrographs	103
24	Comparison of monthly recharge (1962-1964) in Sokoto station polygon with well hydrograph	103
25	Geological section across the Sokoto-Rima river basin. After Oteze (1976)	106

LIST OF APPENDICES

APPENDIX		Page
I	Flow chart for main program...	126
II	Structure of the nested DO loops in the main program	127
III	Computer program used for recharge estimation	128

CHAPTER 1 INTRODUCTION

1.1 Objective

The purpose of this project work was to estimate direct recharge in the Sokoto-Rima river basin, Nigeria, using a soil moisture deficit model and then to determine the sensitivity of the direct recharge estimates to input data and model parameters.

1.2 General

Recharge is the amount of surface water which replenishes the groundwater storage. Recharge takes place when surface water seeps into groundwater storage from the riparian zone, and/or when surface water infiltrates the soil surface and subsequently percolates to groundwater storage. Recharge is of two types, namely, natural and artificial.

Natural recharge can be either direct or indirect recharge. Direct recharge refers to recharge by infiltration of rain at the place where the rain falls. Indirect recharge refers to recharge which occurs when rain first becomes surface runoff and later infiltrates through stream beds or the floors of local areas of concentration, depression or flats. In either case the moisture-holding capacity of the soil at the point of infiltration must first be replenished and only then can water percolate downward to the goundwater body (Jones, 1981).

Artificial recharge is recharge that is brought about due to man's deliberate action.

1.2.1 Justification of the study

The groundwater reserves of any nation is a vital resource which can be exploited to meet it's water demand. The sahelian drought which hit Nigeria, has resulted in desert encroachment, low riverflow, drying up of surface reservoirs and crop failures. For this reason, there is the need to exploit our groundwater reserves on a large scale in order to meet the water demands of agriculture, domestic and industrial water supply.

It should however be noted that in carrying out large scale exploitation of our groundwater reserves, it is very important to estimate recharge to these reserves so as to be able to optimally utilize and efficiently manage our groundwater reserves. And by so doing, we can avoid the hazards of falling water tables, as is presently reported in the Lake Chad basin, Nigeria (Aminu, 1984).

1.3 Outline of Work

The study area of this project is the Sokoto-Rima river basin, Nigeria. The working map used was according to Kowal and Knabe (1972). The recharge area was delimited based on the geological and soil maps of the basin. The entire basin was divided into 14 polygons using Thiessen's method. The point rainfall in each polygon was obtained from the published records of the British West Africa Meteorological service and Meteorological service, Federation of Nigeria. (1960 to 1965). A corrected version of the daily rainfall over each polygon was obtained by multiplying the daily rainfall at each station by a correction factor. The root constants and maximum soil moisture deficits for the crops and soil types in each of the polygons were calculated and weighted areally using landuse and cropping area percentages obtained from Agboola (1979). The potential evapotranspiration estimates used were those calculated by Kowal and Knabe (1972), based on meteorological data from five synoptic stations, two of which are located in the study area while the other three are fairly close to the study area. Runoff coefficients over the basin were calculated from the separation of hydrographs of the three major rivers that drain the basin. All area measurements were carried out with a planimeter.

Direct recharge estimates were carried out by a computer program which consists of a main program and a subroutine that was written, based on a soil moisture deficit model developed after the work of Penman (1949) and Grindley (1967). The estimates were carried out on a one day time step. The computer program was run on a digital computer, CYBER-72 interactive system, located at the Ahmadu Bello University Computer Centre, Zaria, Nigeria. The computer program calculates the direct recharge over each of the 14 polygons separately and the annual mean basin recharge is calculated by areally weighting and summing up the annual recharge over all of the polygons. The mode of operation of the computer program is such that a main program assigns the polygon, year, month and day for which recharge is to be estimated and the recharge estimates are carried out in a subroutine which is called within the main program.

A sensitivity analysis was carried out to determine the sensitivity of the model to input data and model parameters. This consists of varying the input data and model parameters by various percentages and using these new values to run the program. A comparison is then made between the new recharge estimates obtained and the original recharge estimates.

The disposition of this project work is such that in the second chapter, a review of the various methods of direct recharge estimation is presented, while in the third chapter, the theoretical background and description of the model is given. The fourth chapter gives a description of the structure of the computer program used, the study area and how the model parameters and input data were obtained. Some of the problems encountered in the course of the study are also discussed. In the fifth chapter, the results obtained are presented, analysed and discussed, while in the sixth chapter conclusions are drawn based on the results of the analysis of the preceding chapter.

CHAPTER 2 LITERATURE REVIEW

In this chapter, a review of the various methods of direct recharge estimation and comments on them are presented.

2.1 Water Balance Method

Jones (1981) gives the recharge equation used in this method as

$$DRECH_t = P_t - DRO_t - ETP_t \pm S_t \quad 2.1$$

where $DRECH_t$ = direct groundwater recharge during time interval, t.

P_t = rainfall during time interval, t.

DRO_t = direct runoff during the time interval, t.

ETP_t = evapotranspiration from soil moisture during time interval, t.

S_t = change in soil moisture storage during time interval, t.

Kowal (1970), carried out a study on a small catchment in Samaru, Nigeria between 1966 and 1968 and estimated annual seepage (recharge) from the catchment using this method. He however regarded his results as tentative because according to him, their precision can only be evaluated from the results of several years of observations. Kowal and Knabe

(1972) later used this method to prepare a notional water budget for Northern Nigeria and in the process, "contribution to groundwater storage" (recharge) in the 20 polygons into which the entire study area was divided, was estimated on a ten-day basis. The recharge values obtained over the study area range from zero to 652 mm.

The advantage of using this method lies in it's simplicity, while it's disadvantages include (a) the difficulty of measuring actual evapotranspiration from the soil surface (b) the inherent assumptions (i) that estimates of input parameters into equation 2.1 will be error free, (ii) that infiltration rates over the area which it is applied is uniform and (iii) that for the time interval (usually annual) for which equation 2.1 is applied over a given area there is no surface inflow. These assumptions, which are not always true in any given catchment, makes recharge estimates by this technique prone to a lot of errors.

(c) It also does not account for variation of soil and landuse in a catchment, hence assumption b (ii).

(d) When used over very large areas with depressions, not all the balance, after the losses have been subtracted from precipitation, go into groundwater storage. Some also go into the depressions to form depression storage.

2.2 Lysimeter Method

A lysimeter is an artificial device in which a volume of soil planted with vegetation is isolated hydrologically from the surrounding soil (Michael, 1978). It can be used to estimate recharge by simply measuring the amount of water that drains from it's base by gravity. In spite of its simplicity, Kitching et al. (1977) have observed the following disadvantages of using it.

(i) Lysimeters are usually small in size (area and volume) compared with the basin into which recharge is being estimated, thus they do not fully represent the entire basin, they restrict natural root development and introduce large edge effects.

(ii) The repacked soils used do not present, the characteristic natural root development and water flow in the soil.

(iii) Most lysimeters allow for free drainage at the bottom, which is not a natural phenomena.

(iv) Most lysimeters are usually not surrounded by the same type of vegetation in the lysimeters, because the lysimeter vegetation are usually selected for planting.

Holmes and Colville (1970), set up four lysimeters for investigating the water balance of the Gambier plains, South Australia. They gave the water balance of a lysimeter as:

$$P = E + V + \Delta D + \Delta S \qquad 2.2$$

where P = precipitation (measured by rain gauges installed near the lysimeters). E = evaporation (measured by monitoring the soil moisture content recorded by neutron moisture meters installed at different depths of the lysimeters). V = volume of water pumped from the lysimeter (recharge). ΔD = the increment of water held in the sump of the lysimeter (measured by electrical probe). ΔS = increment of water held in the soil profile above the sump (measured by tensiometers installed at various depths in the lysimeter). The recharge estimates obtained from their investigation was however found to be about 58 percent higher than those from an investigation conducted later by Allison and Hughes (1974), who used the tritium tagging method at a site within one kilometre of the lysimeters. This difference, according to Allison and Hughes (1974), may not be unrelated to the non-allowance for surface drainage by the lysimeters.

Kitching and Bridge (1974) and Kitching et al. (1977) set out to overcome the disadvantages earlier mentioned, by designing, constructing and operating a sophisticated lysimeter which attempted to reproduce the natural conditions in the Bunter Sandstone at Styrrup, Nottinghamshire, England. After 3 years of operating the lysimeter, it was observed that the 3-year mean measured recharge was about 175 percent of the estimated recharge using the conventional root constant values and that the measured recharge was consistently greater than the estimated recharge in all the 3 years. The reason adduced for this difference was the over estimation of actual evapotranspiration by the use of conventional root constant values, which are empirical and believed to be high.

Apart from the disadvantages previously mentioned, lysimeters are usually expensive to set up and tedious to operate, as it takes a long time to establish vegetation on them and stabilize the disturbed soils.

2.3 Tracer Method

A tracer as used in groundwater studies, can be defined as a substance whose presence in groundwater provides a means of monitoring groundwater motion, recharge and "age", by determining their concentration in groundwater samples. Tracers used in groundwater studies are of natural and artificial origin.

2.3.1 Natural tracers

While reviewing methods of recharge estimation used in Australia, Williamson and Lawrence (1981), described how inert natural ions (chloride/Bromide ions) can be used to trace movement of water from the surface to the groundwater. They however observed that the method gives lower recharge estimates when compared with other methods. Smith et al. (1970), Atakan et al. (1974), Dincer et al. (1974), Vogel et al. (1974) have all described various methods of using natural tritium in estimating recharge. They also used these methods in estimating recharge in their respective study areas.

2.3.2 Artificial tracers

Artificial tritium, either from thermonuclear tests or laboratory sources, is a common tracer used in recharge estimation, because of it's stability and non-toxic nature. The use of tritium to estimate recharge is based on the concept of soil water movement known as the "piston-flow model", developed by Zimmermann et al. (1967a, 1967b).

Athavale et al. (1980) described a method of using artificial tritium to estimate recharge. Tritium injection sites in a basin are chosen based on how well the sites represents the geology, topography, drainage pattern and soil types of the basin. At the various injection sites, known concentrations of tritium are injected below the root zone before the commencement of the rains.

After the rains, soil core samples are taken and the soil moisture content, bulk density and tracer concentrations at various depth intervals along the core samples are taken. A plot of tracer concentration against depth gives the tritium profile. With the tritium profile, the movement of the tracer can be monitored and the displacement of the tracer from the injection depth determined. Recharge per square centimeter of the soil (W_h) was calculated by using:

$$W_h = \left[M_d/(100 + M_d)\right] \gamma_w h \qquad 2.3$$

where

M_d = dry weight percent of soil moisture

γ_w = wet-bulk density of the soil in situ.

h = displacement of tracer, i.e. the distance between injection depth and the centre of gravity of the profile.

This method has high capital, equipment and manpower requirements. It assumes vertical flow, which is not always true.

2.4 The Soil Moisture Deficit Model

The soil moisture deficit model for recharge estimation was developed from the studies carried out by Penman (1949) and Grindley (1967). Recent studies by Odigie (1983) indicate that by calculating soil moisture deficits and actual evapotranspiration using a set of conditions, the model estimates recharge through the upper soil zone and, it adequately represents the moisture status of the soil.

Potential recharge is usually taken as the remainder when potential evapotranspiration, PET, and direct runoff, DRO, have been subtracted from rainfall, P. In general the water balance equation for a specified period can be written as:

$$P = PET + DRO + \Delta S \qquad 2.4.$$

where ΔS is potential change in storage.

Equation 2.4 can be rewritten as:

$$\Delta S = P - DRO - E_T \qquad 2.5$$

where negative values of ΔS implies an increase in soil moisture deficit (SMD) while positive values indicate potential recharge.

The accuracy obtained from this method depends on the accuracy of the input data. The determination of the evapotranspiration term in equation 2.5 is however prone to certain errors. The term can be measured directly (for instance by lysimeters or evaporation tanks) or indirectly by empirical formulae, such as Penman (1948) formula. Both methods will be relevant only to the extent that evapotranspiration takes place at the potential rate. When evapotranspiration ceases to take place at the potential rate, the point of divergence between potential evapotranspiration (PET) and actual evapotranspiration (AET) is dependent on the soil and vegetation property, referred to as the root constant. The root constant is a measure of the amount of water readily available within the root zone (Penman, 1949).

When the soil is at field capacity, evapotranspiration takes place at the potential rate, because water is adequately supplied to the plant root, there is therefore a reduction in the soil moisture storage by (ΔS) which creates a soil moisture deficit of the same magnitude as ΔS. If the SMD is not checked it continues to increase, and evapotranspiration will take place at the potential rate until the root constant (C) is reached. When the root constant is exceeded, evapotranspiration ceases to take place at the potential rate, because the amount of water freely available for evapotranspiration is restricted. The actual change in storage (ΔS) will now be equal to a factor, F, of the potential change in storage and equation (2.5) becomes:

$$\Delta S = F\ (P - DRO - PET) \qquad 2.6.$$

Indeed equation (2.5) can be written in terms of the actual evapotranspiration (AET) as:

$$\Delta S = P - DRO - AET \qquad 2.7.$$

combining equations (2.6) and (2.7) gives

$$AET = (1.0 - F)\ (P - DRO) + F \times PET \qquad 2.8$$

F is the slope of the drying curve.

The use of equation (2.8) can be demonstrated by assuming, for now, two simple conditions.

(a) When P = 0, DRO = 0 and SMD $<$ C, then F = 1 and from equation (2.8), AET = PET.

(b) When P = 0, DRO = 0 and SMD $>$ C, from equation (2.8), AET = F x PET.

For obvious reasons, other conditions different from the two stated above do arise, such as both or one of the values of either P or DRO being greater than zero. These conditions will be discussed in greater details in the next chapter.

In a situation where rainfall is greater than the potential evapotranspiration, the incoming rainfall first satisfies the evaporative demand before the effective rainfall infiltrates and reduces any existing soil moisture deficit. When the soil moisture deficit is fully made up, the remainder of the infiltrated water percolates downwards to recharge the groundwater storage.

Penman (1950) carried out a water balance of the Stour Chalk Catchment, England by calculating the mean monthly and annual change is storage (recharge) in three presumed land uses over a 15-year period, using the conventional values of root constant and maximum soil moisture deficits (conventional method). He plotted the estimated mean monthly and annual change in storage (recharge) against the observed mean monthly and annual change in well water level. From his plots, he asserted that "......the estimates give a good picture of the changes in storage in the Stour catchment."

Although his plots show a lag between the estimated mean monthly/annual change in storage (recharge) and the observed mean monthly/annual change in well water level. However, the plot of the estimated mean monthly/annual change in storage generally follow the same trend as the plot of the observed mean monthly/annual change in well water level. This observation justifies his assertion.

Lloyd et al. (1966) used the soil moisture deficit model to estimate direct recharge in North eastern Jordan between 1962 and 1965.

Gindley (1967), presented calculations of soil moisture deficits over Great Britain, based on the work of Penman (1949, 1950). He calculated the soil moisture deficits over two landuse area, for two seasons when (i) evaporation exceeds rainfall and (ii) rainfall exceeds evaporation. He assumed there was no soil moisture deficit over the riparian zone. Based on his results, he produced maps of soil moisture deficit over Britain, which he recommends for use as aid in flood warnings. Grindley (1969, 1970) also estimated actual evapotranspiration from soil moisture deficit calculations.

Jones (1981) reported that Lloyd in 1969 estimated direct recharge to the Sandstone Aquifers of South Jordan using the soil moisture deficit model. Recharge estimates were carried out on a ten-day time step by calculating the water budget in the top soil layers of the recharge areas.

Headworth (1970) used the modified form of a computer program, after the work of Grindley (1967), together with data from the Hampshire Downs Chalk outcrop, England to demonstrate that the most suitable root constant for use on the agricultural area of the Downs is 25 mm instead of the 75 mm that was normally used.

Rushton and Ward (1979), contended that there are uncertainties in the existing methods of direct recharge estimation and after reviewing the findings of several authors, they concluded that the conventional method usually prevents the occurrence of summer recharge. Using a conceptual model they obtained results which led them to suggest alternative recharge methods which allow for recharge despite the presence of a regional soil moisture deficit.

In all, nine different methods (the conventional method inclusive) were proposed and all of them were used to estimate recharge to the North Lincolnshire Chalk Aquifer, England, over a 15-year period (1961 to 1975). They assessed the recharge estimates obtained for compatibility with field behaviour, and they concluded that:

(i) the most realistic recharge method is yet to be ascertained, but they advised that it must combine most of the assumptions of the previously suggested alternative methods, in order for it to highlight the complexity of the recharge process;

(ii) field behaviour is best represented only when recharge is allowed to occur when there is a regional soil moisture deficit.

Howard and Lloyd (1979) estimated recharge into the North Lincolnshire Chalk Aquifer, England using the conventional Penman-Grindley method. The sensitivity of the model to input data and model parameters was also determined by varying the original value of the input data and model parameters and using the varied values to estimate recharge. The percentage difference between the new and model recharge estimates gave the sensitivity level of the model to variation of an input data or model parameter.

Also, recharge estimates were carried out on a one-day, ten-day and monthly time step with the daily time step found to be most suitable.

Henry and Palmer (1980) carried out a study in the Callide Valley alluvium, Central Queensland, Australia, using a root zone model which describes moisture behaviour in the main root zone and a clay layer model, whose input was the deep percolation from the root zone model. The clay layer model simulates interflow, deep percolation and consumptive use by large trees. They claimed that the recharge estimates they obtained from the model were in agreement with the values obtained for the same area, using other methods.

Hadgraft and Volker (1980) developed and described a numerical model that was used in assessing rainfall recharge (direct recharge) in the Burdekin Delta aquifer, North Queensland, Australia. This model significantly differs from others due to it's incorporation of recharge from depression storage. But the silence of it's authors on the mode of estimating actual evapotranspiration and on validation of results obtained from it restricts it's application elsewhere.

Sarma _et al._ (1980) developed and described a computer model which divides the crop root zone into segments and computes the water balance in these segments and the entire zone. When used on actual field data (tensiometer measurements, soil moisture tension/soil moisture content curves) the model computes, among others, the daily, evapotranspiration, change in storage within the segments and within the entire root zone, drainage (recharge) from the root zone, infiltration, surface detention and runoff. This model is no doubt a sophisticated model but it's weakness lies in it's suitability over small areas only, because applying it on a large area will be expensive as it will require the installation and monitoring of a lot of tensiometers and moisture probes installed in all the different landuse that abound in that area. Also, it seems that the primary concern of the model is the moisture conditions within the root zone and that drainage (recharge) estimation is only of secondary importance.

Calder _et al_.(1983) used data from six experimental sites in England to test the ability of 35 different models to predict soil moisture deficit (SMD). The performance of a model was assessed by comparing it's predicted SMD values with the SMD values observed from soil moisture content determinations at all the six sites, using neutron probes. None of all the models was found to be particularly superior to others in predicting SMD.

Odigie (1983) estimated direct recharge into the Great Oolite Limestone Aquifer in Southern England, using the SMD model. He compared the use of the areally weighted root constant and maximum SMD with the use of the individual values and he seems to prefer the use of the areally weighted values. He also proposed the use of C and D values that are consistent with the soil and plant properties, over the use of the conventional values.

Anyaeche (1985) estimated direct recharge into the upper zone aquifer of the Lake Chad basin using the soil moisture deficit model after Odigie (1983). Recharge estimates were carried out on a daily basis using areally weighted C and maximum soil moisture deficit.

One disadvantage of the soil moisture deficit model like all similar models, is that the accuracy of it's recharge estimates is highly dependent on the accuracy of some of the input data and model parameters. The model is simple to understand, easy and inexpensive to use. However, the latter attributes make it most appropriate for use in this project work.

2.5 Conclusion

A review of various methods of direct recharge estimation has been carried out and their various merits and demerits have been highlighted. The preference of the soil moisture deficit model over the other methods reviewed has been justified.

CHAPTER 3 THE SOIL MOISTURE DEFICIT MODEL

In this chapter, the description of the soil moisture deficit model after Odigie (1983) is presented.

3.1 Available Moisture

The available moisture (AM) in mm in a given soil depth, d (mm) is the difference between the soil moisture contents at field capacity, MC_{FC} and permanent wilting point, MC_{PWP}.

$$\text{i.e} \quad AM = (MC_{FC} - MC_{PWP}).d/100 \qquad 3.1$$

The maximum soil moisture deficit (D) is the amount of water which a given plant can remove from the soil moisture storage before it permanently wilts and dies. It comprises of the water available within the root zone and those transported into the root zone from zones below, by capillary action and vapour movement (Odigie, 1984). The root constant (C) is the fraction to which the available moisture can be depleted without causing actual evapotranspiration to become less than the potential evapotranspiration. Both C and D are expressed as equivalent depths of rainfall.

3.2 Availability of Soil Moisture

Various postulates abound on the issue of availability of soil water to plants between field capacity and wilting point. Some of these postulates are illustrated in figure 1 and described below:

3.2.1 <u>Equal availability (Curve a)</u>

This postulate, by Veihmeyer and Hendrickson (1949) claims that soil water is available in equal amounts at all stages between field capacity and permanent wilting point. The implication of this postulate is that the activities of the plant proceed uninhibited despite a decrease in available soil moisture and that it (i.e. plant activities) is inhibited, in an abrupt manner, only when permanent wilting point is reached. However, the general notion that soil moisture will be on the decrease in a vegetated soil with no soil moisture replenishment negates this postulate.

3.2.2 <u>Gradually decreasing availability (Curve b)</u>

In their postulate, Richards and Wadleigh (1952), argued that a decrease in the amount of soil moisture leads to a decrease in the amount of water available for plant use. The implication of this being that, it is possible for plant activity to be inhibited, due to water stress, before permanent wilting point is reached.

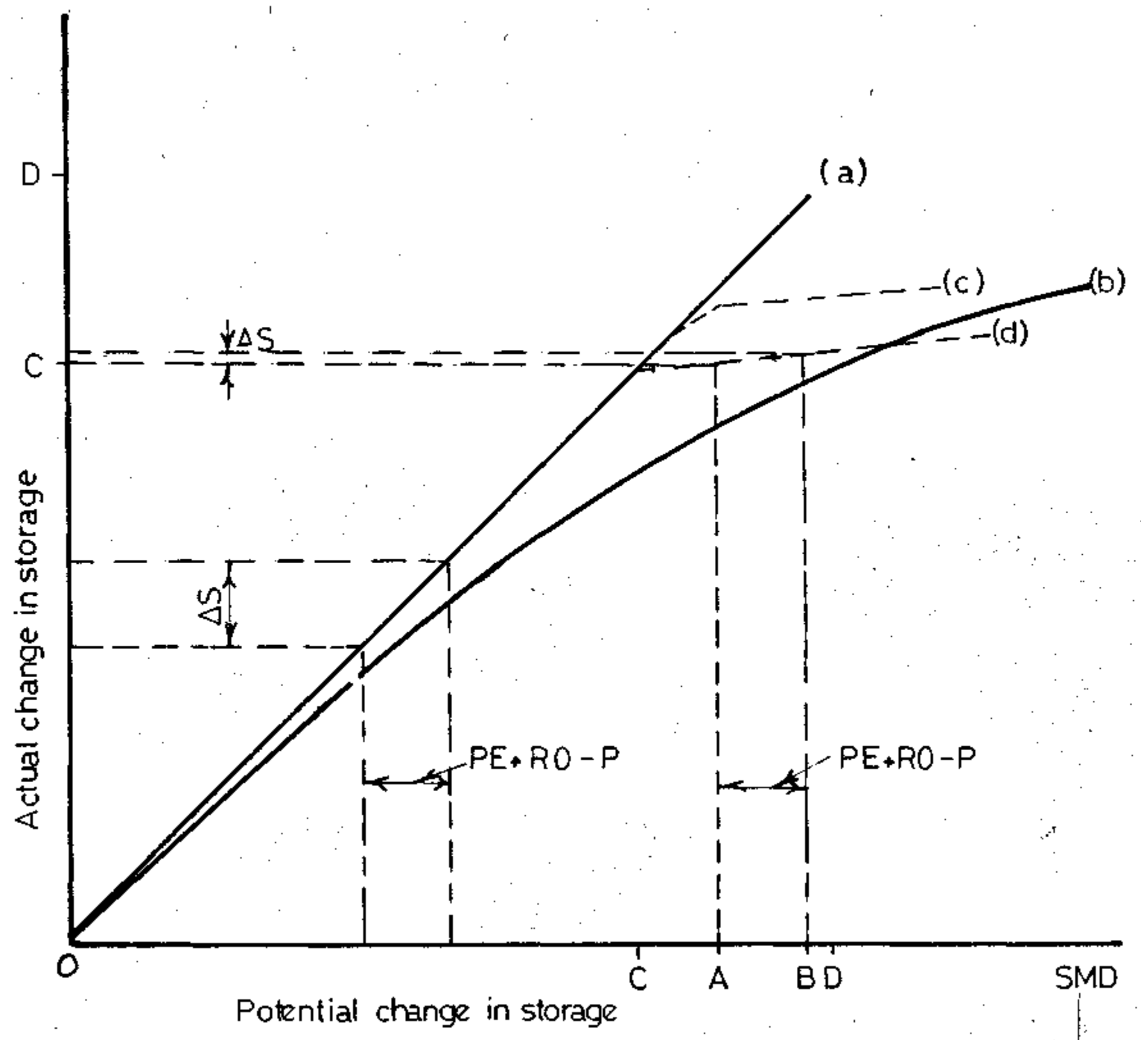


Fig. 1: DRYING CURVE FOR A VEGETATED SOIL, AFTER ODIGIE (1984)

(a) Veihmeyer and Hendrickson (1949)

(b) Richards and Wadleigh (1952)

(c) Penman (1949)

(d) Rushton and Ward (1979)
PE is POT. Evapotranspiration
RO is Runoff
P is Rainfall

3.2.3 Equal availability followed by decreasing availability (Curve c)

This postulate contends that there exists a point between field capacity and permanent wilting point, referred to as the critical point or root constant. Before this critical point, soil moisture is available in equal amounts to the plants, and beyond this point, soil moisture is available to the plant at a decreasing rate. It further contends that immediately beyond the critical point the soil moisture availability first decreases gradually for a short period, beyond which it then starts to decrease rapidly at a rate of between eight and ten percent. This theory was presented by Penman (1949).

Modification of Penman's postulate was undertaken by Rushton and Ward (1979) to the effect that, after the critical point is reached, soil moisture availability decreases suddenly and at a very high rate. This postulate is represented by curve (d) and is used in this study because it is easy to incorporate in a computer program.

3.3 Description of the Soil Moisture Deficit Model

The Computer program which was used in estimating recharge utilizes a subroutine whose flow chart is shown in figure 2. Sample recharge estimates from the subroutine are given in order to

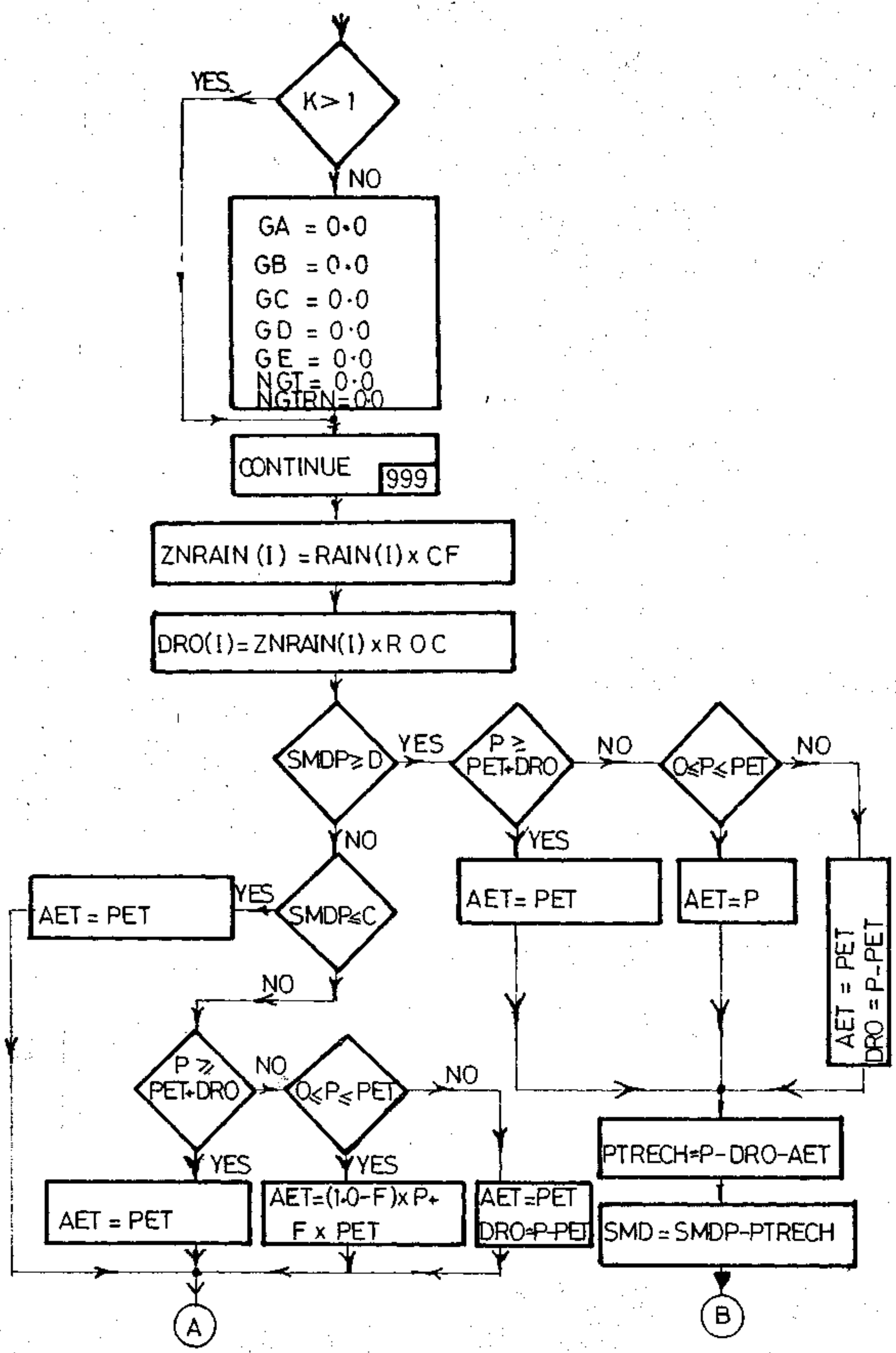
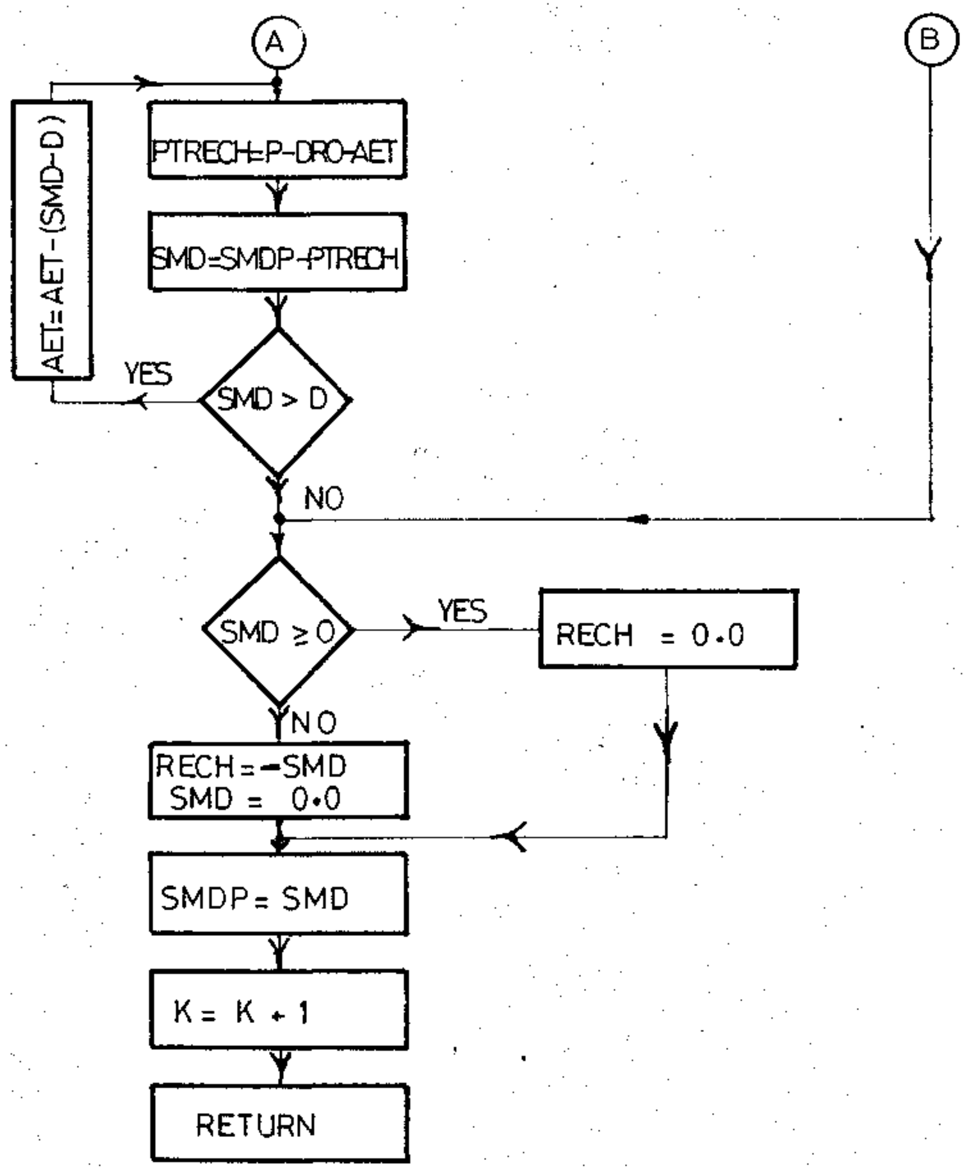


Fig. 2: FLOW CHART OF THE SUBPROGRAM (SUBROUTINE), AFTER ODIGIE (1984)


A
B
AET=AET-(SMD-D)
PTRECH=P-DRO-AET
SMD=SMDP-PTRECH
YES
SMD > D
NO
SMD ≥ 0
YES
RECH = 0.0
NO
RECH=-SMD
SMD = 0.0
SMDP= SMD
K= K + 1
RETURN

highlight the mechanism of the subroutine. The subroutine calculates recharge on a one-day time step, based on the position of the continuously changing soil moisture deficit (SMD) along the drying curve, figure . The SMD at the end of any given time step is taken to be the soil moisture deficit (SMDP), at the beginning of the next time step. When potential evapotranspiration (PET) is greater than or equal to rainfall (P) the direct surface runoff (DRO) is taken to be zero, so as to take care of the effect which foliage intercepted rainfall will have on potential evapotranspiration Odigie (1984). The SMD can assume four positions along the drying curve, namely, (a) SMD = 0 (b) 0<SMD<C (c) C<SMD<D (d) SMD>D. Thus creating four conditions(Odigie, 1984).

(a) SMD = 0

When SMD = 0, water transmission to and within the root zone is at a rate which keeps the soil around the root zone perpetually wet. Thus the plant will have no difficulty in abstracting moisture from the soil to meet the evaporative demand of the atmosphere. Under this condition, potential evapotranspiration equals actual evapotranspiration (AET) and two cases may arise, (i) P ≥ PET + DRO (ii) P < PET + DRO.

In case, a(i), recharge is deemed possible. Potential recharge (PTRECH) to some extent governs the occurrence of recharge and it is given by:

$$PTRECH = P - DRO - AET \qquad 3.2$$

when AET = PET

$$PTRECH = P - DRO - PET \qquad 3.3$$

For case a(i), PTRECH is either zero or positive as against case a(ii) where it will be negative, which implies an increase in SMD. PTRECH is the amount of infiltrated water that goes into satisfying the moisture deficit incurred by soil moisture storage. At the end of any given time step, the deficit is given by:

$$SMD = SMDP - PTRECH \qquad 3.4$$

If PTRECH = 0, no moisture is added or removed from the soil moisture storage and recharge (RECH) is zero, while SMD remains constant. If PTRECH>SMDP equation 3.4 then becomes:

$$SMD = - PTRECH \qquad 3.5$$

where the negative value of SMD implies the excess amount of moisture from soil moisture storage that recharges groundwater.

$$RECH = - SMD \qquad 3.6$$

Substituting SMD in equation 3.5

$$RECH = PTRECH \qquad 3.7$$

Moisture of magnitude, PTRECH, returns the soil moisture storage to field capacity and the SMD to zero after which the excess moisture (if any) recharges the groundwater storage. In case a(i), the evaporative demand is met from the rainfall and soil moisture storage.

(b) $0<SMD<C$

Under this condition the soil-water-plant relationship is as in condition (a) and AET = PET, thus resulting in three possible cases:

(i) P = DRO + PET and PTRECH = 0

(ii) P<DRO + PET and PTRECH = -ve

(iii) P>DRO + PET and PTRECH = +ve

In any of the three situations above, the change in SMD, due to the magnitude and sign of PTRECH, is as discussed under condition (a).

(c) $C<SMD<D$

This condition, under which SMD lies between C and D, presents a complex case, therefore, three simplified cases are presumed to arise from this condition:

(i) P$\geqslant$PET + DRO and PTRECH = +ve

(ii) 0$\leqslant$P<PET and PTRECH = -ve

(iii) (PET + DRO)$\geqslant$P>PET and PTRECH = 0

The expression, DRO, is computed.

In case C(ii), it is possible that due to a sudden change of landuse, SMD exceeds D, this situation is remedied in the model by reducing the AET for the time step by, SMD - D, and recalculating SMD with the adjusted value of AET.

(d) SMD>D

A sudden change in land vegetation such as harvesting or crop failure, is accompanied by an abrupt lowering of the value of D which makes it possible for the SMD accumulated during the growing season to be greater than D, just after the sudden change of land vegetation.

When this situation arises, the model assumes that the soil moisture storage does not contribute towards meeting the evaporative demand.

Two cases arise under which SMD either remains constant as in (i) below or reduces, as in (ii) below.

(i) $0 < P \leq PET + DRO$ and $PTRECH = 0$

(ii) $P > PET + DRO$ and $PTRECH = +ve$

Since the soil moisture deficit model is based on the assumption that recharge takes place only when SMD is zero, it can therefore be seen that recharge will possibly take place only under conditions (a) and (b) specified above.

3.4 Conclusion

In this chapter, some of the postulates on the availability of soil moisture to plants were reviewed. The soil moisture deficit model has been described and four possible positions of SMD along the drying curve explained.

Chapter 4: THE STUDY AREA AND ESTIMATION OF MODEL PARAMETERS

4.1 Description of The Study Area

4.1.1 Location and extent

The study area of this project work covers the portion of the Sokoto-Rima river basin which is on Nigerian territory. The Sokoto-Rima river basin is within the area enclosed by latitudes $11^{\circ}30'$N to $13^{\circ}30'$N and longitudes 4°E to 8°E. Fig. 3. It has a total area of about 80,960 km^2, most of which covers the present day Sokoto state and some parts of Kaduna state. The Sokoto-Rima river basin forms about one tenth of a larger basin, referred to as the Iullemmeden basin, which extends into three other countries, namely, Niger, Benin and Mali(Kogbe, 1979).

4.1.2 Topography

Generally, the landscape of the sedimentary region (in the northern and western half of the study area) is flat to gently rolling with wide shallow valleys. This landscape is occasionally broken by local ridges, scarps and inselbergs, which are common features in the sedimentary region. In the south and east of the study area (the basement complex region), the landscape is frequently interrupted by granitic, gneiss and quartzite inselbergs which are

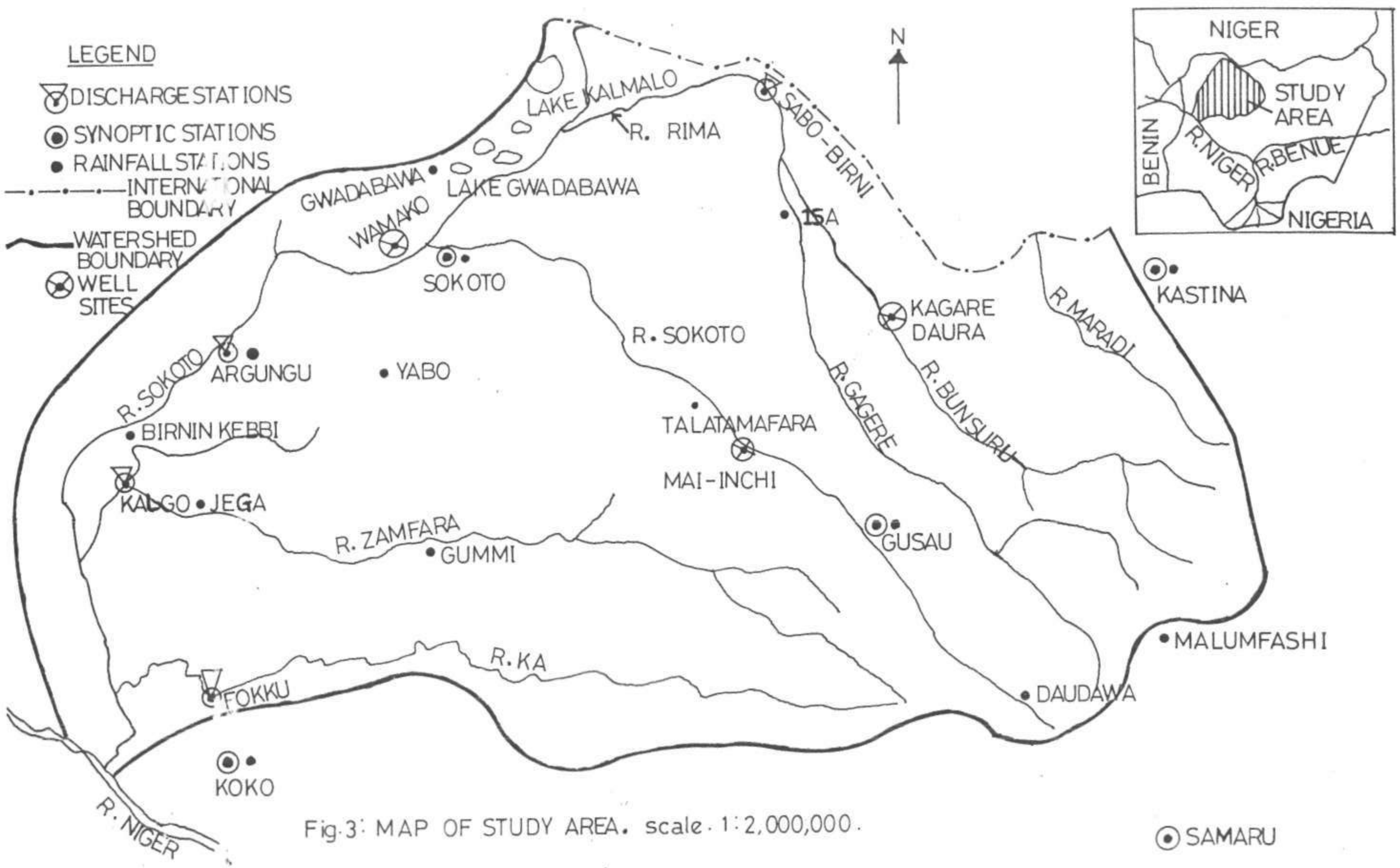


Fig.3: MAP OF STUDY AREA. scale. 1:2,000,000.

common in this region. Numerous shallow valleys which serve as drainage channels of the Sokoto and Rima river tributaries abound in this region. Elevations in the study area range from, less than 183m to 366m above sea level. The lowest elevations occur in the south (near the river Niger) and the highest is in the sedimentary region in the north(Ogilbee and Anderson, 1965; FAO, 1969a; Udo, 1970).

4.1.3 Geology

There are two major geological regions, namely, the sedimentary region and basement complex region. The basement complex mostly consists of igneous and metamorphic rocks. In the sedimentary region there are (i) the Gwandu formation, (ii) the Sokoto group, (which consists of the Kalambaina and Dange formations), (iii) the Rima group (which consists of the Wurno, Dukamaje and Taloka formations) and (iv) the Gundumi, Illo formations.

The geological succession is such that the Gundumi and Illo formations overlies the basement complex. The Rima group overlies the Gundumi and Illo formations, while the Sokoto group overlies the Rima group. The Sokoto group is overlain by the Gwandu formation(Fig. 4). Within Nigeria, the sediments of the Sokoto-Rima river basin dip to the northwest at approximately 3.42 metres per kilometre

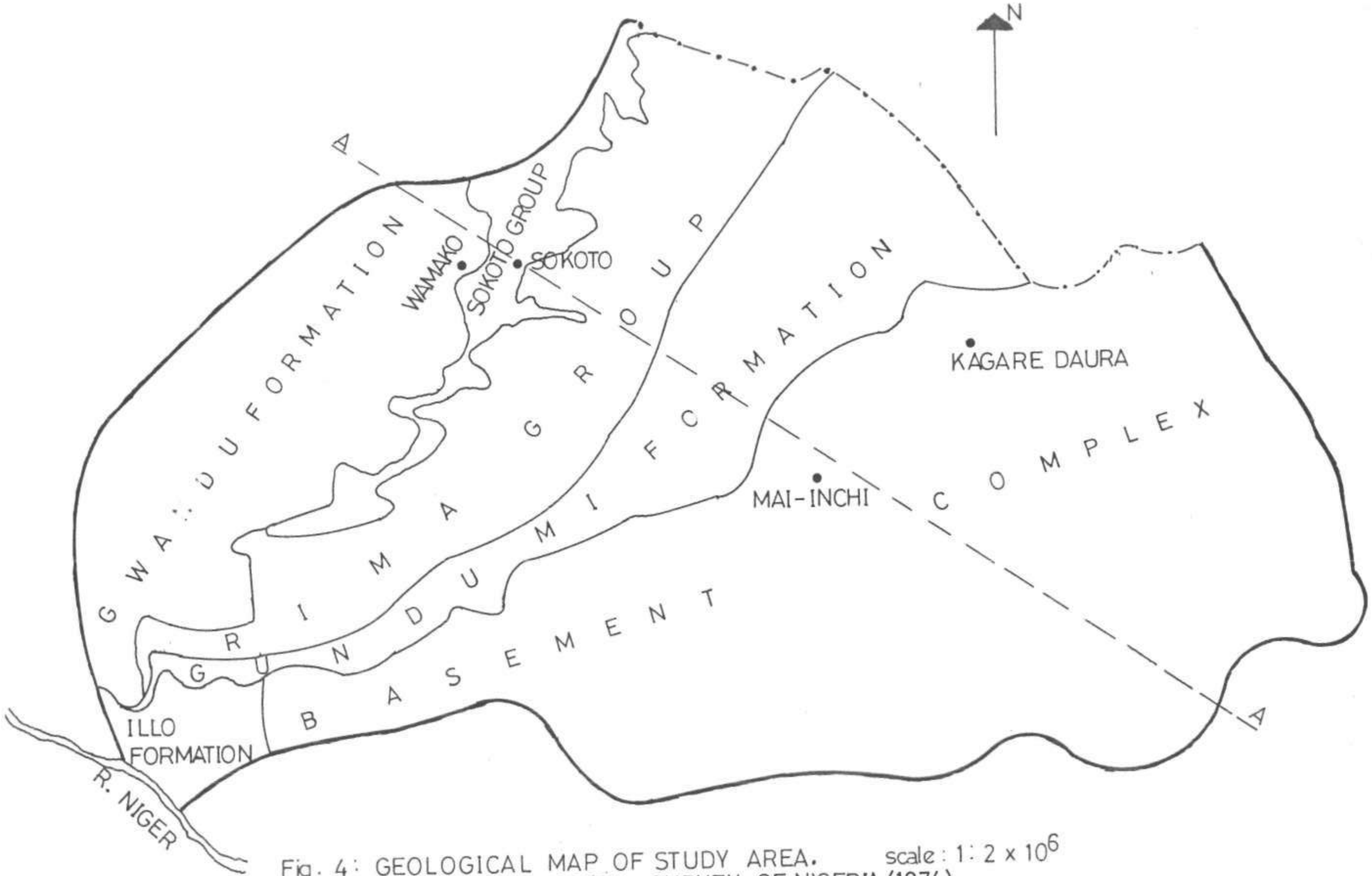


Fig. 4: GEOLOGICAL MAP OF STUDY AREA. scale: 1: 2 x 10^6
SOURCE: GEOLOGICAL SURVEY OF NIGERIA (1974)

and are apparently unfaulted (Parker, 1964; Dupreeze and Barber, 1965; Ogilbee and Anderson, 1965).

4.1.4 Hydrogeology

Groundwater occurs under watertable, sub-artesian and artesian conditions in the aquifers of the sedimentary region of the Sokoto-Rima river basin. In the basement complex region, groundwater occurs mostly under watertable conditions in the weathered zone and cover sands. Groundwater can also be found in the fractured and jointed zones (Mock, 1967; Oteze, 1976). Table 4.1 contains the description of some water bearing formations in the Sokoto-Rima river basin.

The surface laterites of the sedimentary region and the alluvial sediments deposited in river channels and on flood plains all over the basin, also bear water under water table conditions. The lateritic aquifers have been exploited extensively by hand dug wells, while most of the shallow boreholes drilled in the alluvium have proved successful (Dupreeze and Barber, 1965; Ogilbee and Anderson, 1965; Oteze, 1976).

4.1.5 Drainage

The dominant river in the study area is the Sokoto river (Fig. 3). The Sokoto river and the

Table 4.1: Description of Some Water Bearing Formations in the Sokoto-Rima river basin

GROUP	FORMATION	THICKNESS (M)	LITHOLOGIC CHARACTER	WATER BEARING PROPERTIES
		0-15+	Unconsolida[illegible] and sand with some gravel in Fadama (valley floor) of Sokoto and Rima rivers and their larger tributaries.	Yields small to moderate supplies of potable water to shallow wells. May have potential for large yields by induced river infiltration
	GWANDU	0-305+	Semi consolidated fine to coarse-grāned sand and clay, with dark coloured clay shale.	Basal sand member yields moderate supplies of potable water to bore holes under artesian pressure. Upper member yields small to moderate supplies to wells and bore holes under water table and subartesian conditions.
SOKOTO	KALAMBAINA	0-49+	Semi consolidated clayey limestone and marl, with some mudstone and plastic shale	Limestone yields small to moderate supplies of potable water to shallow walls and springs in the outcrop area. Formation is probably not productive at depth.
	DANGE	0-43+	Semi consolidated blue to grey, plastic shale with phosphatic nodules and thin beds of limestone.	Yields little or no water to wells and boreholes. Forms confining bed for artesian water in underlying Wurno formation.
RIMA	WURNO	0-46+	Friable sandstone and sand interbedded with soft mudstone and shale.	Yields moderate supplies of potable water to boreholes under artesian pressure.
	DUKAMAJE	0-27	Dark coloured fossiliferous shale, with thin beds of limestone. Present only in the northern part of the basin.	Yields little or no water to wells and boreholes.
	TALOKA	0-183+	Semi consolidated fine to medium grained sand, sandstone and shale, with lignite and mudstone	Yields small to moderate supplies of potable water to boreholes. Under artesian pressure downdip.
	GUNDUMI	0-305	Semi consolidated fine to coarse grained sand with clay, sandy clay, and conglomerate near the base.	Yields small to moderate supplies of potable unconfined water to wells on the outcrop area. Yields water under artesian pressure at depth.
	BASEMENT ROCK		Granite-gneiss, phyllite, and quartzite.	Yields meagre supplies of water to wells in outcrop area.

Source: Ogilbee and Anderson (1965).

tributaries of the Rima river take their source from the basement complex region and they flow in the northwestern direction. However, some tributaries of the Sokoto river flow in the western direction e.g. rivers Zamfara and Ka. The Sokoto river takes a gradual turn at Sokoto and then flows southwards to join the river Niger. Most of the tributaries of the Sokoto river, with the exception of the Rima and Zamfara, are not perennial streams.

Seasonal springs, due mostly to interflow, are common along the valley slopes of the Sokoto-Rima river basin. However, springs on the Kalambaina limestones have been found to last longer than others. The three most important lakes in the study area are Kalmalo, Kware and Bodinga lakes, to the north of Sokoto. Fig. 3. They derive their flow from the Kalambaina limestones and probably rejected recharge from the Gwandu aquifers(FAO, 1969b; Kogbe, 1979).

4.1.6 Climate

The study area has a semi-arid climate, with a long and severe dry season, lasting from October until May and a short but intensive wet season from May/June to September. The area comes under the influence of two types of winds, the dry hot continental air mass from the Sahara desert and a humid equitorial maritine air mass from the sea.

These air masses bring "harmattan" and rain respectively.

Rainfall

Rainfall from 14 stations inside and near the basin was used in the study. Due to their different locations, Figs. 3 and 5, the period, amount, distribution and the start of, rainfall at each of these stations vary. Here, the start of the rains is defined as a 10-day period during which rainfall is greater than 25.4 mm, followed by two subsequent 10-day period during which rainfall is greater than half evapotranspiration (Kowal and Knabe, 1972).

But, generally, average rainfall over the basin varies from less than 635 mm in the North to 1143 mm in the South (Fig. 5). The rainfall pattern over the basin is a gradual rise (from May/June) to a maximum (in August) and a steep decrease in September - October (Fig. 6). July and August are the peak rainfall months of the basin. The daily rainfall values at each of the 14 stations was corrected to make them representative of the areal rainfall over "their polygons".

Potential evapotranspiration

Monthly variation of potential evapotranspiration over the basin is shown in Fig. 6. Evapotranspiration

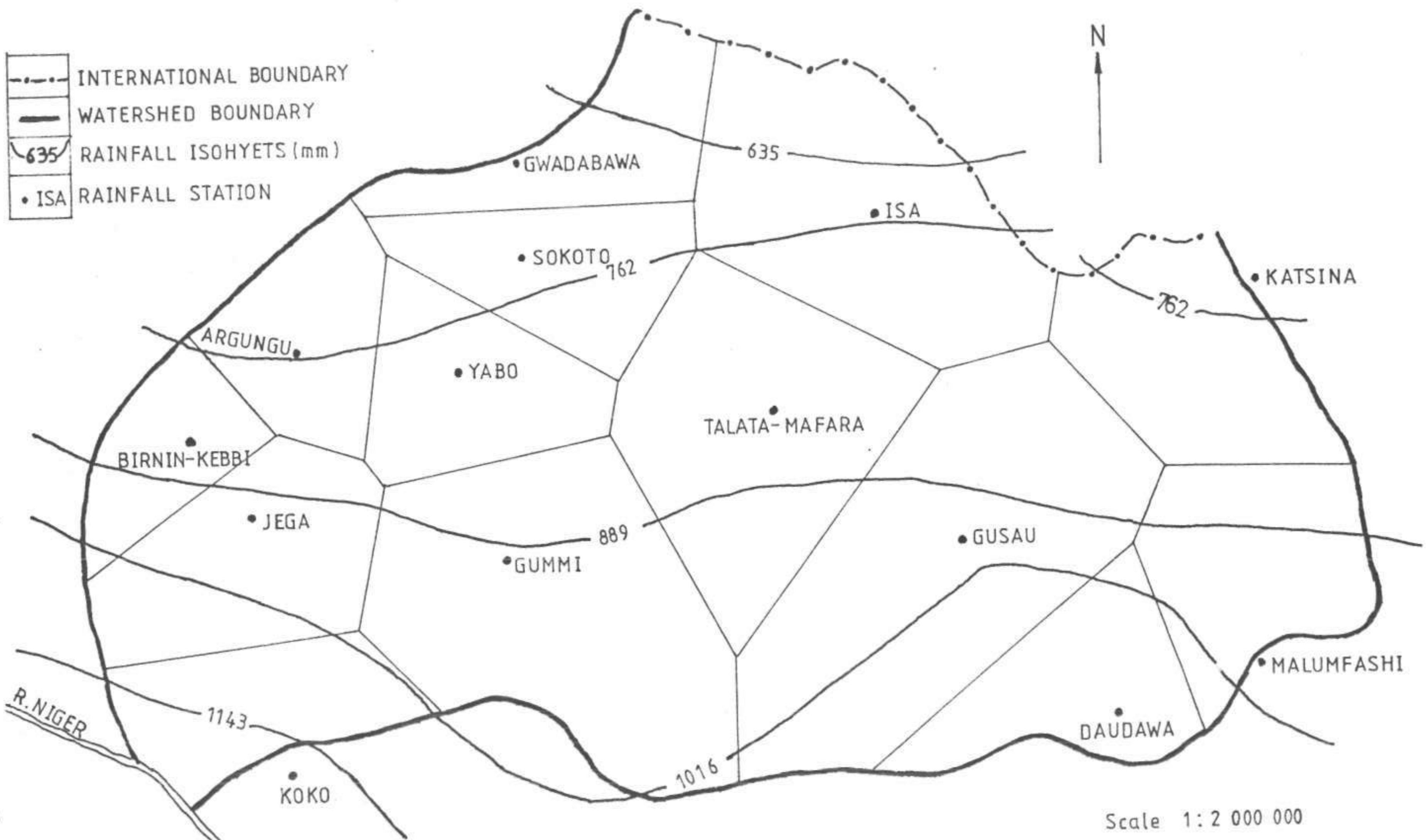


FIG. 5. RAINFALL ISOHYETS, RAINFALL STATIONS AND POLYGONS IN THE STUDY AREA.

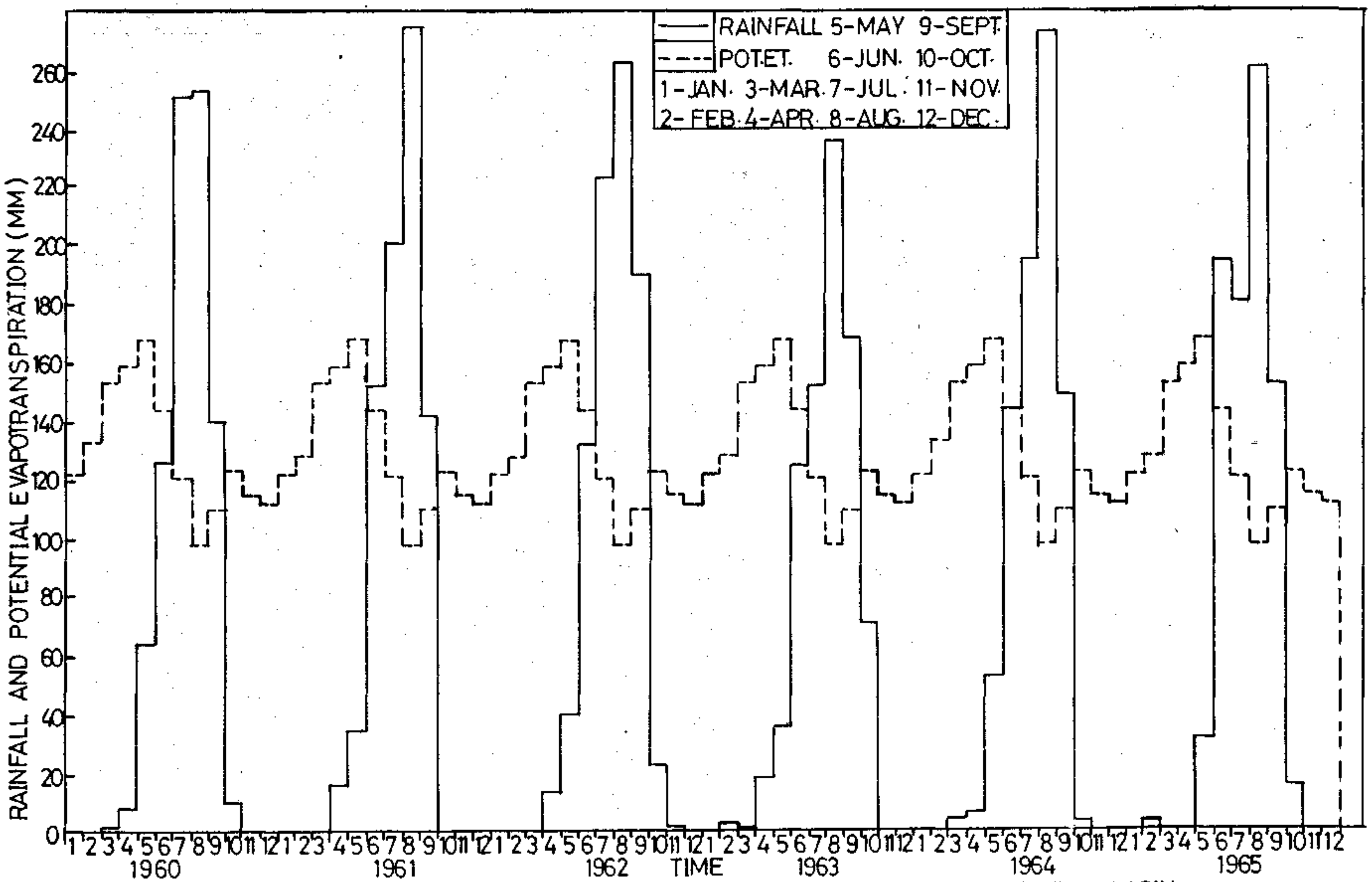


Fig.6: MONTHLY RAINFALL AND POTENTIAL EVAPOTRANSPIRATION IN SOKOTO-RIMA RIVER BASIN.

is lowest in August and starts to increase at the start of the "harmattan" period in November/December, it reaches a peak in April, when the temperatures reach a maximum. After which it starts to decrease with the onset of the rains(Fig. 6). The potential evapotranspiration values used were estimated by Kowal and Knabe (1972) using Penman (1948) formula.

Temperature and humidity

The mean maximum and minimum temperatures occur in April/May (about 35°C to 38°C) and December/January (about 13°C), respectively. The relative humidity is at it's peak of over 90 percent in August and a minimum of 10 percent in February(FAO, 1969a; Udo, 1970).

4.1.7 Vegetation and soils

The study area falls within the Sudan and Northern guinea vegetation zones. Hence, in the Northern parts the vegetation consists of tree or shrub savannah, relatively sparse grasses and scattered fire tolerant trees and shrubs. In the Southern parts, the vegetation is relatively dense and consists mainly of short grasses and deciduous trees.

The soils of the area vary from sandy to loamy soils, with clays occurring mostly along the flood plains.

4.1.8 Land use

Two types of agricultural land has been identified in the study area, namely, the flood plain and upland (FAO, 1969a). On the heavy clayey and silty soils of the flood plains, crops like maize, wheat, sweet potatoes, vegetables, onions, tobacco and sugar cane are grown. On the upland areas the main crops grown are guinea corn, millet and cowpeas. Traditional bushfallow is becoming uncommon due to population pressure (FAO, 1969a; Udo, 1970; Odeh, 1983).

4.2 Sources of Input Data

The rainfall data was obtained from the published records of monthly rainfall summaries, vols. 4-9, (1960 to 1965), of the British West Africa Meteorological Services and Meteorological Services of the Federation of Nigeria.

The potential evaporation data used is according to Kowal and Knabe (1972). They were calculated by the application of Penman (1948) formula, to the meteorological data from the five synoptic stations shown in Fig. 3. The values are considered more reliable than the measured pan evaporation values of (Mock, 1967).

The map of the study area was after Kowal and Knabe (1972), the recharge area was delimited on this map by regarding the clay outcrop area as impermeable. The soil map used was according to Kowal and Knabe (1972). The landuse map and isohyetal map were also obtained from Kowal and Knabe (1972). Drainage and hydrological network maps were obtained from Mock (1967). The geological map was obtained from Geological Survey of Nigeria (1974).

The daily mean discharge data for some rivers in the basin was obtained from the published records of the hydrological section of the Ministry of Agriculture (Irrigation division) Northern Nigeria and the U.N.D.P./F.A.O. Hydrological Year Book (1965-1966).

All area measurements were carried out using an Aristo 1130L planimeter.

Because no area within the basin adequately represents the multifarious meteorological, vegetation and soil conditions within the basin, the entire basin was divided into 14 polygons using the Thiessen's polygon method(Fig. 5).

4.2.1 Water level records

The water level records of the wells within the study (and recharge) areas were obtained from Mock (1967).

4.3 Model Parameters

Each of the model parameters were calculated for the 14 polygons thus:

4.3.1 Areally weighted maximum soil moisture deficit (WD)

In calculating this parameter, the planting dates for each crop grown in the polygons was determined from Anonymous (1980, 1981, 1982) and corroborated by Anonymous (1984). For a given crop, the root depth during it's growing season was determined on a monthly basis. For each of the soil type present in a given polygon, the available moisture (AM) over the root depth during each month in the growing season was determined using equation 3.1. The parameters in equation 3.1 were obtained from Kowal and Knabe (1972) and FAO (1979). The AM in the different soils in a polygon is combined in the proportion of the respective soil areas.

The proportion used here is the area of a soil type in the polygon divided by the total area of the soil types (over which recharge occurs) in the polygon. The areally weighted D for a given polygon and in any month is obtained by weighting the previously combined AM, for the various crops grown in that polygon. The weighting factor used is the percentage of land area covered by each crop grown in the polygon. This was obtained from Agboola (1979).

4.3.2 Areally weighted root constant (WC)

After determining the planting dates, the crop's growing season is grouped into it's different growing stages and the crop coefficient (K_c) for each growth stage was obtained from FAO (1979). K_c for each month in the crop's growing season (K_{cm}) was determined by weighting the K_c values of any month which has more than one K_c value. Potential evapotranspiration (PET) and crop maximum evapotranspiration (MET) for each month in the crop's growing season was determined. MET equals PET times K_{cm}. The MET is used to obtain the soil water depletion fraction, P, from FAO (1979). The C for each month in the crop's growing season equals P times D. The areally weighted C for a given polygon and in any month is obtained by weighting the different root constant's that was calculated for each of the crops grown in the polygon, as was described in the case of the maximum soil moisture deficit above. Note that after a crop's growing season, individual C and D assume the value of 25.4 mm, which is taken as evaporation from bare or fallow soil(Grindley, 1969).

Typical individual monthly values of C and D and areally weighted C and D are presented in Tables 4.2 and 4.3 respectively.

4.3.3 Runoff coefficient (ROC)

The runoff coefficients were calculated as follows:

(i)Mean daily discharge record from three rivers (Rima, Ka, Zamfara), which drain over 85 percent of the entire basin was used.

(ii)A total of nine discharge hydrographs for all the three rivers (for 3 years) were plotted and separated using one of the methods described by Lindsley *et al*. (1975). The total hydrograph and the area under the baseflow line (baseflow) were determined by summation of the hydrograph ordinates and integrating the equations of the baseflow lines over the discharge periods, respectively. The difference between the total hydrograph and the baseflow gave the direct surface runoff (DRO).

(iii)For each year, monthly mean rainfall over each sub-basin (i.e. basins of the three rivers used) was determined using Thiessen's polygon method.

Table 4.2: MONTHLY VALUES OF CROP ROOT CONSTANT AND MAXIMUM SOIL MOISTURE DEFICIT (mm) (FOR 1963) IN ARGUNGU STATION POLYGON

CROPS	MILLET		SORGHUM		COWPEAS		CASSAVA		S/CANE		MAIZE		OTHERS	
	RC	D	RC	D	RC	D	RC	D	RC	D	RC	D	RC	D
JAN.	25.4	25.4	25.4	25.4	25.4	25.4	137.4	173.9	50.7	56.3	25.4	25.4	145.5	224.5
FEB.	25.4	25.4	25.4	25.4	25.4	25.4	138.8	173.9	50.0	56.3	25.4	25.4	134.7	224.5
MAR.	25.4	25.4	25.4	25.4	25.4	25.4	141.2	173.9	49.5	56.3	25.4	25.4	132.2	224.5
APR.	25.4	25.4	25.4	25.4	25.4	25.4	136.7	173.9	88.5	141.6	25.4	25.4	117.9	224.5
MAY	25.4	25.4	25.4	25.4	25.4	25.4	137.7	173.9	94.6	166.6	25.4	25.4	115.6	224.5
JUNE	64.2	71.0	64.2	71.0	25.4	25.4	148.8	173.9	95.6	168.1	49.8	56.3	117.2	224.5
JULY	93.4	109.2	93.4	109.2	36.4	44.6	75.3	85.7	103.2	168.1	71.5	88.7	131.8	224.5
AUG.	131.8	181.3	131.8	181.3	63.5	106.3	95.2	107.8	106.9	173.9	73.9	93.1	153.3	224.5
SEPT.	136.7	181.3	136.7	181.3	57.6	106.3	132.8	173.9	100.3	173.9	86.9	125.4	144.4	224.5
OCT.	164.2	181.3	164.2	181.3	85.7	106.3	109.9	173.9	99.8	173.9	25.4	25.4	143.4	224.5
NOV.	25.4	25.4	164.2	181.3	25.4	25.4	125.6	173.9	103.3	173.9	25.4	25.4	149.3	224.5
DEC.	25.4	25.4	25.4	25.4	25.4	25.4	136.0	173.9	109.7	173.9	25.4	25.4	155.6	224.5

RC is ROOT CONSTANT, D is MAXIMUM SOIL MOISTURE DEFICIT.

Table 4.3: AREALLY WEIGHTED C AND D (mm) (KOKO STATION POLYGON)

YEARS	1960		196		1962		1963		1964		1965	
MONTH	WRC	WD	WRC	WD	WRC	WD	WRC	WD	WRC	WD	WRC	WD
JAN	32.27	36.03	32.27	36.03	32.27	36.03	32.27	36.03	32.27	36.03	32.27	36.03
FEB.	31.58	36.03	31.58	36.03	31.58	36.03	31.58	36.03	31.58	36.03	31.58	36.03
MAR.	31.04	36.03	31.04	36.03	31.04	36.03	31.04	36.03	31.04	36.03	31.04	36.03
APR.	30.87	36.03	30.87	36.03	30.87	36.03	30.87	36.03	30.87	36.03	30.87	36.03
MAY	55.58	64.50	55.58	64.50	31.37	36.03	55.58	64.50	55.58	64.50	55.58	64.50
JUNE	107.80	132.40	107.80	132.40	56.17	65.72	107.80	132.40	107.80	132.40	107.80	132.40
JULY	135.20	188.40	135.20	188.40	102.00	129.50	135.20	188.40	135.20	188.40	135.20	188.40
AUG.	145.20	189.60	145.20	189.60	124.90	169.70	145.20	189.60	145.20	189.60	145.20	189.60
SEPT.	146.60	175.60	146.60	175.60	130.00	169.70	146.60	175.60	146.60	175.60	146.60	175.60
OCT.	90.28	103.10	90.28	103.10	121.10	136.30	90.28	103.10	90.28	103.10	90.28	103.10
NOV.	32.47	36.03	32.47	36.03	82.06	91.93	32.47	36.03	32.47	36.03	32.47	36.03
DEC.	32.74	36.03	32.74	36.03	32.74	36.03	32.74	36.03	32.74	36.03	32.74	36.03

WRC is weighted root constant, WD is weighted max. soil moisture deficit. C is root constant, D is max. soil moisture deficit.

The sum of the monthly mean rainfall gives the annual mean rainfall (AMR) over the sub basins.

(iv)The runoff coefficient (ROC) over a sub-basin in a given year is therefore the DRO divided by the AMR. The average value of ROC over three years was used as the ROC for the years for which discharge data was not available.

(v)The runoff coefficient over each polygon was determined by superimposing the polygons over the map of the sub-basins. Any polygon which falls entirely within a given sub-basin assumes the value of the runoff coefficients for that sub-basin. In cases where a polygon falls within two or more sub-basins, the runoff coefficient is calculated by areal weighting as follows: if polygon AP, for example, falls within three sub-basins, b_1, b_2, b_3, whose runoff coefficients for a given year are r_1, r_2, r_3 respectively. If, a_1, a_2, a_3 are area ratios, i.e. a_1 equals area of polygon AP that falls within sub-basin b_1, divided by the total area of polygon, AP. The same definition holds for ratios a_2 and a_3. The runoff coefficient over polygon AP can therefore be expressed as:

$$ROC_{AP} = \sum_{i=1}^{n} a_i r_i \qquad 4.1$$

where n is the number of sub-basins within which polygon AP falls.

4.3.4 Correction factor

This factor has the purpose of making the station's (point) rainfall more representative of the areal rainfall over a polygon. By assuming a linear relationship between the mean long term point rainfall (MLTPR) and the average rainfall over the polygon (PAR), the correction factor (CF) was derived thus:

$$CF = PAR/MLTPR \qquad 4.2$$

PAR was obtained by finding the average rainfall over each polygon using the isohyetal method. MLTPR is the long term average of the rainfall at the rainfall station from which a polygon is derived. It was obtained from Kowal and Knabe (1972).

The CF was applied to the daily point rainfall (RAIN) to obtain the polygon's daily areal rainfall (ZNRAIN) equation 4.3, which is considered to be more representative of the rainfall over the polygon than is point rainfall.

$$ZNRAIN = RAIN \times CF \qquad 4.3$$

4.3.5 Weighting factors

Two weighting factors (WF and WF1) were used. The first factor, WF, was derived for each polygon, from equation 4.4 below.

$$WF = PRA/TBRA \qquad 4.4$$

where PRA is the recharge area of a polygon (Km^2) and TBRA is the total basin recharge area (Km^2). This factor was used to obtain the annual weighted recharge (WZRECH) and the weighted monthly recharge (WMRECH) in each polygon. It was also used to weight the change in soil moisture storage and the number of days of recharge.

The second factor, WF1, was derived for each polygon, from equation 4.5 below.

$$WF1 = AOP/AOB \qquad 4.5$$

AOP is the area of the polygon (Km^2) and AOB is the area of the Sokoto-Rima river basin. This factor was used to obtain the annual weighted rainfall (WZRAIN) and the weighted monthly rainfall (WMRAIN) in each polygon. It was also used to weight the potential and actual evapotranspiration, direct runoff and the number of rainfall days.

4.4 Basin Recharge

Recharge into the Sokoto-Rima river basin was estimated on a daily, monthly and annual basis. While the average recharge over the basin was estimated on monthly and annual basis. For example, the summation of the WMRECH for the month of June 1960 in all the 14 polygons gives the recharge into the entire basin in June 1960. While the summation of WZRECH for the year 1960 in all the 14 polygons gives the recharge into the entire basin in the year 1960. Other basin parameters were similarly calculated.

4.5 Description of The Structure of The Computer Program

The computer program used comprises of a main program and a subroutine. The subroutine was modified after Odigie (1983). The main program, whose flow chart is shown in Fig. 7, appendix I, comprises of two nested DO loops, Fig, 8, appendix II. The first nested DO loop encountered in the main program comprises of four DO loops. The fourth and innermost DO loop, DO 40 I = 1, M, where M = number of days in a month, assigns the operational day(s) and within this loop the subprogram is called M times and recharge in month, J, year, NYR and polygon, IP is estimated on a daily basis.

Upon exit from the fourth DO loop, some arithmetic and WRITE statements are encountered before the end statement of the third DO loop, DO 38 J = 1, 12, is reached and control is transferred back to the beginning of the loop. The third loop assigns the operational month(s) for recharge estimation and runs 12 times, estimating daily recharge for month, J, year, NYR and polygon IP. When control exits this loop, again some arithmetic and WRITE statements are encountered before the end statement of the second DO loop, DO 33 NYR = 1,6 is reached and control is transferred to the beginning of the loop.

The second loop assigns the operational year(s) and runs six times, estimating recharge on a daily basis for year, NYR and polygon, IP before control exits the loop and goes back to the first, largest and outermost loop, DO 1 IP = 1,14. This loop runs 14 times, during which daily recharge in all 14 polygons is estimated. At the end of this loop control is transferred to the second nested DO loop.

The second nested DO loop comprises of two DO loops. The first DO loop, DO 65 NYR = 1,6, assigns the year (NYR) while the second DO loop, DO 66 IP = 1,14, assigns the polygon (IP). The second nested DO loop calculates the annual mean basin recharge (MBRECH) and the annual mean basin rainfall (MBRAIN).

A copy of the program is given in Fig. 9, appendix III.

4.6 Sensitivity Analysis

The sensitivity of the model to input data and model parameters was determined by varying the following input data and model parameters as follows:

(i) rainfall, ± 2 percent (ii) potential evapotranspiration, ± 5 percent (iii) runoff coefficient, + 100 percent and -75 percent (iv) root constant, ± 50 percent (v) maximum soil moisture deficit, ± 50 percent (vi) unlimited maximum soil moisture deficit, D = 1000mm. (vii) slope of the drying curve, F, + 400 percent and -80 percent. Note that +2 percent implies a 2 percent increase over the original value while -2 percent implies a 2 percent decrease of the original value.

After varying the original values of the input data/model parameters as shown above, the new values were used to obtain new recharge estimates according to the model. The magnitude of the differences between the model and new recharge estimates was determined by computing the sensitivity ratios and sensitivity levels for each percentage parameter variation. This was computed and determined, after Odigie (1983), by using equations 4.6 and 4.7 - 4.10.

$$SN_R = \left[(\text{New estimate-model estimate})/\text{model estimate} \times 100\right] /\text{percentage parameter variation.} \qquad 4.6$$

SN_R is sensitivity ratio.

The four sensitivity levels used are:

$$\text{High:} \quad |SN_R| > 1.0 \qquad 4.7$$

Moderate:	$0.4 \leqslant \lvert SN_R \rvert < 1.0$	4.8
Low:	$0.1 \leqslant \lvert SN_R \rvert < 0.4$	4.9
Nil:	$\lvert SN_R \rvert < 0.1$	4.10

4.7 Problems Encountered

The major problems encountered in this study are those of data and computer facilities.

Data, in some cases were either not available, available but not in adequate quantities or available but inaccurate for use. This has led to the use of alternative, but generalised data and, limitation in the range of the period of recharge estimation. While the computer facility available can be said to be relatively good, it however was inadequate in terms of the storage space, printout volume and computer time required for this study, due to limitations imposed on the use.

Chapter 5 RESULTS AND DISCUSSIONS

5.1 General

In this chapter will be presented the results obtained in this study and these will be analysed and discussed. In view of the large volume of results obtained during the project work and also because it was observed that the data from some of the polygons show similar trends, it was decided to select for presentation and analysis only samples of the overall results.

5.2 Direct Recharge Estimates

The results obtained in the Sokoto-Rima river basin are first presented and discussed. The presentation and discussion of results obtained in Gwadabawa, Koko and Yabo station polygons will later follow. This line of approach was adopted because in the basin Gwadabawa and Koko station polygons had the lowest and highest rainfall amounts, respectively, while Yabo station polygon is the only polygon in the basin where a zero annual recharge was recorded. The station polygon results that are presented highlights some trends that are not observable (due to areal weighting) in the results obtained over the Sokoto-Rima river basin.

5.2.1 Sokoto-Rima river basin

Table 5.1 contains the monthly direct recharge estimates and soil moisture deficit over the basin at the beginning of each month (IMD). In Table 5.2, the analysis of estimated annual recharge in the basin is presented. The comparison of the basin recharge estimates, basin rainfall and actual evapotranspiration on monthly basis, is given in Fig. 10. The direct recharge estimates, rainfall, actual evapotranspiration, change in soil moisture storage (ΔS) and IMD in the basin, were obtained by areally weighting and summing up the values of each of these parameters in all the 14 polygons. The areal weighting was carried out on a monthly and annual basis.

Tables 5.1 and 5.2 show the mean annual recharge over the basin estimated to be 255.0 mm and this amount forms about 30.3 percent of the mean annual rainfall over the basin. In all the six years the month of August consistently recorded the highest rainfall, Fig. 10, and it therefore recorded the highest average monthly recharge which formed 54 percent of the basin's average annual recharge (Table 5.1). This is because August usually has a relatively low IMD, actual evapotranspiration (AET) - among the recharge months and the highest monthly total rainfall. The months of August and

Table 5.1: MONTHLY AND ANNUAL RECHARGE ESTIMATES IN SOKOTO-RIMA RIVER BASIN

YEARS	1960		1961		1962		1963		1964		1965		AVERAGE
MONTH	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.
JAN.	0.0	195.5	0.0	137.5	0.0	146.8	0.0	129.6	0.0	103.4	0.0	136.7	0.0
FEB.	0.0	195.5	0.0	137.5	0.0	146.8	0.0	129.6	0.0	103.4	0.0	136.7	0.0
MAR.	0.0	195.5	0.0	137.5	0.0	146.8	0.0	128.4	0.0	103.4	0.0	134.4	0.0
APR.	0.0	195.5	0.02	137.5	0.0	146.8	0.0	127.7	0.0	99.5	0.0	134.4	0.003
MAY	0.0	193.2	0.0	127.2	0.0	137.2	0.0	117.5	0.0	95.3	0.0	134.4	0.0
JUNE	0.0	150.9	0.6	112.5	3.2	115.1	1.3	104.3	8.3	64.5	10.8	119.3	4.0
JULY	55.2	82.7	49.4	40.8	47.0	59.6	6.3	50.7	44.2	31.5	37.0	37.0	39.8
AUG.	134.4	10.3	153.6	15.4	146.6	8.3	112.4	24.8	151.0	11.0	127.6	23.1	137.6
SEPT.	51.2	4.1	68.0	6.1	96.6	4.5	63.1	7.9	69.0	2.2	69.9	4.1	69.6
OCT.	2.2	31.1	0.0	47.2	2.9	27.6	17.7	17.7	0.0	40.7	0.4	41.0	3.9
NOV.	0.0	133.8	0.0	146.4	0.0	122.3	0.0	78.8	0.0	135.8	0.0	134.5	0.0
DEC.	0.0	137.5	0.0	146.8	0.0	129.6	0.0	103.4	0.0	136.7	0.0	134.5	0.0
ANNUAL	243.0		271.6		296.2		200.8		272.5		245.7		255.0

RECH. is RECHARGE (in mm) AND IMD is the soil moisture deficit at the beginning of each month (in mm).

September, in all six years, had relatively low IMD, with September having the lowest IMD in all six years because the preceeding month of August (in all six years) consistently had the highest monthly total rainfall, Fig. 10, and a uniformly distributed daily rainfall which lowered the soil moisture deficit (SMD) and kept it in check during the month.

Although September had the lowest IMD, nevertheless August (with a higher IMD), Table 5.1, recorded the highest recharge. This is because the rainfall in August was consistently higher and in most cases better distributed than the rainfall in September (for all the six years), Fig. 10. The occurrence of the basin's highest annual recharge of 296.2 mm, coincides with the basin's "wettest" year of 1962, while the basin's lowest annual recharge of 200.8 mm was recorded in 1963, the basin's "driest" year, within the study period (Table 5.1, Fig. 10).

It was also observed, from Table 5.1, that the incidences of recharge in the basin are generally restricted to the wet season months of June to October. An exception to this general rule was created with the occurrence of recharge in Koko station polygon in April 1961. This exception could be explained as follows:

In November 1960, there was a 65 percent drop in the monthly maximum soil moisture deficit (D) over that of the previous month, due to a sudden change in landuse. Therefore in November 1960, the daily soil moisture deficit (SMD(I)) only increased over a very short period before assuming a constant value, when the low D of November 1960 was reached. Therefore, SMD(I) subsequently remained constant and low until the arrival of an early rainfall event in April 1961, whose effective amount (i.e. rainfall left after the satisfaction of evaporative and runoff demands) was enough to offset the low SMD(I) and hence allow recharge to take place.

From Fig. 10, it was observed that in all the months with recharge, rainfall was always in excess of actual evapotranspiration (AET) with the exception of October months of 1960, 1962, 1963 and 1965, where AET was in excess of the rainfall. This implies that there was recharge in these exceptional months inspite of the existence of an SMD. These exceptions are explained as follows.

If in a month, the number of days with moisture deficits exceeds the number of days with moisture gains, it is possible that at the end of the month, the cumulative value of the moisture deficits will

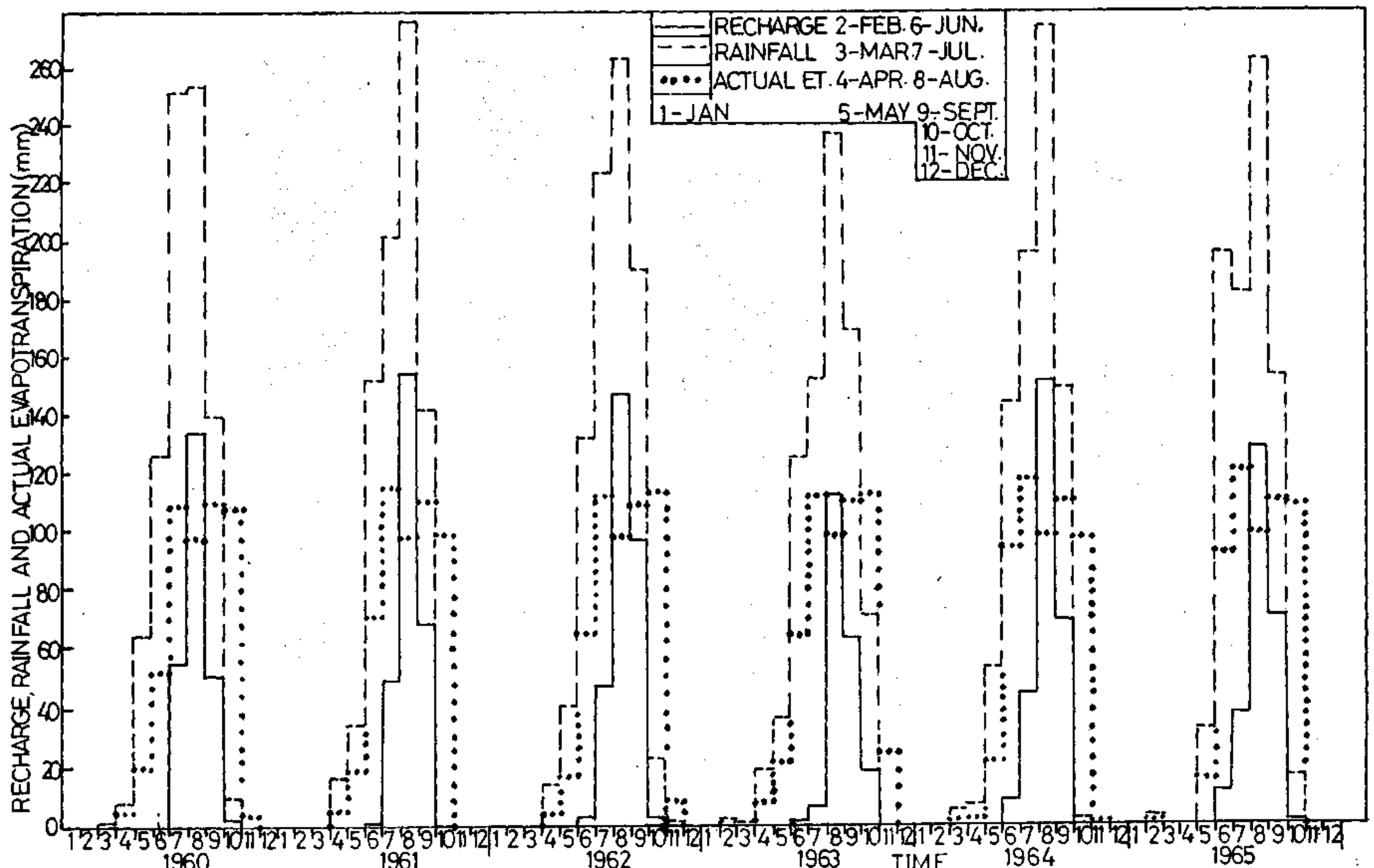


Fig.10: COMPARISON OF MONTHLY RECHARGE, RAINFALL AND ACTUAL EVAPOTRANSPIRATION IN SOKOTO-RIMA RIVER BASIN

outweigh the cumulative value of the moisture gained. Therefore a monthly SMD occurs together with recharge.

From Table 5.2, the annual recharge ranges from 200.8 mm to 296.2 mm, in the years 1963 and 1962 respectively. The year 1963 has the highest AET, the lowest rainfall and ΔS was relatively high as shown in Table 5.2. This implies that the satisfaction of evaporative demand during the year 1963 was more from rainfall than it was from soil moisture storage. There has,on the average, been rainfall over the basin as early as February 1963 and it subsided in November 1963. The combined effect of the low rainfall and high AET in 1963 made less water available for infiltration and therefore less recharge took place. The high IMD and low rainfall in the peak recharge month of August in 1963 may also have contributed to the low recharge of that year (Table 5.1). The high monthly rainfall, low evaporative demand and the relatively low IMD's in the recharge months of 1962, were responsible for the year's high recharge (Fig. 10, Table 5.1).

The year with the highest recharge had the highest number of days of recharge (NDR) while the year with the lowest recharge had the lowest NDR. However, the year with the highest NDR did not have

Table 5.2: ANALYSIS OF ESTIMATED ANNUAL RECHARGE IN SOKOTO-RIMA RIVER BASIN

PARAMETERS	1960	1961	1962	1963	1964	1965	GRAND TOTALS	AVERAGE
RECHARGE (mm)	243.0	271.6	296.2	200.8	272.5	245.7	1529.8	255.0
RAINFALL (mm)	853.6	821.7	885.6	811.4	827.3	841.6	5041.2	840.2
ACTUAL EVAPORANS-PIRATION (mm)	507.5	518.8	526.6	550.9	540.6	543.8	3188.2	531.4
DIRECT RUNOFF (mm)	46.2	44.1	49.4	37.6	44.8	49.4	271.5	45.2
ΔS (mm)	56.9	-13.1	13.4	22.1	-30.6	2.7	51.4	8.6
NO OF DAYS OF RECHARGE	15.8	18.4	20.7	14.9	19.5	18.6	107.9	18.0
NO OF DAYS OF RAINFALL	57.6	56.7	57.2	56.0	50.6	53.1	331.2	55.2

ΔS is change in soil moisture storage the highest number of rainfall days (NYRN), likewise the year with the lowest NDR. From Table 5.2, it has been observed that the relationship between NYRN and NDR does not follow any definite pattern.

5.2.2 Gwadabawa station polygon

Monthly direct recharge estimates and soil moisture deficit over the polygon at the beginning of each month (IMD) are presented in Table 5.3. Analysis of estimated annual recharge and comparison of monthly recharge, rainfall and actual evapotranspiration are presented in Table 5.4 and Fig. 11 respectively. The incidence of recharge is restricted to the rainfall months of July, August, September, although the year 1960 had only one recharge month, while the years 1961, 1962, 1963, 1965 all had two months of recharge, Table 5.3. These unusual trends are explained as follows.

From Table 5.3, July 1960 had no recharge, this is because the month started with a relatively high IMD and had a relatively low rainfall (average of (av.) 4.0 mm/day). Although the rainfall was densely distributed (av. 1 event in 2 days), it was only able to reduce the high IMD by 42 percent at the end of the month. Recharge took place in August 1960

Table 5.3: ESTIMATED MONTHLY AND ANNUAL RECHARGE (mm) IN GWADABAWA STATION POLYGON

YEAR	1960		1961		1962		1963		1964		1965		AVERAGE
MONTH	RECH.	IMD.	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.
JAN	0.0	174.5	0.0	155.4	0.0	173.2	0.0	132.0	0.0	127.4	0.0	172.5	0.0
FEB.	0.0	174.5	0.0	155.4	0.0	173.2	0.0	132.0	0.0	127.4	0.0	172.5	0.0
MAR.	0.0	174.5	0.0	155.4	0.0	173.2	0.0	132.0	0.0	127.4	0.0	172.5	0.0
APRIL	0.0	174.5	0.0	155.4	0.0	173.2	0.0	132.0	0.0	127.4	0.0	172.5	0.0
MAY	0.0	174.5	0.0	155.4	0.0	173.2	0.0	132.0	0.0	127.4	0.0	172.5	0.0
JUNE	0.0	174.5	0.0	154.6	0.0	167.4	0.0	130.3	0.0	126.1	0.0	158.7	0.0
JULY	0.0	135.8	0.0	107.1	19.5	149.2	0.0	114.4	67.6	65.4	0.0	59.4	14.5
AUGUST	7.7	78.1	157.6	2.03	43.4	4.5	71.6	15.0	68.5	6.7	22.4	73.4	61.9
SEPT.	0.0	17.9	33.8	0.0	0.0	6.1	20.4	24.6	69.9	0.01	112.7	0.0	39.5
OCT.	0.0	62.0	0.0	41.4	0.0	106.9	0.0	53.2	0.0	40.7	0.0	59.8	0.0
NOV.	0.0	140.3	0.0	173.2	0.0	122.7	0.0	115.6	0.0	172.5	0.0	153.2	0.0
DEC.	0.0	155.4	0.0	173.2	0.0	132.0	0.0	127.4	0.0	172.5	0.0	153.2	0.0
ANNUAL	7.7		191.4		62.9		92.0		206.0		135.1		115.9

RECH. is Recharge. IMD is polygon soil moisture deficit at the beginning of the month.

due to the high (av. 12 mm/day) and densely distributed (av. 1 event in 3 days) rainfall of the second half of the month. September 1960 did not have recharge, despite it's low IMD, because the monthly rainfall distribution was sparse (av. 1 event in 8 days) in the first 12 days and this led to a rapid build-up of SMD during that period, such that the relatively high rainfall of the later days of the month could not completely make up the SMD previously built up.

In July 1961, IMD was relatively high, Table 5.3, and the rainfall during the first half of the month was small (av. 0.4 mm/day) and sparsely distributed (av. 1 event in 9 days), therefore there was a build up of SMD during this period. The high (av. 15 mm/day) and densely distributed (av. 1 event in 2 days) rainfall of the second half of the month barely brought the SMD close to zero at the end of the month. August 1961, therefore had a low IMD and the highest recharge in all the six years, due to a high monthly total rainfall which was well distributed (av. 1 event in 3 days). Although the IMD in September 1961 was zero, but it did not have a higher recharge than August 1961 because it's rainfall distribution was relatively sparse (av. 1 event in 5 days) and also the monthly total rainfall and the average daily rainfall during the month was less than in August. (285.5 mm cf. 122.8 mm and av. 9.0 mm/day cf. 4.0 mm/day, respectively).

In the year 1962, recharge occurred only in July and August. Despite July's high IMD, there was recharge because the second half of the month had high (av. 11 mm/day) and densely distributed (av. 1 event in 2 days) rainfall which drastically reduced the SMD and brought about recharge at the end of the month. The low monthly total rainfall of 13.8 mm and it's sparse distribution (av. 1 event in 10 days) was not enough to offset the small IMD of 6.1 mm in September 1962, hence the SMD was increasing and consequently no recharge occurred.

July 1963, had a high IMD, Table 5.3, and the distribution/amount of rainfall (av. 1 event in 4 days and 5.3 mm/day respectively) in the first half of the month reduced the SMD by half. In the second half of the month, rainfall distribution and amount was such that it first allowed an increase of the SMD, before drastically reducing it towards the end of the month, but it (SMD) never reached zero. Hence no recharge occurred in July 1963.

From Table 5.3, IMD was relatively low in July of 1965, but the sparse distribution (av. 1 event in 5 days) and low amount (av. 2.3 mm/day) of rainfall in the first half of the month caused a threefold increase of SMD during that period. Therefore, the relatively higher (av. 6.3 mm/day) and better distributed (av. 1 event in 3 days) rainfall of the second half of the month could not reduce the SMD to zero. Thus in July 1965, there was no recharge at all.

From Fig. 11, all the months with recharge generally had monthly rainfall in excess of monthly AET, with the exception of September 1961 and 1963. The reasons for these exceptions have been earlier explained in section 5.2.1. The highest average monthly recharge (which forms 53 percent of the average annual recharge) occurred in August, which has the highest average monthly rainfall of 206.7 mm. In four out of the six years (1960 to 1965) the highest recharge occurred in August, because August had the highest and a relatively well distributed rainfall coupled with it's low IMD's (Table 5.3, Fig. 11). August 1962, September 1964 and 1965 recorded the highest recharge in the respectively indicated years without necessarily having the highest monthly total rainfall, Fig. 11. These exceptions are explained as follows.

July 1962 had the highest monthly total rainfall, but August 1962 had the highest recharge because the IMD at the start of August 1962 was low

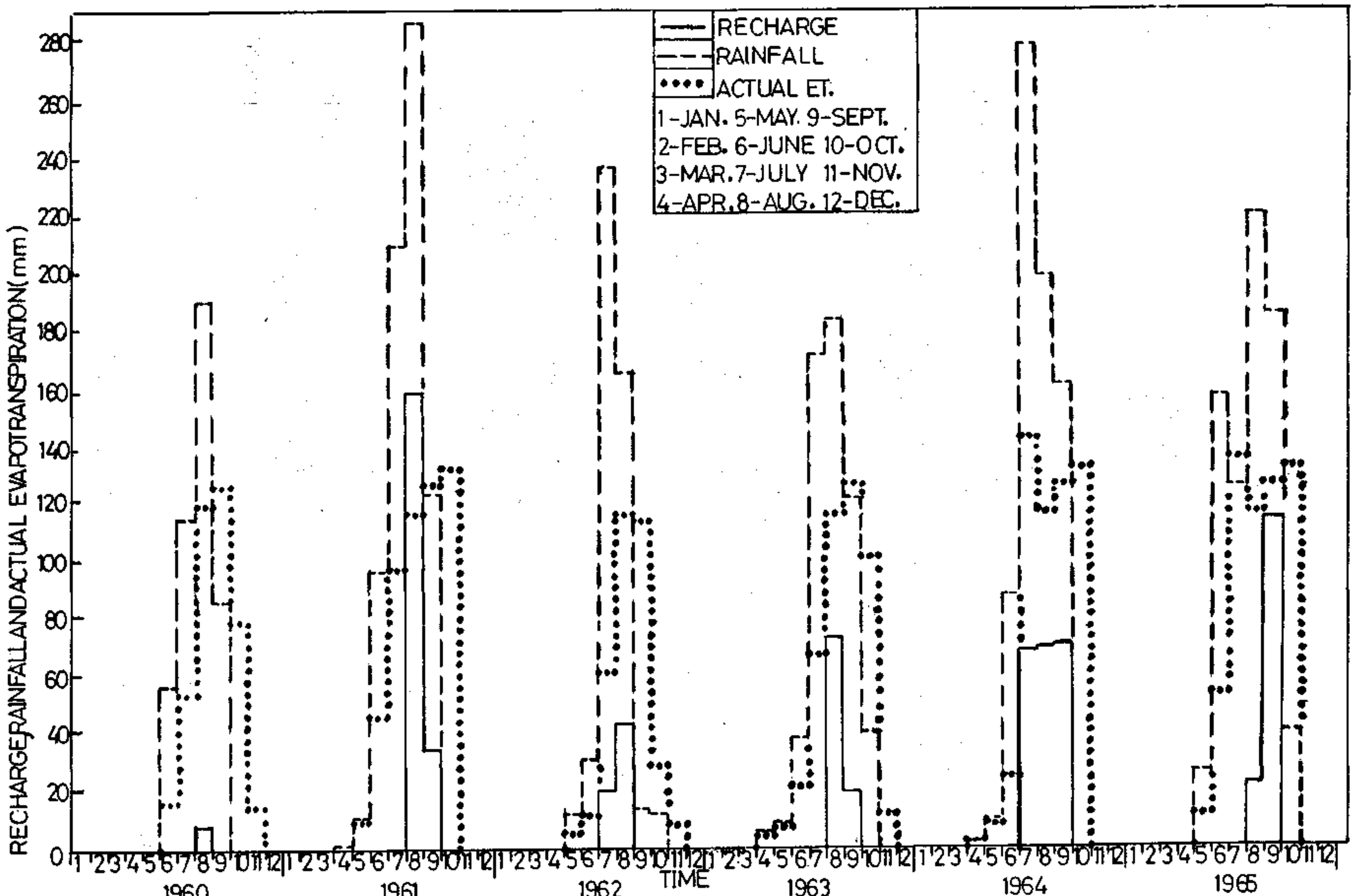


Fig.11: COMPARISON OF MONTHLY RECHARGE, RAINFALL AND ACTUAL EVAPOTRANSPIRATION IN GWADABAWA STATION POLYGON

and the rainfall was fairly well distributed (av. 1 event in 4 days) during the month.

The low IMD and the occurrence of about 76 percent of the monthly total rainfall of September 1964 in the first 12 days of the month, made it possible for the month to have the highest monthly recharge in 1964. In September 1965, IMD was zero and about 95 percent of the total monthly rainfall occurred in the first two weeks of the month, when the increase in SMD was still very small, hence the month had the highest recharge in 1965.

In Table 5.4, the annual total recharge estimates range from 7.7 mm (in 1960) to 206.0 mm (in 1964). The average annual recharge is 115.9 mm. The year 1960 had the least annual rainfall and a relatively (to the annual rainfall) high AET. The distribution and amount of daily rainfall in 1960 (i) produced a high annual AET by generally allowing evapotranspiration to proceed at the maximum rate and (ii) only completely offsetting SMD once in the year. These two factors are responsible for the low annual recharge of 1960. The year 1964 had the second highest annual total rainfall and the highest annual recharge as against 1965 whose annual total rainfall is the highest but has a lower annual recharge. This is because the daily

Table 5.4: ANALYSIS OF ESTIMATED ANNUAL RECHARGE IN GWADABAWA STATION POLYGON

PARAMETER	1960	1961	1962	1963	1964	1965	GRAND TOTALS	AVERAGE
RECHARGE (mm)	7.7	191.4	62.9	92.0	206.0	135.1	695.1	115.9
RAINFALL (mm)	446.2	726.0	470.9	569.4	736.6	752.1	3701.2	616.9
ACTUAL ET. (mm)	404.0	527.4	346.2	456.6	549.7	573.1	2857.0	476.2
DIRECT RUNOFF (mm)	15.4	25.0	20.6	16.2	25.9	24.7	127.8	21.3
ΔS (mm)	19.1	-17.8	41.2	4.6	-45.1	19.3	21.3	3.6
NDR (days)	1	16	4	5	11	9	46	7.7
NYRN (days)	31	41	26	39	34	43	214	35.7

ΔS is change in soil moisture storage. NDR is No of days of recharge

NYRN is No of yearly occurrences of rainfall.

rainfall was well distributed during the recharge months of 1964 than it was during the same period in 1965. Therefore three moderately large monthly incidence of recharge occurred in 1964 as against two monthly incidence of recharge - one small and one large amount - in 1965 Table 5.3. Same explanation goes for the higher recharge obtained in 1961 as against the recharge obtained in 1965. Both 1964 and 1965, have high AET due to high potential recharge and early rains.

While the year with the least recharge had the least NDR, the year with the highest recharge did not correspondingly have the highest NDR. Also no definite relationship seem to exist between NYRN and NDR, Table 5.4.

5.2.3 Koko station polygon

Monthly direct recharge estimates and soil moisture deficit over the polygon at the beginning of each month (IMD) are presented in Table 5.5. Analysis of estimated annual recharge and comparison of monthly recharge, rainfall and actual evapotranspiration are presented in Table 5.6 and Fig. 12 respectively. Monthly recharge estimates vary from zero in January to 489.3 mm in August 1962. The IMD value in August 1962 was zero and August 1962 had the highest monthly total rainfall (both in Koko station polygon and the Sokoto-Rima river basin) in the year 1962 and in all the six years. The daily rainfall amount (av. 20 mm/day) was high and was densely distributed (av. 1 event in 2 days) during the month. Incidences of recharge are mostly restricted to the months of July to September. However, exceptions to this rule abound in 1961, 1962 and 1960, 1963, when recharge was observed to take place in April, June, and October respectively. July 1961 and 1963 had no recharge, Table 5.5. These unusual trends are explained as follows.

The case of April 1961 has been dealt with earlier in section 5.2.1. June 1962, had the highest IMD in 1962 and also when compared with the month of June in other years. In June 1962, the daily rainfall amount was relatively higher and better distributed than that in June of other years, it therefore was able to effect a gradual reduction (during the month) of the high IMD and thus bring about recharge at the end of June 1962.

IMD in October 1960 was relatively low and the monthly total rainfall was relatively high too with about 80 percent of the monthly total rainfall occurring in the first 15 days of the month, before the onset of any appreciable rise in SMD.

October 1963 started with a relatively low IMD and high monthly total rainfall (compared with other

Table 5.5: ESTIMATED MONTHLY AND ANNUAL RECHARGE (mm) IN KOKO STATION POLYGON

YEAR	1960		1961		1962		1963		1964		1965		AVERAGE
MONTH	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.
JAN.	0.0	189.6	0.0	36.0	0.0	97.9	0.0	96.5	0.0	76.7	0.0	95.7	0.0
FEB.	0.0	189.6	0.0	36.0	0.0	97.9	0.0	96.5	0.0	76.7	0.0	95.7	0.0
MAR.	0.0	189.6	0.0	36.0	0.0	97.9	0.0	91.9	0.0	76.7	0.0	95.7	0.0
APRIL	0.0	189.6	0.51	36.0	0.0	97.9	0.0	78.0	0.0	76.7	0.0	95.7	0.08
MAY	0.0	175.4	0.0	36.0	0.0	97.9	0.0	60.3	0.0	76.7	0.0	95.7	0.0
JUNE	0.0	96.7	0.0	58.7	4.4	97.9	0.0	57.2	0.0	48.8	0.0	44.5	0.7
JULY	114.6	110.3	0.0	86.2	54.9	3.7	0.0	33.6	8.8	59.3	40.6	81.5	36.5
AUGUST	120.0	0.0	88.0	23.7	489.3	0.0	53.2	21.1	308.0	4.6	55.6	9.5	185.7
SEPT.	114.4	13.4	87.4	2.8	97.2	2.8	107.9	7.5	255.3	0.0	206.4	0.0	144.8
OCT.	54.3	9.2	0.0	24.5	0.0	38.3	30.4	3.4	0.0	0.0	0.0	3.4	14.1
NOV.	0.0	32.1	0.0	97.9	0.0	96.5	0.0	76.7	0.0	95.7	0.0	93.9	0.0
DEC.	0.0	36.0	0.0	97.9	0.0	96.5	0.0	76.7	0.0	95.7	0.0	93.9	0.0
ANNUAL	403.3		175.9		645.8		191.5		572.1		302.6		381.9

RECH. is recharge. IMD is polygon soil moisture deficit at the beginning of the month.

months of October, Fig. 12), about 98 percent of the month's total rainfall took place in the first 11 days of the month, before any significant rise in the low IMD could take place. Although October 1965 started with the same IMD as October 1963, it did not record any recharge because the monthly total rainfall in October 1965 was only 27.2 mm, much less than that in October 1963, 82.8 mm. Furthermore, it's distribution was such that it allowed, rather than check, the rise of SMD.

Despite the satisfaction of both evaporative and runoff demands by the monthly total rainfall of July 1961, recharge did not take place because the effective rainfall of 62.5 mm was still less than the monthly SMD of 86.2 mm, Table 5.5, and also there was no day, during the month, when the effective rainfall was enough to offset the SMD(I). Same explanation goes for July 1963 which had an effective rainfall of 12.5 mm and a monthly SMD of 33.6 mm (Table 5.5, Fig. 12). From Table 5.5, the highest average monthly recharge of 185.7 mm took place in August, which incidentally has the highest average monthly rainfall of 305.6 mm.

From Fig. 12, it is observed that in all the months with recharge, rainfall was greater than the AET, except in October 1963. This is due to the same reasons as advanced in section 5.2.1. Maximum

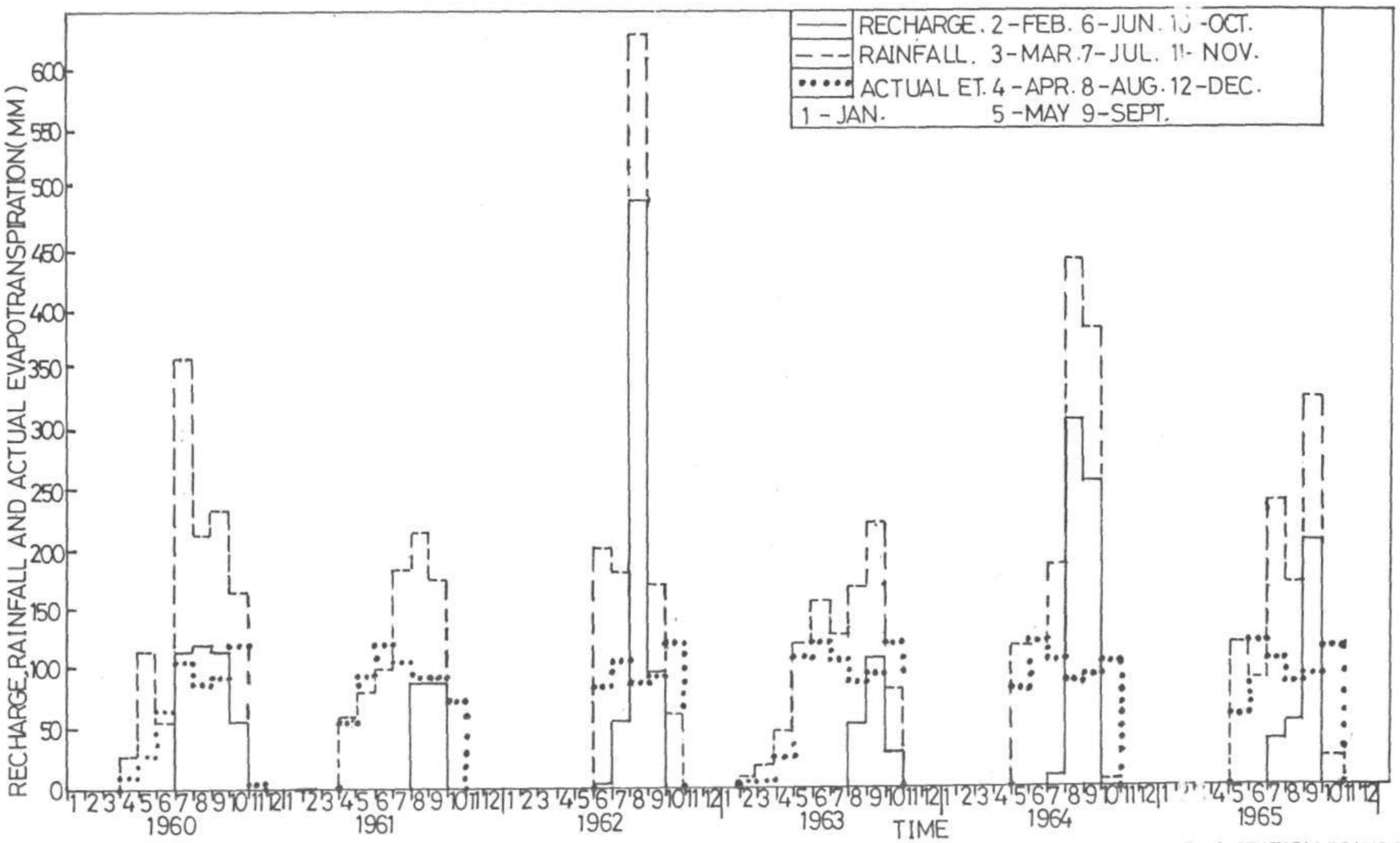


Fig.12: COMPARISON OF MONTHLY RECHARGE, RAINFALL AND ACTUAL EVAPOTRASPIRATION IN KOKO STATION POLYGON

recharge occurred in August of the years 1960, 1961, 1962 and 1964, with the August of these years having the highest rainfall, except in 1960. In 1960, July had the highest rainfall but was largely used to make up the IMD and the SMD that was built up during the month. September 1963 and 1965 had the highest monthly total rainfall in the respective years and relatively low IMD's, Table 5.5. therefore these months logically had the highest recharge in both years.

In Koko station polygon, the annual recharge estimates vary from 175.9 mm in 1961 to 645.8 mm in 1962. The average annual recharge is 381.9 mm, Table 5.6. In 1961, the sparse distribution and small amount of the rainfall in the early wet season led to a build up of the SMD. Such that when the rains became more regular (with a better distribution and amount) most of it was used to offset the previous SMD build up, thus reducing the monthly incidences and amount of recharge in 1961. Both, 1962 and 1964, have approximately the same annual rainfall, but the former has a higher recharge than the latter. This is because June - July, the first two recharge months of 1962, respectively had better rainfall amounts and lower IMD than the same months in 1964, Table 5.5, Fig. 12. Therefore the total recharge in June - July 1962 exceeded those of the same months in 1964. The total recharge for the two

Table 5.6: ANALYSIS OF ESTIMATED ANNUAL RECHARGE IN KOKO STATION POLYGON

PARAMETER	1960	1961	1962	1963	1964	1965	GRAND TOTALS	AVERAGE
RECHARGE (mm)	403.4	175.9	645.8	191.5	572.1	302.7	2291.4	381.9
RAINFALL (mm)	1168.8	810.8	1245.2	954.6	1246.3	972.6	6398.3	1066.4
ACTUAL ET. (mm)	509.8	627.1	489.2	667.1	585.8	578.9	3457.9	576.3
DIRECT RUNOFF (mm)	102.0	69.7	108.7	76.1	107.4	89.2	553.1	92.2
ΔS (mm)	153.6	-61.9	1.4	19.8	-19.0	1.8	95.7	16.0
NDR (days)	26	11	32	17	35	19	140	23.3
NYRN (days)	60	41	49	75	68	63	356	59.3

other recharge months in both years are approximately the same.

From Tables 5.2, 5.4, 5.6, 5.8 it is observed that Koko station polygon has the highest direct runoff (DRO). This is because about 58 percent of Koko station polygon is covered by the basement complex rocks and clay out crops, hence it's high runoff values as against Gwadabawa and Yabo station polygons both of which are entirely located in the sedimentary region of the Sokoto-Rima river basin. While most of the runoff from the Sokoto-Rima river basin comes from the basement complex region, Mock (1967), the land area covered by the basement complex region is less than that covered by the sedimentary region.

From Table 5.6, it is observed that, the year with the lowest recharge has the lowest NDR. But the year with the highest recharge did not have the highest NDR or NYRN. This would imply that the number of incidences of recharge and the magnitude of recharge are not directly related. The same argument goes for NYRN and NDR.

5.2.4. Yabo station polygon

Monthly direct recharge estimates and soil moisture deficit over the polygon at the beginning of each month (IMD) are contained in Table 5.7.

Comparison of recharge, rainfall and actual evapotranspiration is presented in Fig. 13. From Table 5.7, recharge ranges from zero in January to 114.0 mm in August 1964 and it is generally restricted to the period from July to September. June 1965 could be an exception to this rule, as it had the highest monthly total rainfall in that year, about 84 percent of which was recorded in the first two weeks of the month. This type of rainfall distribution rapidly reduced the relatively high IMD and kept it low enough for recharge to occur in the middle of the month.

In September 1960, IMD was zero and no recharge took place because the month's rainfall distribution was such that frequent dry spells in between rainfall events caused a rapid rise in SMD. After such dry spells rainfall was largely used in making up the build up of SMD, which in all the cases was never completely made up, hence there was no recharge in this month.

No recharge took place in July 1962, because of the dry spells in between rainfall events and the relatively small (cf. the daily rainfall in the last week of the month) daily rainfall of the first three weeks of the month which allowed a rise in SMD during this period, such that the higher daily rainfall of the last week of the month could not completely

Table 5.7: ESTIMATED MONTHLY AND ANNUAL RECHARGE (mm) IN YABO STATION POLYGON

YEAR	1960		1961		1962		1963		1964		1965		AVERAGE
MONTH	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.	IMD	RECH.
JAN	0.0	184.6	0.0	163.1	0.0	140.0	0.0	148.8	0.0	80.6	0.0	163.1	0.0
FEB.	0.0	184.6	0.0	163.1	0.0	140.0	0.0	148.8	0.0	80.6	0.0	163.1	0.0
MAR.	0.0	184.6	0.0	163.1	0.0	140.0	0.0	148.8	0.0	80.6	0.0	163.1	0.0
APRIL	0.0	184.6	0.0	163.1	0.0	140.0	0.0	148.8	0.0	80.6	0.0	163.1	0.0
MAY	0.0	184.6	0.0	163.1	0.0	109.4	0.0	144.6	0.0	80.6	0.0	163.1	0.0
JUNE	0.0	124.8	0.0	142.6	0.0	87.1	0.0	141.0	0.0	38.	24.6	155.1	4.1
JULY	26.8	59.5	8.9	33.6	0.0	66.7	0.0	100.1	42.3	30.0	30.2	50.1	13.0
AUGUST	98.2	11.4	102.6	39.1	95.6	35.0	0.0	91.7	114.0	4.5	95.0	22.6	84.2
SEPT.	0.0	0.0	78.1	0.0	98.5	3.6	0.0	9.3	44.4	0.0	40.3	29.2	43.6
OCT.	0.0	31.4	0.0	34.9	0.0	24.8	0.0	54.6	0.0	38.1	0.0	72.9	0.0
NOV.	0.0	144.1	0.0	140.0	0.0	156.7	0.0	64.5	0.0	147.0	0.0	139.8	0.0
DEC.	0.0	163.1	0.0	140.0	0.0	148.8	0.0	80.6	0.0	163.1	0.0	139.8	0.0
ANNUAL	125.0		189.6		194.1		0.0		200.7		190.1		149.9

RECH. is recharge. IMD is soil moisture deficit at the beginning of the month (mm) offset the SMD that was built up over the first three weeks.

In 1963, recharge did not take place throughout the year. This is because, during the rainfall months of July and September, the daily rainfall distribution was such that the long dry spells in between rainfall events allowed for an increase of SMD. And the SMD was only partially offset after subsequent rainfall events. While the month of August 1963 had the highest monthly total rainfall and a dense daily rainfall distribution (av. 1 event in 2 days), the rainfall amount on all the month's rainfall days was not large enough to reduce the SMD(I) to zero.

From Fig. 13, it is observed that unlike in the two polygons earlier discussed, in all the months with recharge in Yabo station polygon, the rainfall was greater than the actual evapotranspiration. This implies that all the recharge months had potential recharge. In 1960, 1961 and 1964, August had the highest monthly total rainfall and correspondingly the highest monthly total recharge. The daily rainfall amounts were adequate and well distributed in all these months. In 1962 the highest monthly total rainfall was in August but September recorded the highest recharge, because IMD in September was less than in August,

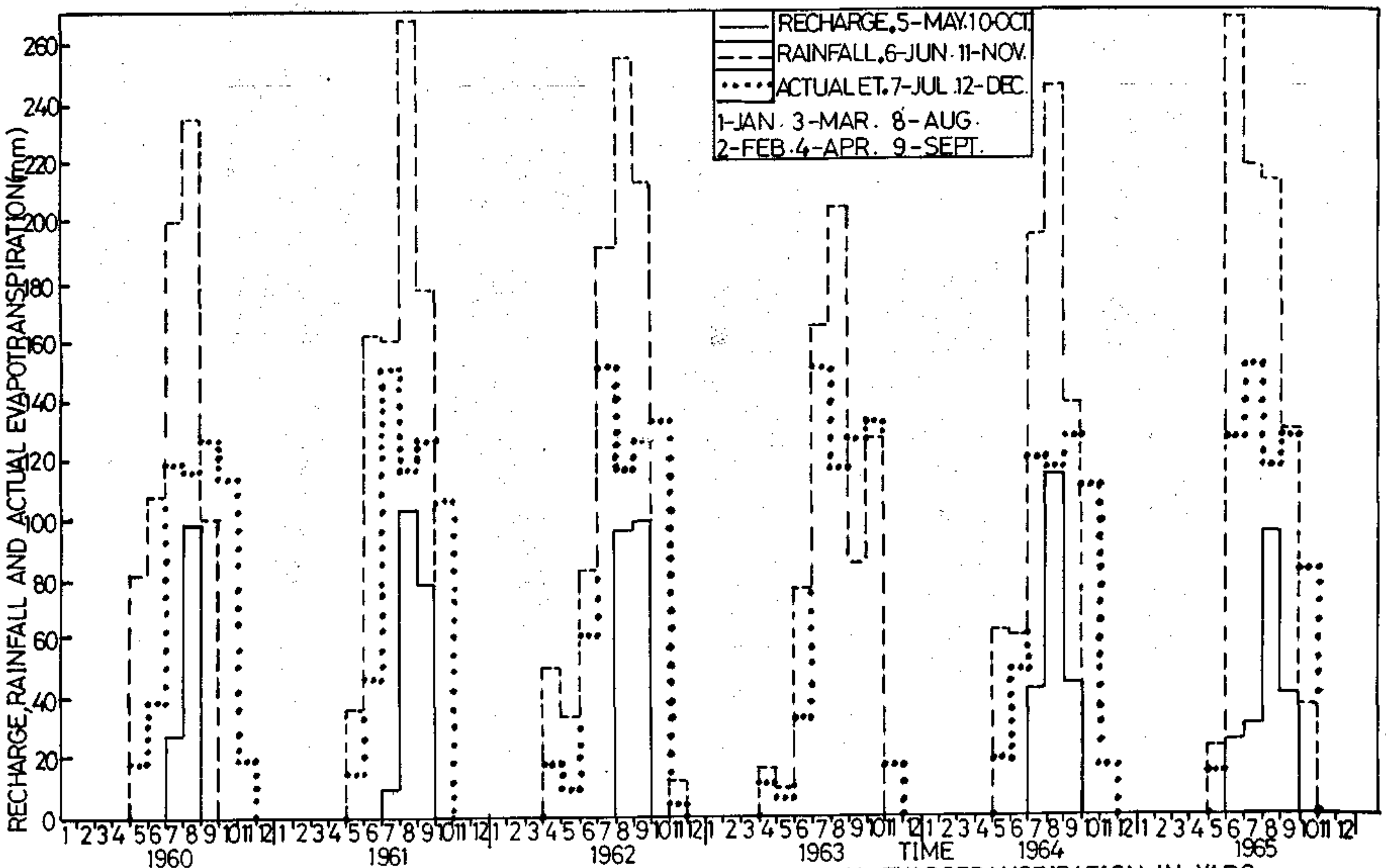


Fig. 13: COMPARISON OF MONTHLY RECHARGE, RAINFALL AND ACTUAL EVAPOTRANSPIRATION IN YABO STATION POLYGON

Table 5.7. Also about 70 percent of the total rainfall in September fell in the first 16 days of the month before any appreciable rise of the month's low IMD. Therefore September had a higher recharge than August. Total rainfall in September was 16 percent less than that of August.

In 1965, June had the highest monthly total rainfall (which largely went into reducing IMD). The daily rainfall distribution in June was same as in August (av. 1 event in 4 days), but August had the highest recharge because in contrast to June, the daily rainfall distribution was such that the short dry spells in between the relatively heavy rainfall events, did not favour any appreciable increase in the relatively low SMD at the beginning of the month and the SMD on the days in between rainfall events. Therefore after each rainfall event the rainfall amount was usually enough to **offset** the SMD.

5.3 Sensitivity Analysis

The results of the sensitivity analysis carried out in Sokoto-Rima river basin, Gwadabawa and Koko station polygons, using the method earlier described in section 4.6, are presented in Tables 5.8, 5.9 and 5.10 respectively. Figs. 14 to 19 contain pictorial representations of the sensitivity of the model to variation of rainfall and potential evapotranspiration (PET). The test results are presented on mean monthly (and restricted to recharge months only in order to save time and space), mean annual and on grand total basis.

5.3.1 Zonal rainfall (ZNRAIN)

It was observed that a two percent variation in ZNRAIN resulted in high (>1.0) sensitivity ratios. This implies that the model is sensitive to ZNRAIN. The results are given in Tables 5.8 to 5.10 and Figs. 14 to 16.

5.3.2 Potential evapotranspiration (PET)

The results as given from Tables 5.8 to 5.10 and Figs. 17 to 19, show that a five percent variation of PET, generally gave sensitivity ratios in excess of 1.0. This would imply that the model is sensitive to PET. Although the months of August and September in Tables 5.8, 5.10 and Figs. 17, 19 had sensitivity ratios which are below 1.0 as against what obtained in the same months in Table 5.9 and Fig. 18. This is because August and September in Koko station polygon and Sokoto-Rima river basin have low PET (88.0 mm/92.6 mm and 97.9 mm/109.6 mm respectively) values as against the higher PET values of Gwadabawa station polygon (115.6 mm and 126 mm) in the same months. Therefore, the variation of the lower PET values in Koko station polygon was not significant enough to produce too large a difference between the new and model recharge estimates.

Table 5.8: SENSITIVITY ANALYSIS USING WEIGHTED MONTHLY, WEIGHTED ANNUAL AND WEIGHTED GRAND TOTALS (SOKOTO-RIMA RIVER BASIN)

	MONTH/ WEIGHTED NO OF DAYS OF RECHARGE	MODEL ESTIMATE (mm)	ZNRAIN		PET		ROC		C		D		F		
			+2	-2	+5	-5	+100	-75	+50	-50	+50	-50	-1000	-80	+400
AVERAGE OF, WEIGHTED MONTHLY, WEIGHTED ANNUALS AND WEIGHTED GRAND TOTAL RECHARGE (mm)	JUNE	6.0	6.9	5.4	5.3	7.3	3.6	8.4	4.7	17.6	5.0	19.0	0.3	6.5	5.1
	WNDR	0.4	0.5	0.4	0.4	0.5	0.2	0.5	0.4	1.2	0.4	1.3	0.09	0.4	0.4
	JULY	47.3	51.9	42.8	41.5	53.8	34.4	56.9	45.0	65.8	45.6	65.3	21.8	48.0	45.4
	WNDR	2.9	3.1	2.7	2.6	3.4	2.4	3.3	2.8	4.0	2.8	4.0	1.2	3.0	2.6
	AUGUST	145.5	151.3	139.5	139.1	152.2	128.4	158.2	143.6	152.6	145.1	151.9	133.4	144.8	144.4
	WNDR	8.8	9.0	8.6	8.3	9.2	8.1	9.2	8.6	9.2	8.8	9.2	8.0	8.8	8.7
	SEPT.	74.4	77.2	71.5	70.9	77.8	65.4	80.9	74.4	74.6	74.4	74.6	72.9	74.4	74.4
	WNDR	5.5	5.5	5.3	5.3	5.7	5.1	5.7	5.5	5.5	5.5	5.5	5.4	5.5	5.5
	OCT.	3.8	4.0	3.6	3.5	4.2	3.2	4.3	3.8	3.8	3.8	3.8	3.8	3.8	3.8
	WNDR	0.4	0.4	0.3	0.3	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	ANNUAL	277.2	291.6	263.0	260.4	295.4	235.0	309.0	271.8	314.6	274.1	316.4	232.4	278.6	273.3
	WNDR	18.0	18.4	17.4	16.9	19.2	16.2	19.1	17.6	20.3	17.9	20.5	14.9	18.0	17.5
	GRAND TOTALS	1663.4	1749.8	1578.0	1562.4	1772.4	1410.0	1854.0	1631.0	1887.5	1645.0	1898.3	1394.5	1671.9	1640.0
	WNDR	107.8	110.6	104.3	101.5	115.0	97.4	114.5	105.7	121.6	107.2	122.8	89.6	108.3	105.1
SENSITIVITY RATIO (SN_R)	JUNE	6.0	7.5	-5.0	-2.3	4.3	-0.4	0.5	-0.4	3.9	-0.3	4.3	-0.2	0.1	-0.04
	JULY	47.3	4.9	-4.8	-2.4	2.8	-0.3	0.3	-0.1	0.8	-0.07	0.8	-0.1	0.02	-0.01
	AUGUST	145.5	2.0	-2.1	-0.9	0.9	-0.1	0.1	-0.03	0.1	-0.005	0.09	-0.02	-0.001	-0.002
	SEPT.	74.4	1.9	-2.0	-0.9	0.9	-0.1	0.1	0.0	0.005	0.0	0.005	-0.005	0.0	0.0
	OCT.	3.8	2.6	-2.6	-1.6	2.1	-0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ANNUAL	277.2	2.6	-2.6	-1.2	1.3	-0.2	0.2	-0.04	0.3	-0.02	0.3	-0.04	0.01	-0.004
	GRAND TOTALS	1663.4	2.6	-2.6	-1.2	1.3	-0.2	0.2	-0.04	0.3	-0.02	0.3	-0.04	0.01	-0.004

WNDR is weighted no of days of recharge.

Table 5.9: SENSITIVITY ANALYSIS USING AVERAGE MONTHLY, AVERAGE ANNUALS AND GRAND TOTALS (GWADABAWA STATION POLYGON)

	MONTH/ NO OF DAYS OF RECHARGE (NDR)	MODEL RECHARGE (mm)	ZNRAIN			PET		ROC		C		D		F	
			+2	-2	+5	-5	+100	-75	+50	-50	+50	-50	=1000	-80 (=0.02)	+400 (=0.5)
AVERAGE MONTHLY, AVERAGE ANNUAL AND GRAND TOTAL RECHARGE (mm)	JULY	14.5	17.1	13.6	12.4	17.9	11.4	18.5	12.0	45.0	14.5	45.7	5.7	15.8	13.5
	NDR	0.67	0.83	0.67	0.5	0.83	0.5	0.83	0.67	1.83	0.67	1.83	0.5	0.83	0.67
	AUGUST	61.8	66.7	57.2	55.4	68.2	52.5	68.6	56.3	81.3	61.6	78.5	28.0	62.1	58.9
	NDR	4.33	4.83	4.17	4.0	5.0	4.0	4.83	4.17	5.5	4.33	5.5	2	4.33	4.33
	SEPTEMBER	39.4	41.0	37.8	37.4	41.4	36.6	41.5	39.4	39.4	39.4	39.4	38.5	39.4	39.4
	NDR	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.57	2.67	2.67
	ANNUAL	115.8	124.9	108.7	105.3	127.7	100.6	128.7	107.8	167.1	115.6	163.7	72.2	110.1	111.9
	NDR	7.67	8.33	7.5	7.17	8.5	7.17	8.33	7.5	10.2	7.67	10	5.2	7.83	7.67
	GRAND TOTALS	695.0	749.8	652.5	632.1	766.4	604.0	772.6	647.2	1002.5	694.0	982.4	433.7	704.2	671.4
	NDR	46	50	45	43	51	43	50	45	61	46	60	31	47	46
SENSITIVITY RATIO (SN_R)	JULY	14.5	8.96	-3.10	-2.90	4.69	-0.21	0.37	-0.34	4.21	0.0	4.30	-0.2	0.11	-0.02
	AUGUST	61.8	3.96	-3.72	-2.07	2.07	-0.15	0.15	-0.18	0.63	-0.01	0.54	-0.18	0.006	-0.01
	SEPTEMBER	39.4	2.03	-2.03	-1.02	1.02	-0.07	0.07	0.0	0.0	0.0	0.01	-0.01	0.0	0.0
	ANNUAL	115.8	3.93	-3.06	-1.81	2.06	-0.13	0.15	-0.14	0.89	-0.003	0.83	-0.12	-0.06	-0.01
	GRAND TOTALS	695.0	3.93	-3.06	-1.81	2.06	-0.13	0.15	-0.14	0.89	-0.003	0.83	-0.12	-0.06	-0.01

Table 5.10: SENSITIVITY ANALYSIS USING AVERAGE MONTHLY, AVERAGE ANNUAL AND GRAND TOTALS (KOKO STATION POLYGON)

	MONTH/ NO OF DAYS OF RECHARGE (NDR)	MODEL RE-CHARGE (mm)	ZNRAIN		PET		ROC		C		D		F		
			+2	-2	+5	-5	+100	-75	+50	-50	+50	-50	=1000	-80 (=0.02)	+400 (=0.5)
AVERAGE MONTHLY, AVERAGE ANNUAL AND GRAND TOTAL RECHARGE (mm)	JUNE	0.7	1.3	0.1	0.0	1.0	0.0	2.3	0.0	5.2	0.6	5.7	0.0	0.9	0.0
	NDR	0.2	0.2	0.2	0	0.2	0	0.3	0	0.7	0.2	0.7	0	0.2	0
	JULY	36.4	40.0	32.9	31.1	41.9	19.6	50.8	31.3	62.8	36.4	57 6	20.7	37.5	32.2
	NDR	2.2	2.5	2.0	1.7	2.5	1.2	2.5	2	3.3	2.3	3.3	1.0	2.3	1.8
	AUGUST	185.7	193.3	178.0	177.4	193.4	148.5	211.2	183.5	192.5	185.5	192.5	179.4	185.5	183.9
	NDR	9.5	9.8	9.2	8.7	10.0	7.7	10.0	9.5	9.8	9.5	9.8	9.0	9.5	9.5
	SEPT.	144.7	149.3	140.2	140.7	148.9	122.9	161.2	144.7	144.7	144.7	144.7	144.7	144.7	144.7
	NDR	10.3	10.5	10.2	10.2	10.5	9.3	10.8	10.3	10.3	10.3	10.3	10.3	10.3	10.3
	OCT.	14.1	14.7	13.4	13.2	15.1	11.0	16.3	14.1	14.1	14.1	14.1	14.1	14.1	14.1
	NDR	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	ANNUAL	381.9	399.1	364.8	362.5	400.6	302.2	443.4	373.8	422.5	381.7	419.8	359.0	382.9	375.0
	NDR	23.2	24.2	22.5	21.7	24.2	19.2	24.8	22.8	25.3	23.3	25.5	21.3	23.5	22.8
	GRAND TOTALS	2291.5	2394.7	2189.0	2175.6	2403.6	1813.3	2660.4	2242.9	2535.0	2290.2	2518.8	2154.0	2297.4	2250.0
	NDR	139	145	135	130	145	115	149	137	152	140	153	123	141	137
SENSITIVITY RATIO (SN_R)	JUNE	0.7	42.9	-42.9	-20	8.6	-1.0	3.0	-2.0	12.9	-0.2	14.3	-0.3	0.4	-0.3
	JULY	36.4	4.9	-4.8	-2.9	3.0	-0.5	0.5	-0.3	1.4	0.0	1.2	-0.1	0.04	-0.03
	AUGUST	185.7	2.0	-2.1	-0.9	0.8	-0.2	0.2	-0.02	0.07	-0.002	0.07	-0.01	0.0	-0.002
	SEPT.	144.7	1.6	-1.6	-0.6	0.6	-0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	OCT.	14.1	2.1	-2.5	-1.3	1.4	-0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ANNUAL	381.9	2.2	-2.2	-1.0	1.0	-0.2	0.2	-0.04	0.2	-0.001	0.2	-0.01	0.003	-0.004
	GRAND TOTALS	2291.5	2.2	-2.2	-1.0	1.0	-0.2	0.2	-0.04	0.2	-0.001	0.2	-0.01	0.003	-0.004

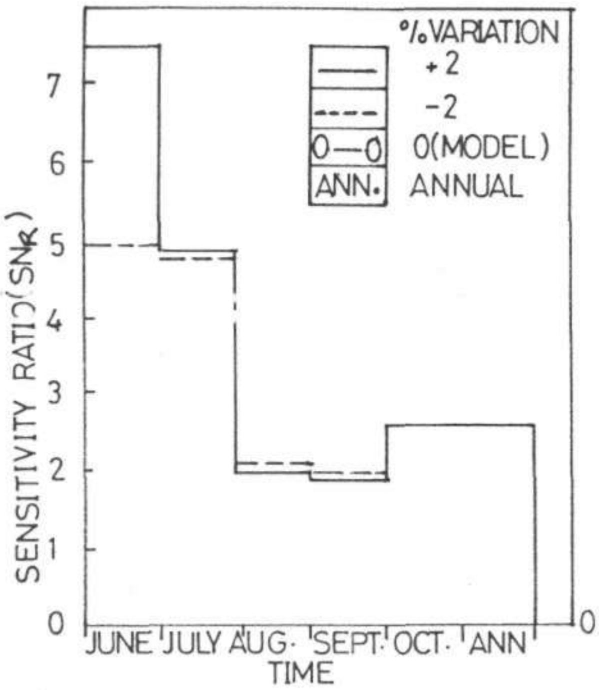


Fig.14: SENSITIVITY OF MODEL TO VARIATION OF ZNRAIN (SOKOTO-RIMA RIVER BASIN)

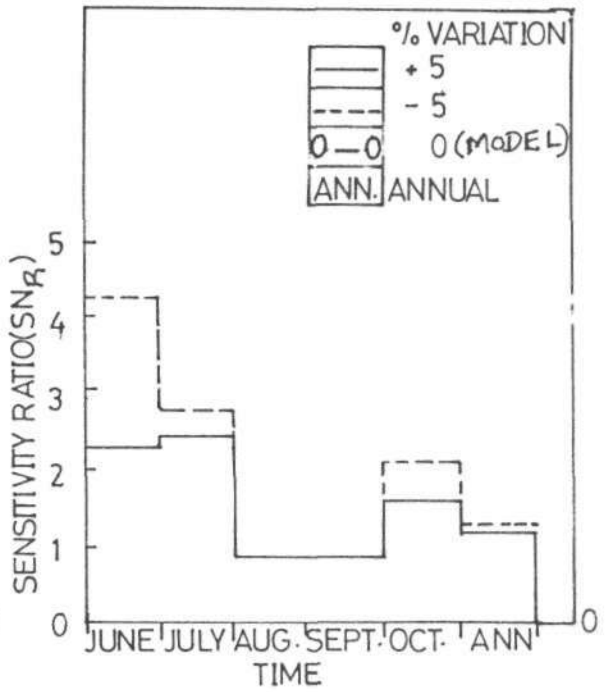


Fig.17: SENSITIVITY OF MODEL TO VARIAT-ION OF PET.(SOKOTO-RIMA RIVER BASIN)

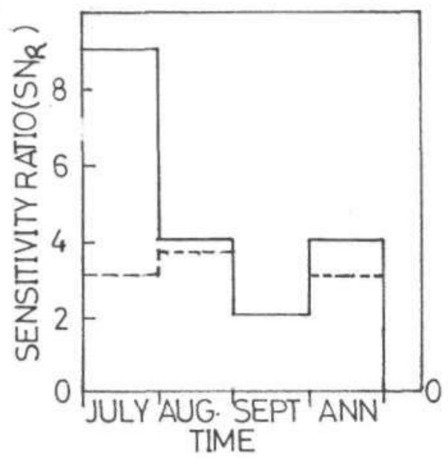


Fig.15: SENSITIVITY OF MODEL TO VARIATION OF ZNRAIN (GWADABAWA STATION ,POLYGON)

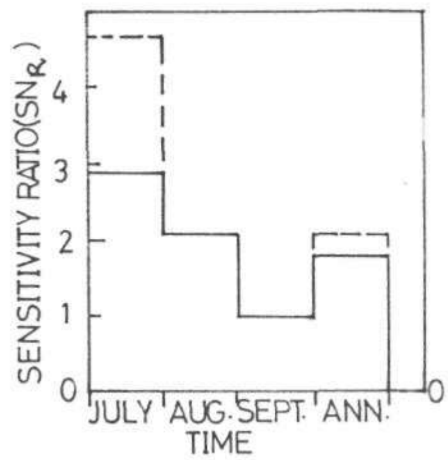


Fig.18: SENSITIVITY OF MODEL TO VARIATION OF PET. (GWADABAWA STATION POLYGON)

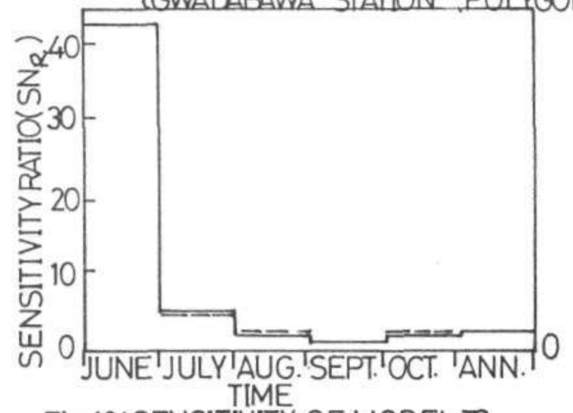


Fig.16: SENSITIVITY OF MODEL TO VARIATION OF ZNRAIN (KOKO STATION POLYGON)

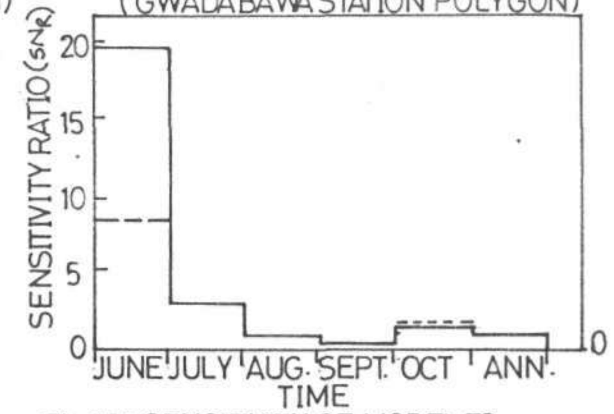


Fig.19: SENSITIVITY OF MODEL TO VARIATION OF PET. (KOKO STATION POLYGON)

5.3.3 Runoff coefficient (ROC)

Generally, the sensitivity ratios (Tables 5.8 to 5.10) are low (i.e. < 0.4), indicating that the model is slightly sensitive to ROC. In Koko station polygon, Table 5.10, the sensitivity ratios, although generally less than 0.4, are higher than in Gwadabawa station polygon, Table 5.9. This is because Koko station polygon has a higher runoff, for reasons earlier stated in section 5.2.3.

5.3.4 Root constant (C) and maximum soil moisture deficit (D)

In Tables 5.8 and 5.10 are given the model's sensitivity to C which was generally nil. Although the model's sensitivity to C ranges from low to high in the early recharge month(s). This is because a change in C only becomes significant when the SMD build up is high enough to cause a reduction in the rate of evapotranspiration. During the early recharge month(s), SMD build up is usually high (cf. the late recharge month(s)) and therefore the model is usually more sensitive to C in the early recharge month(s) than in the late recharge month(s). As shown in Table 5.9, the model's sensitivity to C ranges from nil to high. This is because two of the three recharge months in Gwadabawa station polygon fall in the early recharge month(s) during which the model is usually more sensitive to C. The sensitivity of the model to C depends on the position of SMD along the drying curve

Fig. 1. When SMD$<$C, the model is insensitive to C (as in the late recharge month(s)). But when SMD$>$C the model becomes sensitive to C (as in the early recharge month(s) when SMD is usually high).

Shown in Tables 5.8 and 5.10 are the model's sensitivity to D. It was generally nil, with the model being sensitive to D only in the early recharge month(s) and insensitive to same in the late recharge month(s). When SMD $<$ C, the model is insensitive to D, but when C $<$SMD$\leqslant$D the model becomes sensitive to D. The latter case is more prevalent during the early recharge month(s) because the SMD then is usually high. Hence the model is more sensitive to D at that time, than in the late recharge month(s).

5.3.5 <u>Slope of drying curve</u> (F)

Generally, sensitivity of the model to F is nil. However, Gwadabawa station polygon, Table 5.9, is more sensitive to F than Koko station polygon, Table 5.10. This is because, the factor, F, becomes relevant only when SMD falls between C and D. The higher PET values coupled with the lower C values in Gwadabawa station polygon always tends to bring SMD within the said range more frequently than is the case in Koko station polygon, the model will therefore be more sensitive to F in Gwadabawa station polygon than in Koko station polygon.

5.3.6 Effect of parameter variation on number of days of recharge (NDR)

From Tables 5.8 to 5.10, it can be seen that parameter variations have led to variations in the NDR. It was found that NDR is highly sensitive to variation of ZNRAIN and PET. NDR was found to be insensitive to variation of ROC and F, and a positive variation of C and D. NDR was found to be slightly sensitive to a negative variation of C and D. The sensitivity of NDR to the variation of all the parameters, ranged from moderate to high in the early recharge month(s). This is because the early recharge month(s) is/are more sensitive to variation of input data and model parameters than is the recharge in the late recharge month(s).

5.3.7 Amount and incidence of recharge

Generally, it was found that a variation of recharge estimate was due mainly to a variation of the magnitude of recharge from particular storms, rather than a variation of the number of days of recharge. However, when PET was varied and C and D were decreased, the variation of recharge was due, both to the variation of NDR and the variation of the magnitude of recharge from particular storms, Table 5.9.

5.3.8 Conclusion

It was observed:

(i) that the model is sensitive to rainfall and PET;

(ii) that the model is slightly sensitive to ROC and a reduction in C and D, Tables 5.8 to 5.10;

(iii) that the model is insensitive to F and a positive variation of C and D, Table 5.8 - 5.10;

(iv) that variation of recharge estimates, as a result of parameter variations, is mainly due to variations in the recharge of particular storms. Although, in some cases, it may also be due to variation of NDR;

(v) that, as shown in Tables 5.9 and 5.10, the same percentage variation of a given parameter can produce different sensitivity levels at different locations in the basin;

(vi) that the model was relatively more sensitive to parameter variations in the early recharge month(s) than in the mid and late recharge month(s). This is probably due to the relatively low rainfall, high SMD and high potential evapotranspiration of the early recharge month(s).

5.4 Isorecharge Map

Figures 20 to 22 are isorecharge maps showing recharge distribution in the Sokoto-Rima river basin for the years 1962 (with the highest annual recharge), 1963 (with the lowest annual recharge) and the average annual recharge over each polygon. From figures 20 and 22 it is observed that, with a south-north movement in the basin there is a general decrease in the amount of recharge. This could be due to the fact that rainfall amounts follow the same pattern, Fig. 5. It was however observed, from figure 21 that there was at first an increase in recharge amounts, with a south-north movement in the basin, then a peak recharge is reached at a point near the middle of the basin, after which there was a general decrease of recharge amount towards the north. This can be explained thus; in the year 1963 the peak recharge point (Gusau station polygon) recorded the highest amount of rainfall in the basin and also the highest amount of recharge. The concentric "recharge rings" around this station is therefore due to the location of the highest recharge point in the neighbourhood of relatively lower recharge points.

5.5 Validation of Incidence of Recharge

The incidence and amount of recharge are model outputs that must be validated in order to

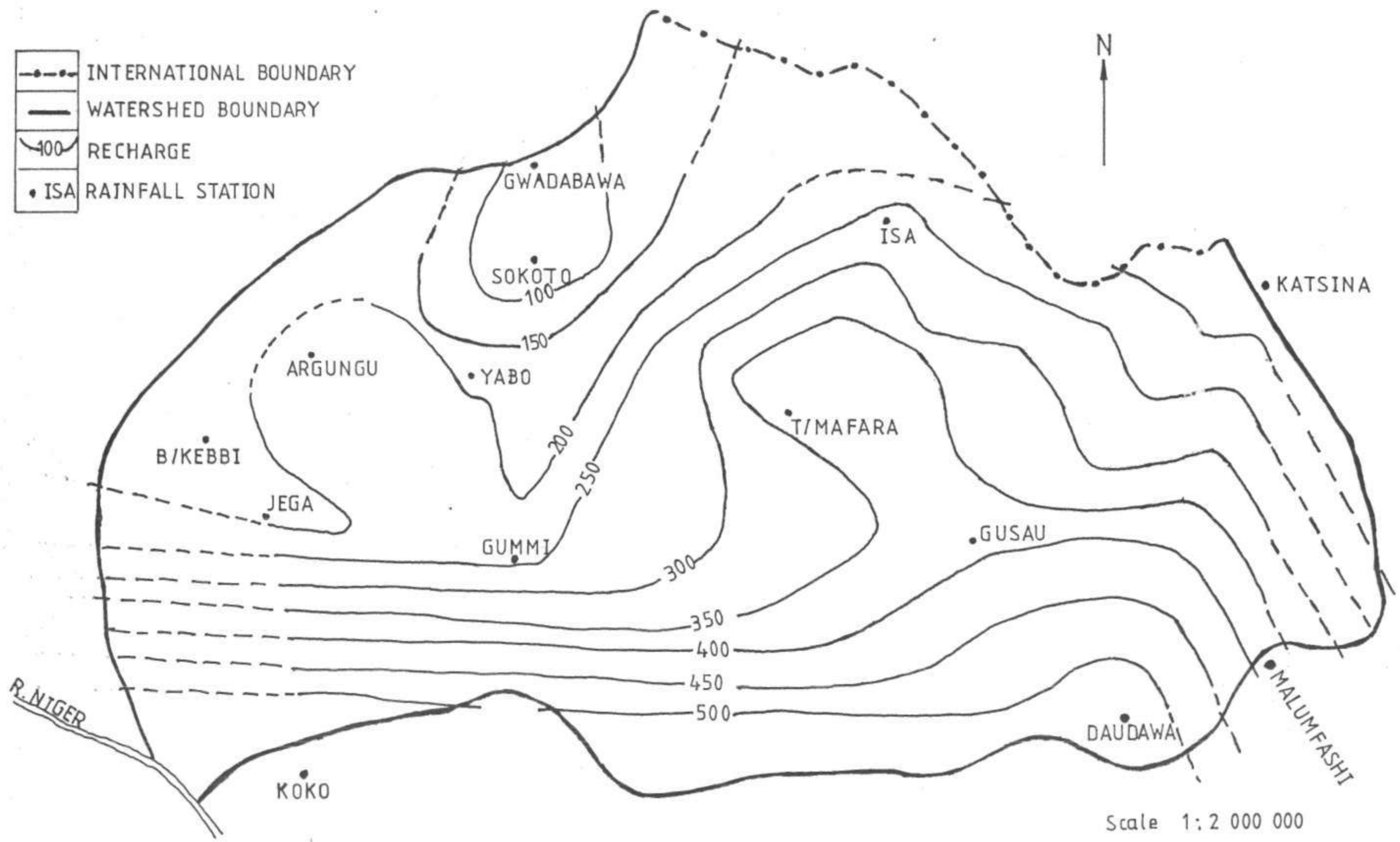


FIG. 20 VARIATION OF RECHARGE ACCROSS THE SOKOTO - RIMA RIVER BASIN (1962)

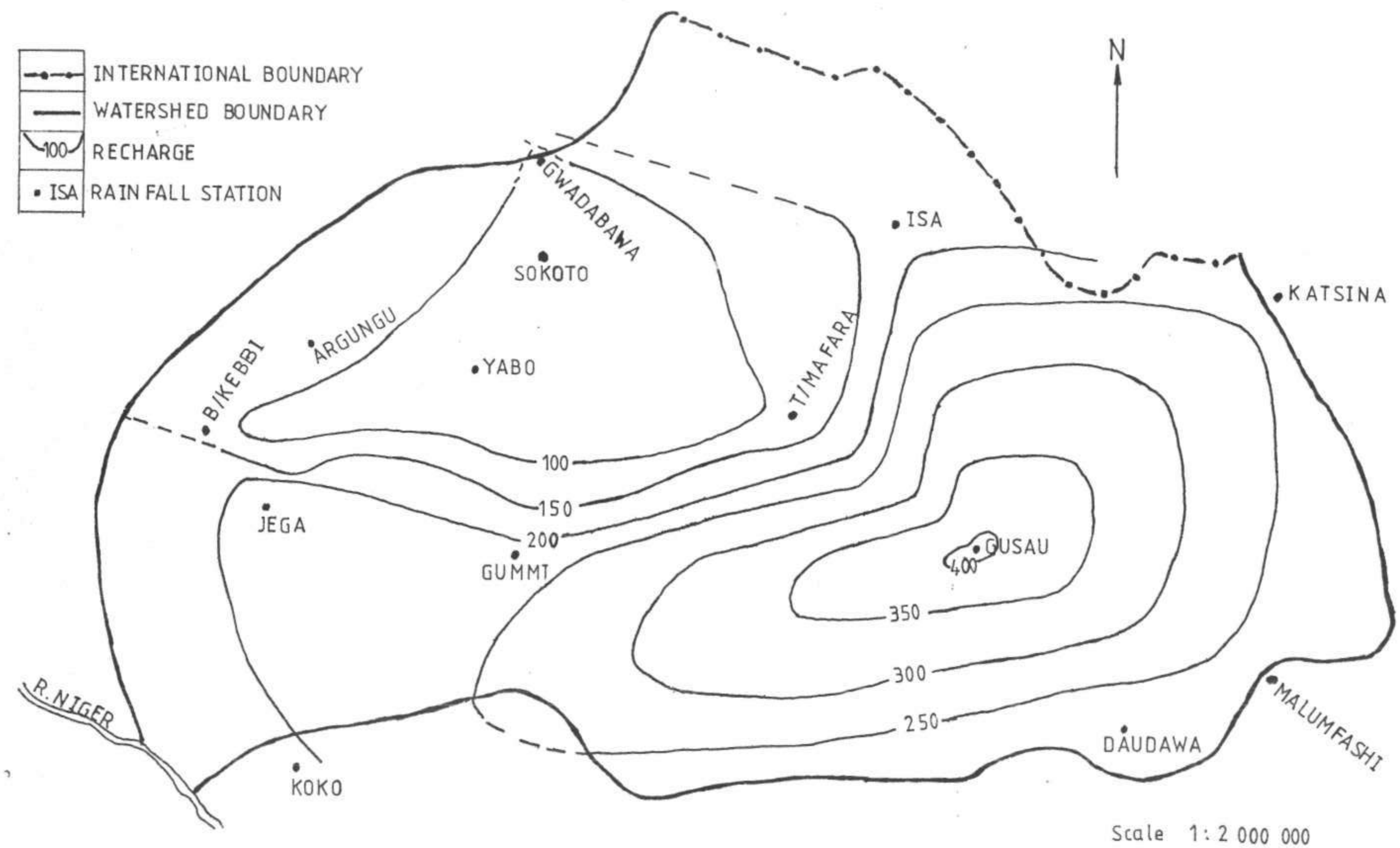


FIG. 21 VARIATION OF RECHARGE ACCROSS THE SOKOTO-RIMA RIVER BASIN (1963)

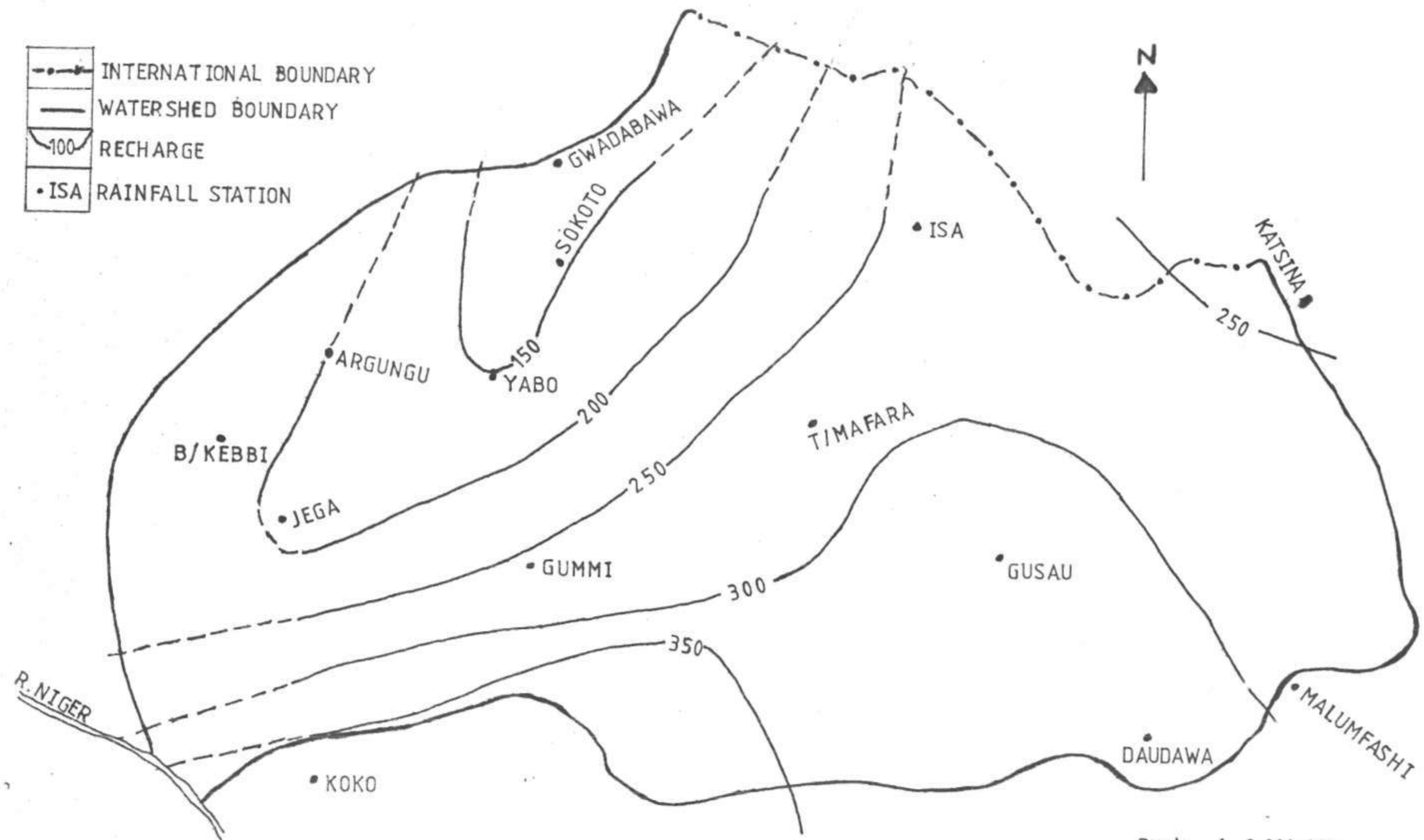


FIG. 22 AVERAGE ANNUAL RECHARGE OVER THE SOKOTO RIMA-RIVER BASIN (1960 - 1965)

render recharge estimates credible. Recharge amounts are best validated by comparing them with springflow measurements or recharge estimates carried out by any other reliable and accurate method(s). Examples of which have been previously reviewed in chapter two. The data presently available makes the validation of the amount of recharge impossible for now, hence further work is required before the recharge amounts can be fully validated. But attempts are made to validate the incidence of recharge thus.

Figure 23 shows the plot of monthly recharge (in two polygons - Talata/Mafara and Isa) and the observed well water level against time, in two towns (Mai-inchi and Kagare Daura) located respectively within the two polygons. From figure 23A, the rise in the well hydrograph started in the month of June 1962 rising to it's peak at the end of September 1962. This subsequently remained approximately constant, before it started to drop towards the end of October. In 1963, the well hydrograph started to rise at about the middle of May, all through to the end of October after which it started to drop. In figure 23B, the rise in the well hydrograph started at the end of June 1962 until the end of September 1962, beyond which the hydrograph plot was extrapolated. In 1963, as in 1962, the well hydrograph started to rise by the end of June and it kept on rising until mid-November, after which it started to drop.

One unusual trend that is noticeable from figures 23A and 23B is the tendency of the well hydrographs to rise in the absence of recharge. This trend can be explained by referring to figure 3, which shows the location of the observation wells. From this figure, the location of both wells at Mai-inchi and Kagare-Daura (very close to rivers Sokoto and Bunsuru respectively) is suggestive that they are located in the valley of both rivers and hence the aquifers which the wells tap are linked with the rivers.

The link between the river and the aquifer tapped by the well allows for the creation of a hydraulic gradient between the river and the aquifer, due to the previous decline of the water level in the aquifer (and hence the well).

This factor, coupled with the quick response of the rivers to rainfall in the basement complex as confirmed by Oteze (1976) when he states that, "...... In these areas, there is a very quick response of the stream discharge to rainfall......", makes it possible for the river to recharge the aquifer indirectly shortly after the arrival of the rains when the SMD has not yet been made up. In light of the above, it is therefore possible for the well hydrographs to start rising shortly after the arrival of the rains as is now the case.

In figure 23A the well hydrograph remained approximately constant for the greater part of October 1962 after which it then started to drop. This is probably because the relatively small amount of recharge (7.0 mm) and rainfall recorded in that month was just barely enough to offset the rate of withdrawal from the well. (It should be noted that these wells are used wells). That the well hydrograph in figure 23B, continued to rise until about mid-November 1963, despite the fact that October 1963 was the last month in which recharge occurred in Isa station polygon and also the month in which rainfall stopped, suggests that the recharge area of the aquifer which the well taps is farther away from the well.

Figure 24 shows the plot of monthly recharge (in Sokoto station polygon) and well water level (at Wamako) against time. The Well at Wamako is located in the Kalambaina limestone aquifer. From figure 24, the well water level started to rise as from early June 1962 until mid-September, after which it remained constant and finally started to drop at

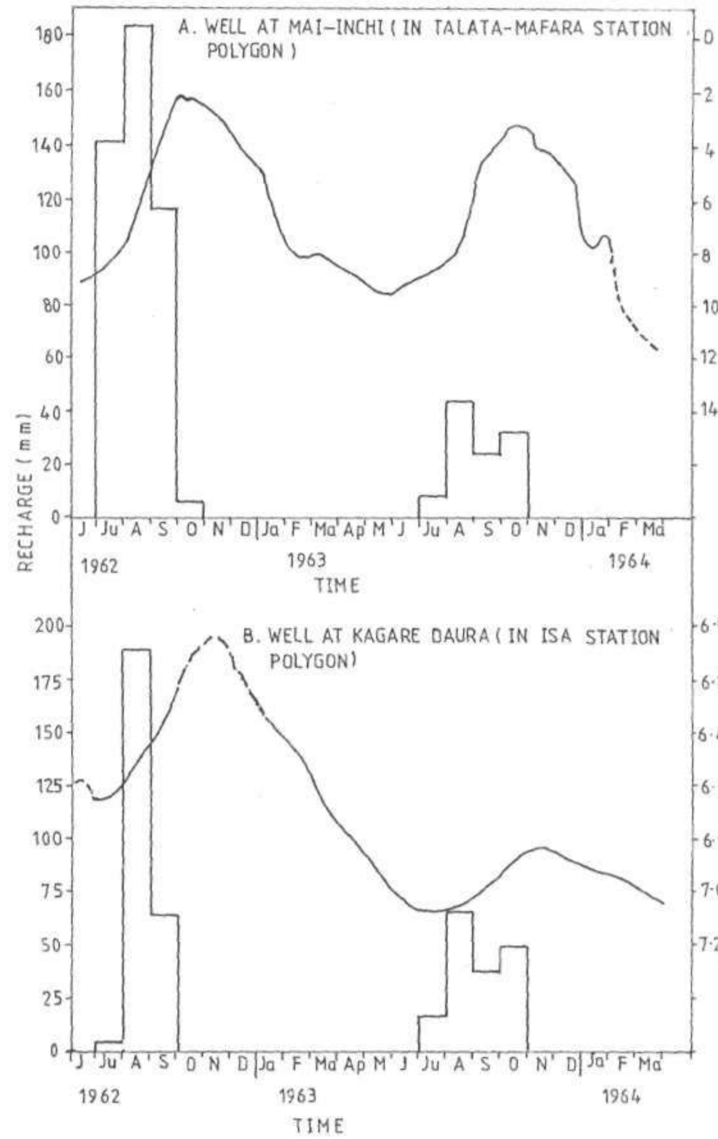


Fig. 23. Comparison of monthly recharge (1962—1964) in two polygons with well hydrographs

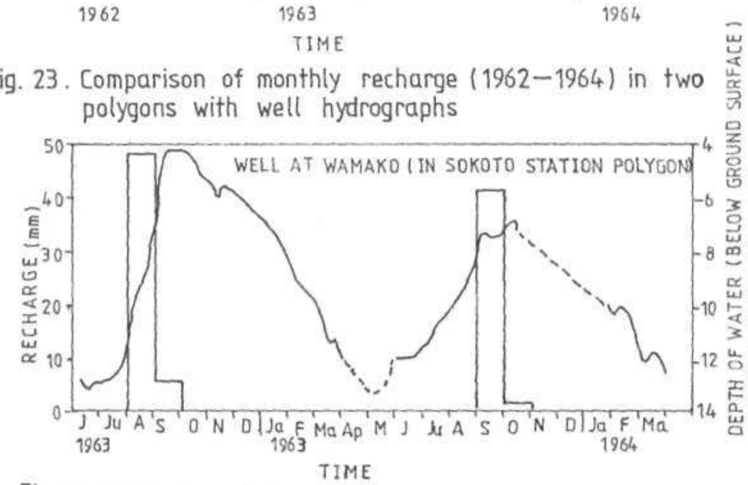


Fig. 24 Comparison of monthly recharge (1962—1964) in Sokoto station polygon with well hydrograph

the ending of September. In November 1962 and March 1963, some kinks are observed as the drop continued. From April 1963, the well water level started to rise until late May 1963 after which it remained constant until mid-June 1963, after mid-June 1963, it started to rise with some kinks observable in September 1963 and October 1963. It finally started to drop (according to extrapolated values) at about early October 1963. In 1962, recharge was first recorded about two months after the well water level started to rise, while in 1963, recharge was first recorded about four months after the well water level had started to rise. In the author's view the implication of this observation is that the well is recharged both directly and indirectly.

But while commenting on the well in question, Mock (1967) rules out the possibility of indirect recharge of the well when he stated that ....."The calcerous layer outcrops just above the river. Therefore, interference from the river need not be considered." Mock's view was supported by Oteze (1976) when he argued that, between Sabon-Birni and Wamako (figure 3), the Rima river loses water as influent seepage to the Rima group aquifers, but not to the Kalambaina limestones, a part of which is intersected by the Sabon-Birni - Wamako stretch of the Rima river. He further supported this argument by saying that, "It is unlikely to recharge the Kalambaina limestones (as was suspected by the committee set up by the North-West state government to study the effects of drilling boreholes in the drought affected areas) because the valley bottom is mostly below the level of the limestones." "It" here refers to the seepage loses from the Rima and Sokoto rivers between Sabon-Birni and Wamako.

However, in light of figures 24, 25 and the statements and river hydrograph plots credited to both Oteze (1976) and Mock (1967) respectively, the author is of the opinion that the above stated contentions of Mock (1967) and Oteze (1976) are suspect, because the fact that there is a time lag of two months (in 1962) and four months (1963), figure 24, between the start of the rise in well water level and the time recharge was first recorded is suggestive of indirect recharging of the well at Wamako. Indirect recharging is possible in two ways, viz, (i) From Oteze (1976)'s statements (a) that "The Kalambaina limestones outcrop over an area of 3,200 km^2 above the Dange formation. Outcrops of these rocks can be seen on the sides of the river valleys around Sokoto"..... "The exposed outcrops on the valley sides and those areas where the overlying clays are absent constitute the recharge zones from precipitation" and (b) the river hydrographs

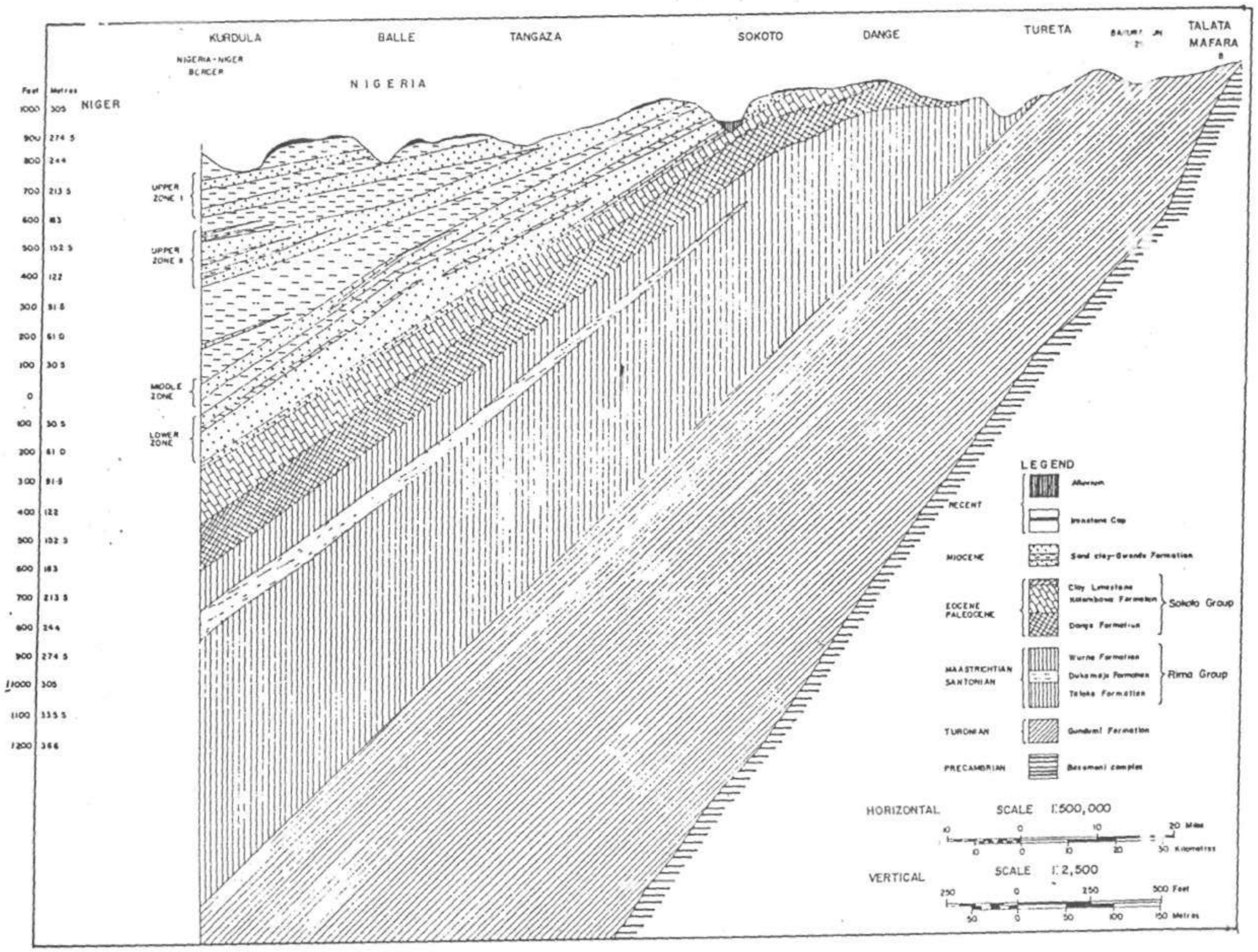


Fig. 25 Geological Section Across The Sokoto Basin, After Oteze (1976). **Section Line (A-A) On Fig. 4**

of the Sokoto river by Mock (1967) which indicate a rise in river stage with the arrival of the rains (in June 1962 and May 1963). It is therefore possible that when the river stage rises, the level of water will reach the level of "the exposed outcrops on the valley sides", thus recharging the limestones indirectly. (ii) Oteze (1976) established the fact that both the Rima and the Sokoto rivers loose water to the alluvium when he stated that .... "Long stretches of the Rima river loose water to the alluvium by influent seepage. Part of the water lost by the Rima between Sabon Birni and Sokoto is gained by the alluvium". Oteze (1976) further stated that:

> When the dry season is advanced the only source of water for the Sokoto river around Sokoto is the Kware lake, which has been shown to have a daily over flow into the Rima valley of 31,800 m^3 of water. At the same time a great part of this water discharged into the river infiltrates into the alluvium.

In light of the above statements and from figure 25 (which is the geological section across line A-A, Fig. 4) where it can be seen that there is a link between the alluvium and the Kalambaina limestones at Sokoto, it can therefore be concluded that some of the river water lost to the alluvium recharges the Kalambaina limestone indirectly. The indirect recharge flows towards the North-West direction, roughly in the same direction as the dip. From figure 3, it can be seen that Wamako lies Northwest of Sokoto.

A combined plot of the hydrograph of the well at Wamako and the river hydrograph of Sokoto river as presented by Mock (1967), showed that some of the observed kinks in the well hydrograph coincides with points of rise and fall of the water level hydrograph of the Sokoto river. It can therefore be said that fluctuations in river water levels are probably due to fluctuations in rainfall amounts, and this also induced fluctuations in well water levels. Furthermore, since the well in question is a used well, irregular drawing of water from it at the intervals between successive water level measurements could be responsible for the kinks observed in the well hydrographs.

Finally, another possible explanation for the case in point is the occurrence of rapid recharge, a phenomena which is known to occur in limestone and chalk aquifers due to their tendency to develop cracks. Care should however be taken in advancing this argument because all of the evidence so far available to the author are silent on the issue of rapid recharge in the Kalambaina limestone aquifer.

5.6 Conclusion

The average monthly direct recharge estimates into the Sokoto-Rima river basin ranges from zero to 153.6 mm, while the average annual direct recharge estimates ranges from 200.8 mm in 1963 to 296.2 mm in 1962. The basin's recharge months are from June to October. It was found that the magnitude of rainfall is generally not the sole determinant of the magnitude of recharge, but that some other factors like the SMD and distribution of rainfall also determine the magnitude of recharge during a given period.

Despite the SMD model's claim to the contrary, recharge took place with the existence of a soil moisture deficit. Generally, a decrease in the magnitude of recharge with a south to north movement in the basin was observed. There does not seem to be any direct relationship between (i) the magnitude of recharge and NDR and (ii) NDR and NYRN. The evidence obtained from this study strongly indicates the possibility of indirect recharge in some parts of the basin.

The model was found to be sensitive to rainfall and potential evapotranspiration and it was also found to be more sensitive to parameter variations in the early recharge month(s) than in the late recharge month(s). The model's sensitivity to certain parameters was found to vary with location in the basin.

Chapter 6: RECOMMENDATIONS AND CONCLUSION

A study to quantify the amount of recharge to the Sokoto-Rima river basin using a soil moisture deficit model has been carried out. Also the sensitivity of the model to input data and model parameters have been determined. The achievements, suggestions and recommendations based on the results obtained from the study are presented below.

6.1 Objectives Achieved

The Sokoto-Rima river basin was divided into 14 polygons and the recharge into each polygon was estimated. Generally the polygons located in the southern and middle parts of the basin had higher recharge estimates than those in the northern parts, partly due to the relatively higher rainfall in the southern/middle parts of the basin. The monthly recharge estimates in all the polygon stations within the basin ranges from a minimum of zero to a maximum of 489.3 mm (78 percent of the monthly total rainfall), while the annual recharge estimates ranges from a minimum of zero to a maximum of 645.8 mm (52 percent of the annual rainfall). The average monthly recharge estimates ranges from a minimum of zero to a maximum of 187.7 mm (61 percent of the average monthly rainfall) in all the polygons. The average annual recharge estimate ranges from a minimum of 115.9 mm (in Gwadabawa station polygon) to a maximum of 381.9 mm (in Koko station polygon). These recharge estimates form 19 and 36 percent, respectively, of the average annual rainfall.

The mean annual direct recharge into the Sokoto-Rima river basin was determined by finding the mean of the basin annual recharge estimates. The mean annual basin direct recharge was found to be 255.0 mm, for the period 1960 - 1965. When taken as equivalent recharge over the basin's recharge area of 75,156 km^2, it gives the volume of recharge into the basin as $1.92 \times 10^{10} m^3$. This amount represents about 30 percent of the mean annual basin rainfall of 840.2 mm. The monthly basin recharge values ranges from zero to 153.6 mm, with the maximum consistently occurring in August, for the period 1960 - 1965. About 54 percent of the average annual basin recharge occurred in August. Also from the recharge estimates obtained at the station polygons, the highest recharge mostly occurred in the month of August. The annual mean basin recharge value ranges from 200.8 mm to 296.2 mm.

It was found that recharge occurred in some months despite the existence of a SMD at the end of the month. The analysis of some results obtained in the study indicate the possibility of indirect recharge in certain parts of the Sokoto-Rima river basin.

It was observed that the magnitude and incidence of recharge depends more on the rainfall amount and distribution than on the magnitude of the initial soil moisture deficit. Depending on it's daily distribution pattern within the month, a rainfall of a given magnitude may or may not overcome the SMD throughout the month.

6.1.1 Sensitivity of recharge estimates

(i) The recharge estimates were found to be sensitive, at various levels, to variations in the input and model parameter. The recharge estimates were particularly sensitive to variations in rainfall and potential evapotranspiration.

(ii) The sensitivity levels resulting from variations in the different parameters differ from month to month. The recharge of the early recharge month(s) was found to be more sensitive to parameter variations than the recharge of the late recharge month(s).

(iii) The effects of varying the root constant (C) and the maximum soil moisture deficit (D) becomes manifest only when the SMD build up has reached the level where it can cause a reduction in the rate of evapotranspiration, i.e. between C and D. Hence recharge estimates in the early recharge month(s) are highly sensitive to variations of C and D while the reverse is the case during the mid and late recharge month(s).

6.1.2 Validation of recharge estimates

In some cases, the inability of the incidences of recharge to logically explain the rise in well hydrographs at certain times of the year has, among other reasons, led to the inevitable conclusion that indirect recharge also forms another component of the total recharge in the Sokoto-Rima river basin.

6.1.3 Variation of basin recharge

Annual isorecharge maps were plotted for the basin and it was found that recharge estimates, generally decreases with a south to north movement in the basin. This follows the same pattern as rainfall in the basin.

6.2 Recommendation and Suggestions For Further Studies

6.2.1 Recommendations based on the results of the study

The groundwater from the southeastern and eastern parts of the basin flow in the northwest direction, which is the direction towards which the sediments of the Sokoto-Rima river basin dip. Hence the groundwater can be tapped easily and economically by locating wells and boreholes in a belt (after the basement complex region) along the southwest/northeast axis of the basin. This is probably why the Gwandu aquifers, which occupies the extremes of this location, are the most prolific aquifers in the basin.

From results of the sensitivity analysis, it was found that throughout the basin, recharge estimates were highly sensitive to variations in rainfall and potential evapotranspiration. It was also slightly sensitive to variations in runoff coefficient in areas with high runoff. It was moderately sensitive to a decrease of C and D in areas with short rooted and sparse vegetation.

In view of the above findings, it is therefore recommended that much energy, time and money should be spent in ensuring that these parameters are measured or calculated accurately in the respective areas where the model has been found to be sensitive to them.

Hydrograph analysis of the major rivers in the basin, supported by observations from literature, Mock (1967), Oteze (1976), indicate very low and in some cases immeasurable flow in these rivers during the dry season. This implies that a water supply system based solely on these rivers will face a crisis during the dry season. It is therefore suggested that more emphasis be placed on groundwater development to augment surface water sources during this period, as against the present emphasis on surface water development through the construction of dams.

The state of data collection, storage and retrieval in the basin needs to be critically examined and improved to ensure an efficient, accurate and complete data bank from which data can be easily obtained for research and other purposes.

6.2.2 Suggestion for further studies

It is suggested that further studies on recharge estimation in the Sokoto-Rima river basin should:

(i) adopt a more practical and on-site method(s) of recharge estimation, like the tracer or tritium injection methods. The results from these other methods will be useful in calibrating the soil moisture deficit model in the Sokoto-Rima river basin. Also on-site monitoring of soil moisture at various times of the year in the basin is suggested as it will provide an acceptable and more accurate estimate of C and D.

(ii) Determine the magnitude and extent of river-aquifer interaction in the basin.

(iii) Determine the feasibility of artificial recharge (using flood water) of the major aquifers in the basin, in light of an earlier suggestion of emphasizing groundwater development.

(iv) Delineate more accurately the recharge area of the aquifers in the basin. This is a basic step in the realization of suggestion (iii). Although an attempt at this was made in this study, but, suffice it to say that this attempt can be considered as approximately accurate, because the recharge areas of individual aquifers were not determined. It may therefore be vague and inadequate for use as the recharge area of individual aquifers.

6.3 Conclusion

Finally, as stated earlier, recharge estimation is important in setting a safe limit on exploitation of groundwater reserves, optimal utilization and taking an inventory of the groundwater resources of a given area. And from the suggestions of the previous section, it can be seen that a lot more work needs to be done on this important subject of recharge estimation in the Sokoto-Rima river basin.

The author considers this project work as a preliminary step in this direction and hopes that on coming researchers will use this work as a stepping stone for building up.more knowledge on the water resources of the Sokoto-Rima river basin.

REFERENCES

Agboola, S.A. (1979).
An Agricultural Atlas of Nigeria, Oxford University Press, 1979, 248 pp.

Allison, G.B. and Hughes, M. W. (1974).
Environmental tritium in the Unsaturated zone: estimation of recharge to an unconfined aquifer, in Isotope techniques in groundwater, 1974. Proceedings of a Symposium. International Atomic Energy Agency, Vienna. Vol. 1, pp 55-72.

Aminu, J. (1984).
"Borno Water table shrinks". The Punch, Vol. 8, No. 14, 313. Wednesday, August, 1, 1984.

Anonymous (1980).
"Recommended practices for the production of maize", extension recommended practices No. 3, Agricultural Extension and Research Liason Services (A.E.R.L.S), A.B.U., Zaria.

Anonymous (1981).
"Guide to the production of Sugar Cane". Extension guide No. 6, A.E.R.L.S., A.B.U., Zaria.

Anonymous (1982).
"Guide to the production of Cassava". Extension guide No. 17, A.E.R.L.S, A.B.U., Zaria/National Root Crops Research Institute, Umudike.

Anonymous (1981).
"Production of Onions". Extension guide No. 2, A.E.R.L.S./A.B.U., Zaria.

Anonymous (1982).
"Guide on the production of peppers". Extension guide No. 43, A.E.R.L.S./A.B.U., Zaria.

Anonymous (1984).
Personal Communications between Extension and Agronomy Specialists at I.A.R/A.E.R.L.S. A.B.U., Zaria.

Anyaeche, O.L. (1985).
"Estimation of Direct Recharge To The Upper Zone Aquifer of the Lake Chad basin", Unpublished M.Sc. thesis, Dept. of Water Resources and Env. Engrg. A.B.U., Zaria.

Atakan, Y., Roether, W., Munnich, K.O., and Matthes, G. (1974).
The Sandhausen Shallow Groundwater Tritium Experiment in Isotope Techniques in Groundwater Hydrology, 1974, Vol. 1, pp. 21-43, Proceedings of a Symposium. International Atomic Energy Agency, Vienna.

Athavale, R.N., Murti, C.S. and Chand, R. (1980).
"Estimation of Recharge to the Phreatic Aquifers of the Lower Maner Basin, India, by using the Tritium injection Method". Journal of Hydrology, 45: 185-202.

British West Africa Meteorological Services (1960).
Federation of Nigeria. Monthly rainfall summary, Vol. 4.

Calder, I.R., Harding, R.J. and Rosier, P.T.W. (1983).
"An objective assessment of soil moisture deficit models." Journal of Hydrology, 60: 329-355.

Dincer, T., Al-Mugrin, A. and Zimmermann, U. (1974).
"Study of the infiltration and recharge through the sand dunes in arid zones with special reference to the stable isotopes and thermonuclear tritium." Journal of Hydrology, 23: 79-109.

Du Preeze, J.W. and Barber, W. (1965).
The distribution and chemical quality of groundwater in Northern Nigeria. Geological Survey of Nigeria bulletin No. 36, 93pp.

FAO (1969a).
Soil and Water resources survey of the Sokoto Valley, Nigeria, Final report, Volume 1, General. United Nations Development Programme (U.N.D.P.)/Food and Agriculture Organisation (F.A.O.) of the United Nations.

FAO (1969b).
Soil and water resources of the Sokoto Valley, Nigeria, Final report, Volume IV - Climate and Hydrology. U.N.D.P./F.A.O.

FAO (1979).
Yield response to Water. FAO irrigation and drainage paper No. 33. FAO/UN, Rome. 193 pp.

FAO/UNDP/Ministry of Works and Water Resources (1965/66).
Hydrological year book. 1 April, 1965 - 31 March, 1966.

Geological Survey of Nigeria (1974).
Geological Map of Nigeria. Compiled by the Geological Survey and Published by the geological survey division, Federal Ministry of Mines and Power, Nigeria. 1974.

Grindley, J. (1967).
"The estimation of Soil moisture deficits." The Meteorological Magazine, Vol. 96, No. 1137.

Grindley, J. (1969).
"The calculation of actual evaporation and soil moisture deficits over specified catchment areas." Meteorological Office, Bracknell Hydrological Memoirs, No. 38.

Grindley, J. (1970).
Estimating and mapping of evaporation in Proceedings of a Symposium on World water balance. International Association of Scientific Hydrology. Publication No. 92, pp. 200-213.

Hadgraft, R.G. and Volker, R.E. (1980).
A Model for Predicting Aquifer Recharge from Rainfall and River flow in Proceedings of Groundwater Recharge Conference 1980, Australian Water Resources Council, Townsville, No. 3, pp. 108-118.

Headworth, H.G. (1970).
"The Selection of Root Constants for the Calculation of Actual Evaporation and Infiltration for Chalk Catchments", Journal of the Institution of Water Engineers, Vol. 24, pp. 431-446.

Henry, J.L. and Palmer, J.R. (1980).
Natural and Artificial Recharge of Groundwater in the Callide Valley in Proceedings of Groundwater Recharge Conference 1980. Australian Water Resources Council, Townsville, No. 3, pp. 72-87.

Holmes, J.W. and Colville, J.S. (1970).
"Grassland Hydrology in a Karstic Region of Southern Australia". Journal of Hydrology, Vol. 10, pp. 38-58.

Howard, K.W.F. and Lloyd, J.W. (1979).
"The sensitivity of parameters in the Penman evaporation equations and direct recharge balance". Journal of Hydrology, 41: 329-344.

Hydrological Section, Ministry of Agriculture (irrigation division) (1964).
Hydrological data, water levels and discharges in Rima-Sokoto basin. Hydrological publication No. 2, 1964. Govt. Printers. Kaduna.

Hydrological Section, Ministry of Agriculture (irrigation division) (1965).
Hydrological publication, No. 3, 1965.

Jones, K.R. (1981).
Arid Zone Hydrology for Agricultural Development FAO irrigation and drainage paper 37. FAO/UN Rome.

Kitching, R. and Bridge, L.R. (1974).
"Lysimeter installations in sandstone at Styrrup, Nottinghamshire." Journal of Hydrology, 23: 219-232.

Kitching, R., Shearer, T.R. and Shedlock, S.L. (1977).
"Recharge to Bunter Sandstone determined from lysimeters". Journal of Hydrology, 33: 217-232.

Kogbe, C.A. (1979).
Geology of the S-E-sector of the IULLEMEDEN basin. Bulletin, Department of Geology, A.B.U., Zaria. Vol. 2, No. 1.

Kowal, J. (1970).
"The Hydrology of a small catchment basin at Samaru, Nigeria. II. Assessment of the main components of the water budget". Nigerian Journal of Agricultural Science. Vol. 7, No. 1, April. pp. 41-52.

Kowal, J.M. and Knabe, D.T. (1972).
An agroclimatological atlas of the northern states of Nigeria, with explanatory notes. Ahmadu Bello University Press, A.B.U., Zaria, Nigeria. 111 pp.

Lindsley, R.K., Kohler, M.A. and Paulhus, J.L.H. (1975).
Hydrology for Engineers. McGraw-Hill Inc. second edition. 482 pp.

Lloyd, J.W., Drennan, D.S.H. and Bennell, B.M.U. (1966).
A groundwater recharge study in north eastern Jordan in Proceedings of the institution of Civil Engineers, 35: 615-631.

Mock, F.J. (1967).
Report on Soil and Water Resources Survey of the Sokoto valley. Volume II - Climate and Hydrology open file report, UNDP/FAO, Rome.

Meteorological Service (1961, 1962, 1963, 1964, 1965).
Federation of Nigeria, Monthly rainfall summary, Vols. 5-9.

Michael, A.M. (1978).
Irrigation Theory and Practice. Vikas Publishing house Pvt Ltd. India. 801 pp.

Odeh, I.O.A. (1983).
"A study of some salt affected soils in the Sokoto-Rima basin". Unpublished M.Sc. (Soil Science) thesis, Dept. of Soil Science, Faculty of Agriculture, A.B.U., Zaria.

Odigie, L.I.O. (1983).
"Mathematical model of limestone aquifer with river-aquifer interaction". Ph.D Thesis, University of Birmingham.

Odigie, L.I.O. (1984).
"The estimation of recharge in a Catchment with limited soil depth". Inter departmental seminar paper, Dept. of Civil Engineering, A.B.U., Zaria.

Ogilbee, W. and Anderson, R. (1965).
Exploratory drilling for groundwater in Western Sokoto province, Nigeria with particular reference to Artesian aquifers in the Gwandu formation. United States Geological Survey, Geological Survey of Nigeria and United States agency for international development. 96 pp.

Oteze, G.E. (1976).
The hydrogeology of the north-western Nigeria basin, pp. 373-390, in Kogbe, C.A. (ed)., Geology of Nigeria. Elizabethan Publishing Co., Lagos, Nigeria, 1976. 436 pp.

Parker, D.H. (1964).
Paleocene Fossils from Sokoto province, north western Nigeria. Records of geological survey Nigeria, Vol. 7, pp. 23-76.

Penman, H.L. (1948).
"Natural evaporation from open water, bare soil and grass". Proceedings of the Royal Society of London, Series A, Vol. 193, pp. 120-145.

Penman, H.L. (1949).
"The dependence of transpiration on weather and soil conditions". Journal of Soil Science, 1: 74-89.

Penman, H.L. (1950).
"The water balance of the stour catchment area". Journal of the institution of water engineers, 4, 457-469.

Richard, L. and Wadleigh, C. (1952).
"Soil Water and Plant Growth". Agronomy, 2: 13.

Rushton, K.R. and Ward, C. (1979).
"The Estimation of Groundwater Recharge". Journal of Hydrology, 41: 345-361.

Sarma, P.B.S., Rao, N.H. and Rao, K.V.P. (1980).
"Calculation of Water Balance in the Crop Root Zone by Computer". Journal of Hydrology, 45, 123-131.

Smith, D.B., Wearn, P.L., Richards, H.J. and Rowe, P.C. (1970).
Water Movement in the Unsaturated Zone of High and Low Permeability strata by Measuring Natural Tritium in Proceedings Series, Isotope Hydrology, 1970. I.A.E.A. and U.N.E.S.C.O., 1970, pp. 73-87.

Udo, R.K. (1970).
Geographical Regions of Nigeria. University of California Press, Los Angeles, California. 212 pp.

Veihmeyer, F.G. and Hendrickson, A.H. (1949).
"Methods of Measuring Field Capacity and Permanent Wilting Percentages in Soils". Soil Science, 68: 75-94.

Vogel, J.C., Thilo, L. and Van dijken, M. (1974).
"Determination of Groundwater Recharge with Tritium". Journal of Hydrology, 23: 131-140.

Williamson, R.J. and Lawrence, C.R. (1981).
Review of Methods for Estimating Recharge in Australia in Proceedings of Groundwater Recharge Conference 1980, Australian Water Resources Council, Townsville, No. 3, pp. 108-118.

Zimmermann, U., Munnich, K.O. and Roether, W. (1967a). Downward movement of soil moisture traced by means of hydrogen isotopes. In: isotope techniques in the hydrologic cycle. Geophysical Monograph, II. American Geophysical Union, Washington, D.C. pp. 28-36.

Zimmermann, U., Ehhalt, D. and Munnich, K.O. (1967b). Soil water movement and evapotranspiration in Isotopes in Hydrology. I.A.E.A. Vienna. pp. 567-585.

APPENDIX I

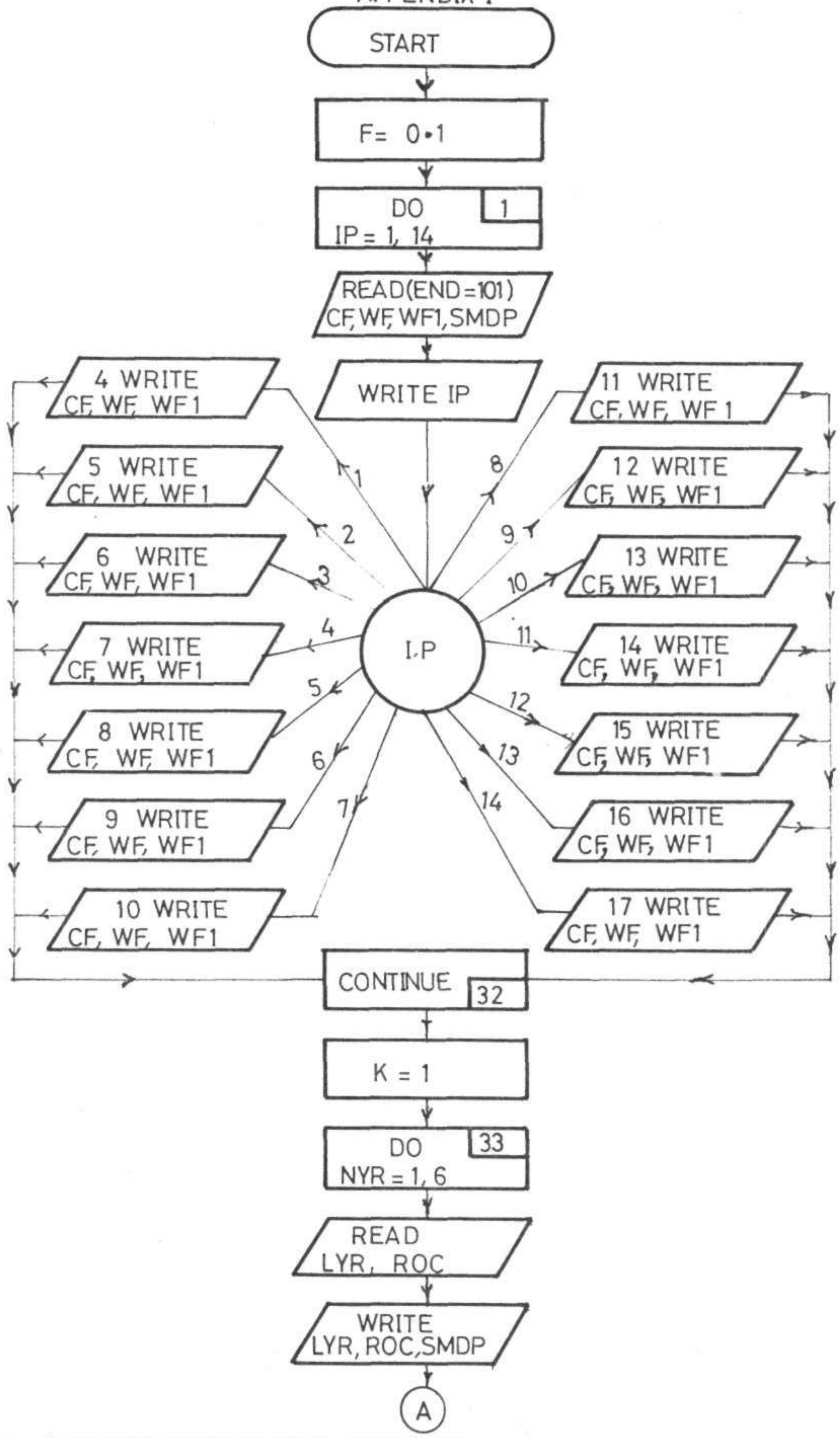
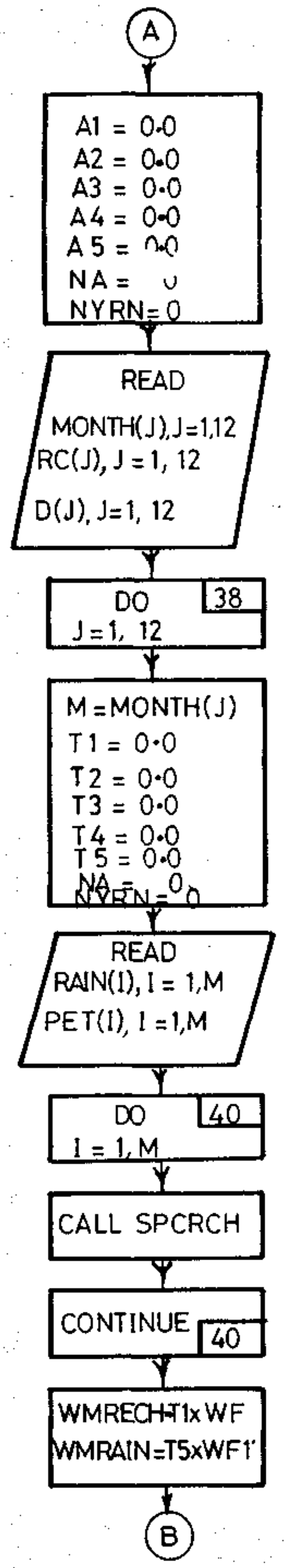
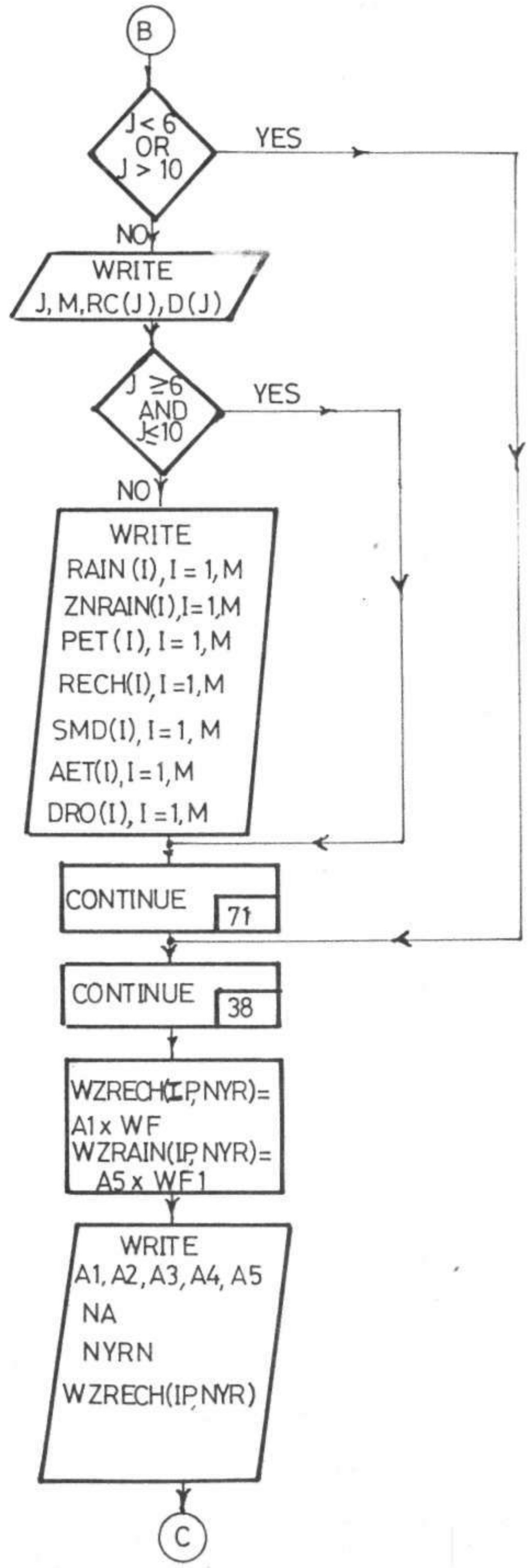
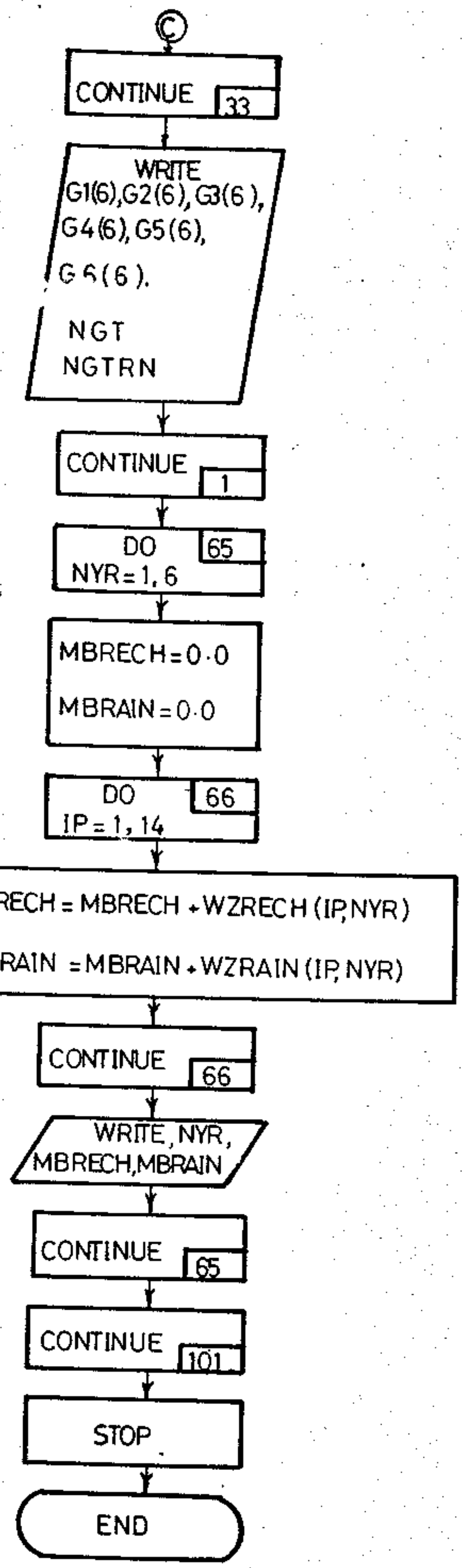


Fig:7: FLOW CHART FOR MAIN PROGRAM

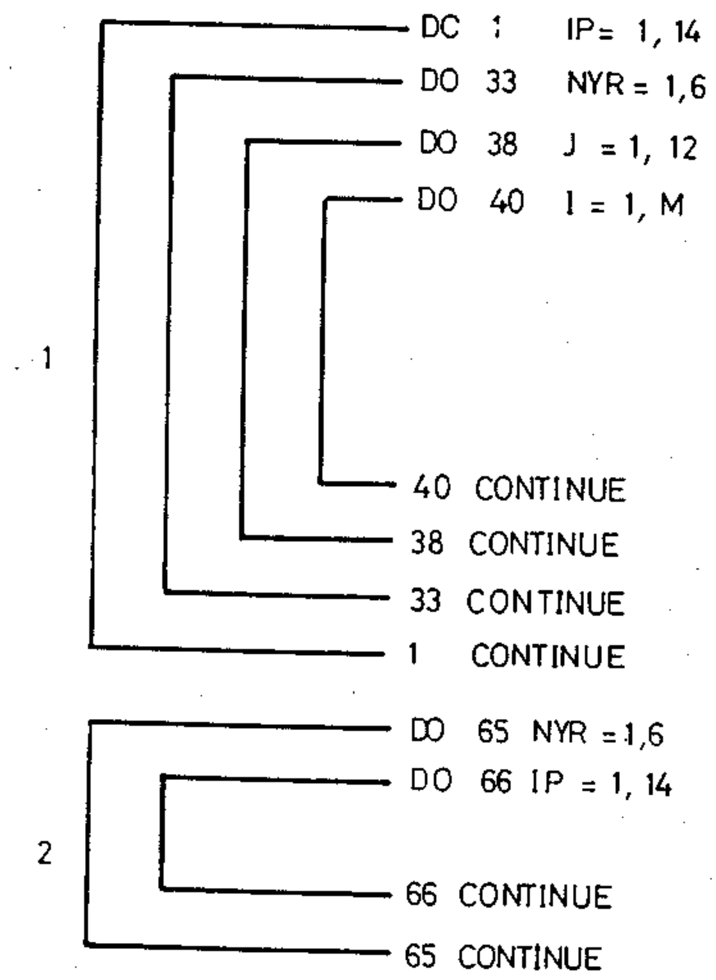

A
A1 = 0·0
A2 = 0·0
A3 = 0·0
A4 = 0·0
A 5 = 0·0
NA = 0
NYRN = 0
READ
MONTH(J),J=1,12
RC(J), J = 1, 12
D(J), J=1, 12
DO 38
J = 1, 12
M = MONTH(J)
T 1 = 0·0
T 2 = 0·0
T 3 = 0·0
T 4 = 0·0
T 5 = 0·0
NA = 0
NYRN = 0
READ
RAIN(I), I = 1,M
PET(I), I = 1,M
DO 40
I = 1, M
CALL SPCRCH
CONTINUE 40
WMRECH=T1x WF
WMRAIN=T5xWF1'
B



B
J < 6
OR
J > 10
YES
NO
WRITE
J, M, RC(J), D(J)
J ≥ 6
AND
J ≤ 10
YES
NO
WRITE
RAIN (I), I = 1, M
ZNRAIN(I), I = 1, M
PET (I), I = 1, M
RECH(I), I = 1, M
SMD(I), I = 1, M
AET(I), I = 1, M
DRO (I), I = 1, M
CONTINUE
71
CONTINUE
38
WZRECH(IP, NYR) =
A1 x WF
WZRAIN(IP, NYR) =
A5 x WF1
WRITE
A1, A2, A3, A4, A5
NA
NYRN
WZRECH(IP, NYR)
C


C
CONTINUE 33
WRITE G1(6),G2(6),G3(6),
G4(6),G5(6),
G6(6).
NGT
NGTRN
CONTINUE 1
DO 65
NYR=1,6
MBRECH=0.0
MBRAIN=0.0
DO 66
IP=1,14
MBRECH=MBRECH+WZRECH(IP,NYR)
MBRAIN =MBRAIN+WZRAIN(IP,NYR)
CONTINUE 66
WRITE, NYR,
MBRECH,MBRAIN
CONTINUE 65
CONTINUE 101
STOP
END

APPENDIX II



1 - FIRST LOOP

2 - SECOND LOOP

Fig. 8 STRUCTURE OF THE NESTED DO LOOPS IN THE MAIN PROGRAM

```
10    WRITE(5,24) CF,WF,WF1
   24 FORMAT(1H0,52X,11HISA POLYGON/1H ,52X,4HCF =,F7.3,4X,4HWF =,F7.3
     1,4X,5HWF1 =,F7.3)
      GO TO 32
11    WRITE(5,25) CF,WF,WF1
   25 FORMAT(1H0,52X,12HJEGA POLYGON/1H ,52X,4HCF =,F7.3,4X,4HWF =,F7.3,
     14X,5HWF1 =,F7.3)
      GO TO 32
12    WRITE(5,26) CF,WF,WF1
   26 FORMAT(1H0,52X,15HKATSINA POLYGON/1H ,52X,4HCF =,F7.3,5X,4HWF =,
     1F7.3,5X,5HWF1 =,F7.3)
      GO TO 32
13    WRITE(5,27) CF,WF,WF1
   27 FORMAT(1H0,52X,12HKOKO POLYGON/1H ,52X,4HCF =,F7.3,4X,4HWF =,F7.3,
     14X,5HWF1 =,F7.3)
      GO TO 32
14    WRITE(5,28) CF,WF,WF1
   28 FORMAT(1H0,52X,13HMALUMFASHI POLYGON/1H ,52X,4HCF =,F7.3,5X,
     14HWF =,F7.3,5X,5HWF1 =,F7.3)
      GO TO 32
15    WRITE(5,29) CF,WF,WF1
   29 FORMAT(1H0,52X,14HGOKOTO POLYGON/1H ,52X,4HCF =,F7.3,5X,4HWF =,
     1F7.3,5X,5HWF1 =,F7.3)
      GO TO 32
15    WRITE(5,30) CF,WF,WF1
   30 FORMAT(1H0,52X,21HTALATA-MAFARA POLYGON/1H ,52X,4HCF =,F7.3,8X,
     14HWF =,F7.3,3X,5HWF1 =,F7.3)
      GO TO 32
17    WRITE(5,31) CF,WF,WF1
   31 FORMAT(1H0,52X,12HYABO POLYGON/1H ,52X,4HCF =,F7.3,4X,4HWF =,F7.3,
     14X,5HWF1 =,F7.3)
   32 CONTINUE
      K=1
C YEAR LOOP STARTS
      DO 33 NYR=1,5
      READ(5,34) LYR,ROC
   34 FORMAT(I5,F6.3)
      WRITE(5,35) LYR,ROC,SMDP
   35 FORMAT(52X,I4,F8.3,5X,F7.2)
      A1=0.0
      A2=0.0
      A3=0.0
      A4=0.0
      A5=0.0
      NA=0
      NYRN=0
      READ(5,36) (MONTH(J),J=1,12)
   36 FORMAT(12I3)
      READ(5,37) (RC(J),J=1,12)
      READ(5,37) (D(J),J=1,12)
   37 FORMAT(12F6.2)
C MONTH LOOP BEGINS
      DO 33 J=1,12
      M=MONTH(J)
      T1 = 0.0
      T2 = 0.0
      T3 = 0.0
```

```
      T4 = 0.0
      T5 = 0.0
      N=0
      NMRN=0
      READ(5,39)(RAIN(I),I=1,M)
      READ(5,39)(PET(I),I=1,M)
   39 FORMAT(12F6.2)
C DAY LOOP BEGINS CALCULATION OF RECHARGE VIA SUBROUTINE
      DO 40 I=1,M
      CALL SPCRCH(SMD,RECH,SMDP,PTRECH,AET,SMDPR,DRO,RC,D,ZNAET,
     1ZNPET,T1,A1,T5,A4,T3,A3,T2,A2,T4,A5,S1,S2,S3,S4,S5)
   40 CONTINUE
      WMRECH=T1*WF
      WMRAIN=T5*WF1
      WRITE(6,41)J,M,RC(J),D(J)
   41 FORMAT(1H0,62X,2I5/1H ,62X,12HROOT CONST.=,F5.2/1H ,62X,
     115HMAX. S.M.D. (D)=,F5.2)
      WRITE(6,60)
   60 FORMAT(1H0,62X,14HRAINFALL IN MM)
      WRITE(6,43)(RAIN(I),I=1,M)
      WRITE(6,42)
   42 FORMAT(1H0,62X,20HZONAL RAINFALL IN MM)
      WRITE(6,43)(ZNRAIN(I),I=1,M)
      WRITE(6,44)
   44 FORMAT(1H0,62X,29HPOT. EVAPOTRANSPIRATION IN MM)
      WRITE(6,43)(PET(I),I=1,M)
      WRITE(6,45)
   45 FORMAT(1H0,62X,14HRECHARGE IN MM)
      WRITE(6,43)(RECH(I),I=1,M)
      WRITE(6,46)
   46 FORMAT(1H0,62X,27HSOIL MOISTURE DEFICIT IN MM)
      WRITE(6,43)(SMD(I),I=1,M)
      WRITE(6,47)
   47 FORMAT(1H0,62X,31HACTUAL EVAPOTRANSPIRATION IN MM)
      WRITE(6,43)(AET(I),I=1,M)
      WRITE(6,48)
   48 FORMAT(1H0,62X,19HDIRECT RUNOFF IN MM)
      WRITE(6,43)(DRO(I),I=1,M)
   43 FORMAT(1H ,2X,16F8.2)
      WRITE(6,49)
   49 FORMAT(1H0,62X,13HMONTH  TOTALS)
       WRITE(6,50) T1,T2,T3,T4,T5
   50 FORMAT(1H ,10X,8HTMRECH =,F7.2,10X,7HTMAET =,F7.2,10X,7HTMPET =
     1,F7.2,10X,7HTMDRO =,F7.2,10X,8HZMRAIN =,F7.2)
      WRITE(6,53)N
   53 FORMAT(1H0,40X,41HNUMBER OF MONTHLY OCCURRENCES OF RECHARGE
     15H(N) =,I4)
      WRITE(6,63)NMRN
   63 FORMAT(1H0,40X,49HNUMBER OF MONTHLY OCCURRENCES OF RAINFALL(NMRN)
     1=,I4)
      WRITE(6,69)
   69 FORMAT(1H0,62X,33HMONTHLY WEIGHTED RECHARGE AND RAINFALL)
      WRITE(6,70)WMRECH,WMRAIN
   70 FORMAT(1H0,62X,8HWMRECH =,F7.2,10X,8HWMRAIN =,F7.2)
   38 CONTINUE
      WZRECH(IP,NYR)=A1*WF
      WZRAIN(IP,NYR)=A5*WF1
```

```
      WRITE(6,51)
   51 FORMAT(1H0,62X,14HANNUAL  TOTALS)
      WRITE(6,52)A1,A2,A3,A4,A5
   52 FORMAT(1H ,10X,8HATRECH =,F7.2,10X,7HATNAET =,F7.2,10X,7HATPET =
     1,F7.2,10X,7HATDRO =,F7.2,10X,8HAZRAIN =,F7.2)
      WRITE(6,61)NA
   61 FORMAT(1H ,40X,40HNUMBER OF YEARLY OCCURRENCES OF RECHARGE
     15H(NA) =,I4)
      WRITE(6,64)NYRN
   64 FORMAT(1H0,40X,48HNUMBER OF YEARLY OCCURRENCES OF RAINFALL(NYRN) =
     1,I4)
      WRITE(6,53)
   53 FORMAT(1H0,62X,37HANNUAL WEIGHTED RECHARGE AND RAINFALL)
      WRITE(6,54)WZRECH(IP,NYR),WZRAIN(IP,NYR)
   54 FORMAT(1H0,62X,8HWZRECH =,F6.2,10X,8HWZRAIN =,F6.2)
   33 CONTINUE
      WRITE(6,56)
   56 FORMAT(1H0,62X,12HGRAND TOTALS)
      WRITE(6,57)B1(6),B2(6),B3(6),B4(6),B5(6)
      WRITE(6,59)NGT
   59 FORMAT(1H0,38X,48HGRAND TOTAL OCCURRENCES OF RECHARGE IN SIX YEARS
     17H(NGT) =,I4)
   57 FORMAT(1H ,10X,8HGTRECH =,F7.2,10X,7HGTNAET =,F7.2,10X,7HGTPET=
     1,F8.2,10X,7HGTDRO =,F7.2,10X,9HGTZRAIN =,F8.2)
      WRITE(6,62)NGTRN
   62 FORMAT(1H0,38X,57HGRAND TOTAL OCCURRENCES OF RAINFALL IN SIX YEARS
     1(NGTRN) =,I4)
    1 CONTINUE
      DO 65 NYR=1,6
      MBRECH=0.0
      MBRAIN=0.0
      DO 66 IP=1,14
      MBRECH=MBRECH+WZRECH(IP,NYR)
      MBRAIN=MBRAIN+WZRAIN(IP,NYR)
   66 CONTINUE
      WRITE(6,63)
   63 FORMAT(1H0,62X,10HBASIN MEAN)
      WRITE(6,67)NYR,MBRECH,MBRAIN
   67 FORMAT(1H0,10X,I2,10X,8HMBRECH =,F7.2,10X,8HMBRAIN =,F7.2)
   65 CONTINUE
  101 CONTINUE
      STOP
      END
      SUBROUTINE BPORCH(SMD,RECH,SMDP,PTRECH,AET,SMDPR,DRO,RC,D,
     1ZNAET,ZNPET,T1,A1,T5,A4,T3,A3,T2,A2,T4,A5,B1,B2,B3,B4,B5)
      DIMENSION MONTH(12),RAIN(31),ZNRAIN(31),PET(31),DRO(31),AET(31),
     1ZNPET(31),RC(12),D(12),RECH(31),ZNAET(31),SMD(31),B1(6),
     2B2(6),B3(6),B4(6),B5(6)
      COMMON MONTH,I,J,NYR,RAIN,PET,ROC,F,CF,ZNRAIN,K,N,NA,NGT,NMRN,NYRN
     1,NGTRN
      IF(K.GT.1) GO TO 999
      GA=0.0
      GB=0.0
      GC=0.0
      GD=0.0
      GE=0.0
      NGT=0
```

```
      NGTRN=0
  999 CONTINUE
      ZNRAIN(I)=RAIN(I)*CF
      DRO(I)=ZNRAIN(I)*ROC
      IF(ZNRAIN(I).LE.PET(I)) DRO(I)=0.0
      IF(SMDP.GE.D(J)) GO TO 300
      IF(SMDP.LE.RC(J)) GO TO 301
      IF(ZNRAIN(I).GE.PET(I)+DRO(I)) GO TO 304
      IF(ZNRAIN(I).GE.0.0.AND.ZNRAIN(I).LE.PET(I)) GO TO 307
      AET(I)=PET(I)
      DRO(I)=ZNRAIN(I)-PET(I)
      GO TO 302
  304 AET(I)=PET(I)
      GO TO 302
  307 AET(I)=(1.0-F)*(ZNRAIN(I)-DRO(I))+F*PET(I)
      GO TO 302
  301 AET(I)=PET(I)
  302 PTRECH=ZNRAIN(I)-DRO(I)-AET(I)
      SMD(I)=SMDP-PTRECH
      IF(SMD(I).GT.D(J)) GO TO 303
      GO TO 309
  303 AET(I)=AET(I)-(SMD(I)-D(J))
      GO TO 302
  300 CONTINUE
      IF(ZNRAIN(I).GE.PET(I)+DRO(I)) GO TO 310
      IF(ZNRAIN(I).GE.0.0.AND.ZNRAIN(I).LE.PET(I)) GO TO 311
      AET(I)=PET(I)
      DRO(I)=ZNRAIN(I)-PET(I)
      GO TO 312
  310 AET(I)=PET(I)
      GO TO 312
  311 AET(I)=ZNRAIN(I)
  312 PTRECH=ZNRAIN(I)-DRO(I)-AET(I)
      SMD(I)=SMDP-PTRECH
  309 CONTINUE
      IF(SMD(I).GE.0.0) GO TO 305
      RECH(I)= -SMD(I)
      SMD(I)=0.0
      GO TO 306
  305 RECH(I)=0.0

  306 SMDPR=SMDP
      SMDP=SMD(I)
      ZNAET(I)=AET(I)
      ZNPET(I)=PET(I)
      IF(RECH(I).GT.0.0)N=N+1
      IF(RECH(I).GT.0.0)NA=NA+1
      IF(RECH(I).GT.0.0)NGT=NGT+1
      IF(ZNRAIN(I).GT.0.0)NMRN=NMRN+1
      IF(ZNRAIN(I).GT.0.0)NYRN=NYRN+1
      IF(ZNRAIN(I).GT.0.0)NGTRN=NGTRN+1
C CALCULATE MONTHLY TOTALS
      T1=T1+RECH(I)
      T2=T2+ZNAET(I)
      T3=T3+ZNPET(I)
      T4=T4+DRO(I)
      T5=T5+ZNRAIN(I)
```

```
C CALCULATE ANNUAL TOTALS
      A1=A1+RECH(I)
      A2=A2+ZNAET(I)
      A3=A3+ZNPET(I)
      A4=A4+DRO(I)
      A5=A5+ZNRAIN(I)
C CALCULATE GRAND TOTALS
      G1(NYR)=GA+RECH(I)
      G2(NYR)=GB+ZNAET(I)
      G3(NYR)=GC+ZNPET(I)
      G4(NYR)=GD+DRO(I)
      G5(NYR)=GE+ZNRAIN(I)
      GA=G1(NYR)
      GB=G2(NYR)
      GC=G3(NYR)
      GD=G4(NYR)
      GE=G5(NYR)
      K=K+1
      RETURN
      END
```