

PERFORMANCE OF PHYSICALLY BASED MODELS IN DESIGNING RAIN
WATER HARVESTING CROP SYSTEMS

BY

STEPHEN SHUBILA KAMUGISHA



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ABSTRACT

Three physically based models were used to simulate the effects of rain water harvesting on Sorghum yield in semi-arid Hombolo, Dodoma, Tanzania over three seasons. The models are :

- . Runoff estimation Model (THIRST)
- . Crop Growth Model (PARCH)
- . Soil water availability Model

Different components of the models relevant to rain water harvesting were combined to form a complete model to estimate runoff, soil moisture content and crop yield. Rain water harvesting with storage was simulated by supplying runoff collected and stored in reservoirs as supplementary irrigation water for days when soil moisture content was below the allowable value. The performance of the models was tested by comparison between estimated and measured values using regression analysis.

There is a fairly good agreement between observed and simulated runoff for a 10 x 20 m catchment with $r^2 = 0.804$. For a 10 x 40 m catchment the correlation between measured and estimated runoff is relatively low with $r^2 = 0.712$.

The simulated moisture trend is the same when compared to the measured soil moisture with correlation coefficient $r^2 = 0.607$, however the model tend to overpredict the soil moisture content.

The trend of simulated sorghum yield show direct relationship of increase in yield due to increase in water quantity and distribution with a correlation coefficient $r^2 = 0.622$. The model show inadequacy in predicting the upper limit of water input and hence the effects of water logging on crop yield.

From the study it is recommended that:

- . the runoff sub-model should incorporate a subroutine for simulating surface depression storage resulting from the changing surface micro relief.
- . rain intensity files should be provided where possible for more reliable results, and further work should be done on the simplified rainfall disaggregator to develop more reliable results.
- . validation of Raws and Brakensiek (1989) pedotransfer functions for soils of semi-arid areas is required.

- . the soil water balance sub-model of PARCH should be modified to simulate the lateral soil water flows, infiltration and drainage with greater perfection.
- . the PARCH model should develop the ability to simulate the effects of anaerobis in the root zone with greater perfection by either reducing establishment during early growth, or by reducing root uptake of water during later growth stages.

DECLARATION

I, STEPHEN SHUBILA KAMUGISHA do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my original work and that it has never been submitted for a degree in any other University.

Signature.....*Stephen Shubila Kamugisha*.....

Date.....*20th/1/2006*.....

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LIST OF SYMBOLS

A	Area cultivated, ha.
BD	Soil bulk density, gm/cm ³
CN	Run-off Curve number
D _i	Initial moisture deficit, mm
E	Evapotranspiration mm/day
Ea	Field application Efficiency
e _s	Saturated vapour pressure at dew point, mb
F(t)	Cumulative infiltration at time, t
f _p (t)	Potential infiltration rate at time, t
I	Cumulative interception at time, t
I ₃₀	Maximum thirty minutes rainfall intensity, mm h ⁻¹
g	Gross crop water requirement, mm
In	Net crop water requirement, mm
K _{fs}	Hydraulic Conductivity at field saturation, mm
M _{fc}	Field capacity, M ⁻¹
MinAm	Permanent wilting point, mm m ⁻¹
NE	North East
PARCH	Predicting Arable Resource Capture in Hostile Environment
Q	Daily run-off amount
R	root depth, M

R(t)	Cumulative run-off at time,t
P(t)	Cumulative rainfall at time,t
Ra	Daily rainfall
RAM	Readily Available Moisture
RWH	Rain water Harvesting
S	Retention parameter
Sa	Available soil moisture
S _{av}	Wetting front Suction,mm
Sc,i	Soil moisture at time, i
SS	Cumulative Surface storage at time,t
TAM	Total Available moisture,mm m ⁻¹
THIRST	The Harvest of Incident Rainfall in Semi-Arid Tropics

1.0 INTRODUCTION

1.1 General

The semi-arid zone of Tanzania occupies about one third (295,000 km²) of the total area of Tanzania and extends from North East towards South West across the central part of the country. The major occupation for the people in the semi-arid areas of Tanzania is agriculture, and rainfall is one of the major constraint in agricultural production (Nieuwolt, 1973; Ngana, 1991).

The problems of semi-arid areas as regards rainfall for agriculture is of both quantity and distribution. There is a high fluctuation of monthly rainfall from the mean, the variation being highest at the beginning and end of the season (Table 1).

Table 1.1 Monthly rainfall variability in Dodoma

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
x	0.0	0.0	23.1	108.5	132.4	109.1	111.7	52.1	3.8	0.0	0.0	0.0
s.d	-	-	41.5	65.2	79.7	65.1	62.5	51.4	7.2	-	-	-
c.v	-	-	180.0	60.0	60.0	60.0	56.0	99.0	189.0	-	-	-

Source: Ngana (1983)

The amount, intensity, and distribution of the rain are of decisive importance for crop yields. In Hombolo, Dodoma the year may be divided into two distinct seasons, a dry season lasting from May to October and a rain season lasting from November to April (Table 1.2). Most of the rains fall between December and March. Dry spells occurring in between December and April have significant influence on crop growth and yield. There is a 30% risk (i.e. 3 years out of 10) of dry spell of 11, 17, 20 and 15 days, for January, February, March, and April, respectively (Table 1.2). Maximum observed dry spells for these months vary between 17 and 34 days. Therefore, in order to ensure a good yield in 7 out of 10 years an increase in quantity and improvement in distribution of water available to crops is required to supply water to cover the shortages for 34 days of dry spell.

Rain Water Harvesting or runoff farming attempts to increase the water availability and distribution to crop growth by inducing, collecting, storing, and conserving local surface runoff for agriculture in arid and semi-arid regions (Boers and Ben-Asher 1982).

Table 1.2 Summary of long term rainfall characteristics for Hombolo

Month	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	season total
Rainfall (mm)													
Minimum	0.0	0.0	0.0	0.0	35.7	39.7	7.0	0.8	0.0	0.0	0.0	0.0	326.3
Mean	0.0	3.8	33.9	113.5	133.7	121.7	111.4	61.6	5.9	0.0	0.0	0.0	591.9
70%	0.0	0.0	9.6	60.8	83.8	81.8	82.0	20.8	2.8	0.0	0.0	0.0	518.0
Maximum	0.3	43.6	88.5	290.5	293.7	253.1	180.0	212.2	24	0.7	0.5	0.0	881.6
Wet days													
3 mm +	0	2	2	6	8	7	7	5	0	0	0	0	37
5 mm +	0	1	1	5	6	6	5	3	0	0	0	0	22
10 mm +	0	1	1	3	4	4	2	2.2	0	0	0	0	18
Longest dry spell (days)													
Minimum	30	21	5	5	4	3	4	1	8	22	31	31	
30%	30	31	27	19	11	17	20	15	31	30	31	31	
Mean	30.1	30.5	19	17	8	12	14	13	29	34	31	31	
Maximum	31	31	30	41	17	25	27	34	48	58	31	31	

1 = Probability of exceeding; 2 = Risk

Source: Hatibu et al. (1995)

How these four facets of rain water harvesting interact is illustrated by the micro-catchment in Fig. 1.1.

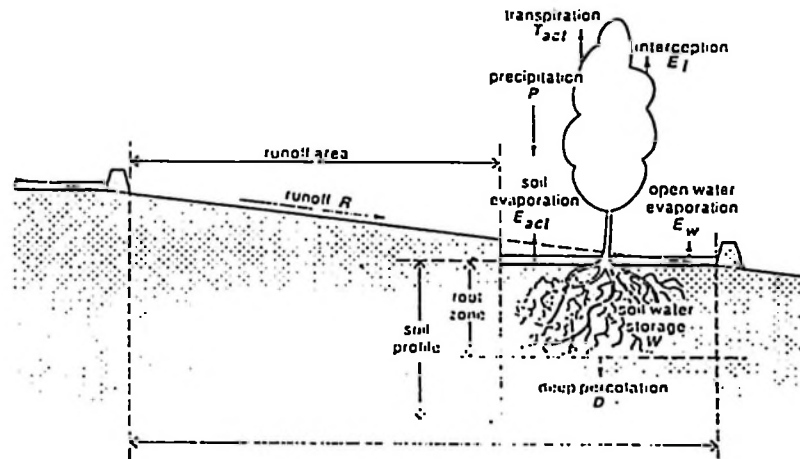


Fig. 1.1 Micro-catchment consisting of runoff area and a basin area with a crop. [After Boers, Th.M. (1994)]

A micro-catchment is a small catchment, in the order of few hundred square metres, consisting of a runoff area with a maximum flow distance of 100 m and an adjacent basin area with a tree, bush, or row crop. The aim of Micro-catchment water harvesting is to induce runoff and collect this water in the basin area, where it is stored and conserved in the root zone for consumptive use or stored in a reservoir for later use. Besides runoff water, the basin area also receives direct rainfall.

In designing a micro-catchment system several design factors are considered. The first design factor to consider is the micro-catchment size. The catchment should be able to provide sufficient runoff to satisfy the gross water application requirements to avoid moisture stress in the plants. The runoff produced should not exceed the designed amount to avoid it resulting into waste and water logging. This factor is expressed in micro-catchment design as the Catchment-Basin Area Ratio (CBAR). A ratio that is too large for the prevailing conditions can result in deep percolation losses, and on the other hand, a large ratio promotes infiltration which reduces direct evaporation losses.

The question of what CBAR is best for a particular crop at a particular area depend very much on climate, soil conditions, and crop water requirements. In most semi-arid zones, where RWH is practical for agricultural production, long term climatic and soil data are often scarce. This has been a problem when designing a water harvesting system. In semi-arid Tanzania the designs have been done basing on long term experiments or trial and error experience (Mwakalila, 1992).

The results of agricultural experiments under semi-arid conditions are particularly difficult to interpret, and the considerable variation due to unreliable rainfall makes it difficult to extrapolate such results from one site or one season to another. This makes evaluation of the new designs difficult. The key issue in the introduction of improved designs is how to extrapolate experiences or experimental results from site to site or between seasons, and how to prescribe technologies that are relevant to the land, labour management and capital resources of each individual farmer. The best approach of dealing with this problem is to use the technique of simulation models. This allows for manipulation of past, present, and future data with relatively low cost, quick result, and enable prediction of the future conditions.

Three physically based models were used in this study to simulate the effect of rain water harvesting on sorghum crop. The models include a runoff yield estimation model THIRST (Young, 1994) (The Harvesting of Incident Rainfall in the Semi-arid Tropics), a crop growth model PARCH (Bradley and Crout, 1992) (Predicting Arable Resource Capture in Hostile environment) and a soil water availability model.

The PARCH model (Bradley and Crout, 1992) simulates crop growth as affected by water and light. Currently the model simulate sorghum growth adequately, but as yet can not model the effects of fertility on crop growth.

The data inputs for running this model are:

- . Climatic variables: (Rainfall (mm), Pan evaporation (mm), Maximum and minimum temperature(°C), Saturated deficit (Kpa), and Irradiance (MJ) on daily basis).
- . Soil characteristics: (texture, and bulk density).
- . Crop data: (Plant population, planting date).

The outputs include, total dry weight, grain weight, leaf weight, root weight, and daily transpiration, evaporation, and soil water content.

The THIRST model (Young,1994) is sub-divided mainly into two distinct components. The first component is a climate generator constructed mainly to synthesize data for areas which have none, and infilling and extrapolation of data for areas which have little. The technique used is that of Hutchinson (1990) which generates point data from a continuous Markov occurrence process. The second component is a catchment area runoff sub model simulating runoff on the

basis of soil characteristics, land use, and topography according to the Green and Ampt (1911) infiltration equation. The climatic and soil inputs variable are the same as those of PARCH components. Another important input is the catchment characteristic which affect the amount of runoff induced. The output include runoff intensities on daily basis.

The soil water availability model was developed to simulate rain water harvesting systems with storage reservoirs. Under this model the runoff stored in a reservoir is supplied to the crop for supplementary irrigation on days with water deficit. The model read daily crop water requirement and where there is deficiency it estimates the amount of water to be added to the crop as supplementary irrigation. The input include the crop transpiration, root depth, soil moisture content, and soil physical characteristics.

This study was aimed at combining these three models to form a rain water harvesting model, and test its performance as decision tool in the design of rain water harvesting catchments for sorghum production in Hombolo, Dodoma Tanzania.

1.2 Objectives of the Study

The main objective of this study was to assess the performance of THIRST and PARCH models in the design of rain water harvesting crop systems in semi-arid areas of Tanzania using historical climatic and agronomic research data.

The specific objectives of the research were:

- (1) To assess the adequacy of the THIRST Model in estimating runoff from catchment area.
- (2) To develop an intermediate model for the estimation of soil water availability.
- (3) To test the adequacy of the PARCH model in simulating crop yield.

2.0 LITERATURE REVIEW

2.1 Rainfall - Runoff Models

Rain water harvesting is a system which seeks to encourage runoff from the catchment to the cropped area. In order to avoid erosion or waterlogging, it is vital that the amounts of water generated by runoff be accurately quantified. There are a number of widely used runoff models in literature, but only two types will be discussed in this study. The first type of runoff models is empirical in nature and requires only two parameters (Boers et al. 1986, Oron & Enthoven, 1987). The parameters include the runoff threshold value which sets the minimum rainfall amount for runoff to occur, and the runoff coefficient which sets the percentage of rainfall arriving as runoff.

$$Q = \text{Max} (0, aR-b) \quad (\text{mm}) \quad (1)$$

Where Q is daily runoff amount, R is daily rainfall amount, a and b are parameters.

Another two parameter model which has also been used (Hari Krishna, 1989; Namde, 1987), is based upon the USDA curve

number method (USDA-SCS, 1972):

$$Q = \frac{(R - 0.2S)^2}{(R + 0.8S)}, \quad R > 0.25 \quad (2)$$

$$S = \frac{254(100 - 1)}{CN} \quad (mm) \quad (3)$$

S is the retention parameter and CN is the curve number.

R, and Q are as described in equation 1.

The second type of runoff models are the physically based models which predict runoff by modelling the infiltration process combined with overland flow. A number of catchment models such as ANSWERS (Beasley et al. 1990) attempt to do this, as do some erosion models such as WEPP (Nearing et al. 1989, 1990). However, only two such model of water harvesting have been identified (Oron and Enthoven, 1987) and (Young, 1994). In these models, infiltration is predicted using a modified form of the Green and Ampt (1911) equation and overland flow is predicted using a kinematic wave equation, and simple rainfall excess equation respectively.

The best model to simulate runoff production for rain water harvesting should incorporate environmental factors which

influence parameter values.

These include:

- . catchment size, slope and relief,
- . soil hydrological characteristics (e.g.infiltration capacity, water retention capacity and depression storage),
- . tendency to crust formation, and vegetation cover.

These properties may not be stable over the season and may interact with antecedent soil moisture in determining parameter values for a given day.

The physically based models attempt to deal with the above mentioned dynamic behaviour. Although the simple empirical two parameter models require much less computational effort than the infiltration excess models, they are site specific and their accuracy depend very much on the user's judgement. The experience of the user can affect their performance and they can only simulate daily runoff volume. For compatibility with the soil-water and crop growth models, the physically based models (THIRST) was preferred.

2.2 Crop Growth Models

Although a simple soil water status output would give an idea of the effects of RWH, in order to quantify these effects in terms of what the farmer is interested in (the yield), some idea of the implications for crop growth is necessary. A crop growth model (CGM) fulfils this role.

Designing a crop production system using a CGMs have the potential for providing useful quantitative information for decision making and eliminating much of the repetitive trial and error experiences. This approach has been used by many researchers as a tool to try to design the most appropriate systems given site characteristics, and to act as a tool for technological transfer both from research to the farmer and from location to location.

Crop Growth Models are classified in four levels (Penning de Vries et al. 1989). Level 1 models consider only climatic variables. These include empirical statistical models which are widely used in agro-climatic analysis. Their most suited applications are for predicting crop yield using a single

variable, e.g rainfall. In environments where particular environmental variable is a primary yield-limiting factor, the predictive value of these models has been demonstrated (Fisher, 1924; Lomas, 1972). Their deficiency lies in their site-specificity and inability to adequately describe complex and dynamic causal relationships between crop growth, yield and environmental factors. Those in level 2, model the effect of several environmental factors on crop yield. In general, these models relate one or more derived parameters, such as heat units, soil moisture deficits, and evapotranspiration to yield. They have been shown to be helpful in assessing strategies (Nix, H.A and Fitzpatrick, E.A, 1969; Baier, 1973; Baier et al 1976; Slabbers et al 1979; Stewart J,I., and Hash C.T., 1982; Liang et al 1983) but require considerable calibration with yield data that are often unavailable. Level 3 models include an account of soil fertility; and those in level 4 attempt to include all other possible stress factors. PARCH focuses on water stress and light and thus falls into level 2.

Although the CGMs have proved to be very effective as decision making tools in crop-production strategic planning, their adoption should be cutaneously undertaken. When one is considering to use a model, one should initially develop an

understanding of its workings, capabilities and shortcomings. Model accuracy (validation) is undoubtedly a major consideration of model utility. Hardware (computer) execution speed, and input data requirements are other considerations determining model utility. Model accuracy is described in terms of accuracy of simulated process parameters which in turn, is determined by comparing simulated with measured process parameters to establish confidence in the model.

Angus et al (1974) noted that strategic suggestions for formulating production strategies based on sophisticated level 3 and 4 models are of a qualitative nature and have little practical utility. Because of the paucity of validation data, complex models requiring exhaustive input data are not often adopted as management tools for strategic (or tactical) decision making. Despite their limitations discussed earlier, level 1 models are the most commonly used primarily due to formulation simplicity and minimum data requirements. As a compromise, level 2 model (PARCH) was chosen. Although it has measurable parameters, its demands upon computer time are relatively low and the parameters can be easily (and cheaply) measured or estimated.

3.0 MODEL DESCRIPTION

3.1 THIRST Model

THIRST (Young, 1994) is a physically based model being developed at the University of New Castle Upon Tyne to simulate the RWH under the tropical semi-arid conditions. The model groups together various hydrologic components and is subdivided into three distinct parts: a climate generator; a runoff sub-model; and a soil moisture sub-model. The validation phase of THIRST is still underway with data sets being collected in semi-arid Tanzania.

To facilitate the use of the model by extension officers as a design tool in the field, the model uses physical parameters that can be easily (and cheaply) measured or estimated, which regress easily against the less easy to measure parameters required. Presently only the runoff sub-model and rainfall disaggregator are complete. The rainfall disaggregator is a sub model which takes daily rainfall amount and, based upon historical relationships generates intensity data at intervals specified by user.

The runoff sub-model used in THIRST has soil characteristics and rainfall intensity data, as its input. The model calculates runoff based on the Green and Ampt (1911) equation which postulates that potential infiltration rate can be calculated by:

$$fp(t) = K_{fs} \left(1 + \frac{S_{av} D_i}{F(t)} \right) \quad (4)$$

Where: K_{fs} = Hydraulic conductivity at field saturation
 S_{av} = Wetting front suction
 D_i = Initial moisture deficit
 $fp(t)$ = Potential infiltration rate at time, t
 $F(t)$ = Cumulative infiltration at time, t

It was formulated for infiltration under ponded conditions into a homogeneous soil profile with uniform initial soil moisture. The movement of infiltrated water is assumed to occur as an advancing wetting front, the depth of which controls the rate of infiltration. The diffusion of soil moisture is not modelled.

The amount of infiltration during a time-step in the model is predicted using an "old value" scheme. Potential infiltration rate is calculated at the beginning of a time step.

Rainfall at less than this rate is assumed to infiltrate during the time-step, and a new theoretical potential infiltration rate is calculated. If this theoretical potential infiltration rate is less than the rainfall rate during the preceding time step is recalculated using smaller sub-time-step, otherwise, all the incident rainfall is assumed to infiltrate.

Runoff is calculated simply as rainfall excess:

$$R(t) = [P(t) - I(t) - F(t) + SS(t)] \quad (5)$$

Where: $R(t)$ = Cumulative Runoff at time, t
 $P(t)$ = Cumulative Rainfall at time, t
 $I(t)$ = Cumulative Interception at time, t
 $SS(t)$ = Cumulative Surface Storage at time, t

Interception and surface storage are modelled simply as abstractions from incident rainfall and generated runoff respectively. The soil water parameters used (i.e K_{fs} , S_{av} , etc) are all obtained using pedotransfer functions which regress easily - measured soil characteristics (soil texture, organic matter, bulk density, etc) against the less easy to measure parameters required. Rawls and Brakensiek (1989) provide a comprehensive and widely used range of these pedotransfer functions calibrated on 1323 soils in the USA.

3.2 PARCH Model

PARCH (Bradley and Crout, 1992) is the model developed at the Tropical Crops Research Unit at the University of Nottingham for predicting the growth of crops in response to water and light. The model is intended as a tool to examine the many factors important in determining the effectiveness of semi-arid agriculture. Currently the model can simulate sorghum growth adequately.

PARCH works by looping through a series of sub-models. Each iteration represents a period of real time, for most of sub-models this time step is one day. Figure 3.1 shows the flow of control between the subroutines at different levels.

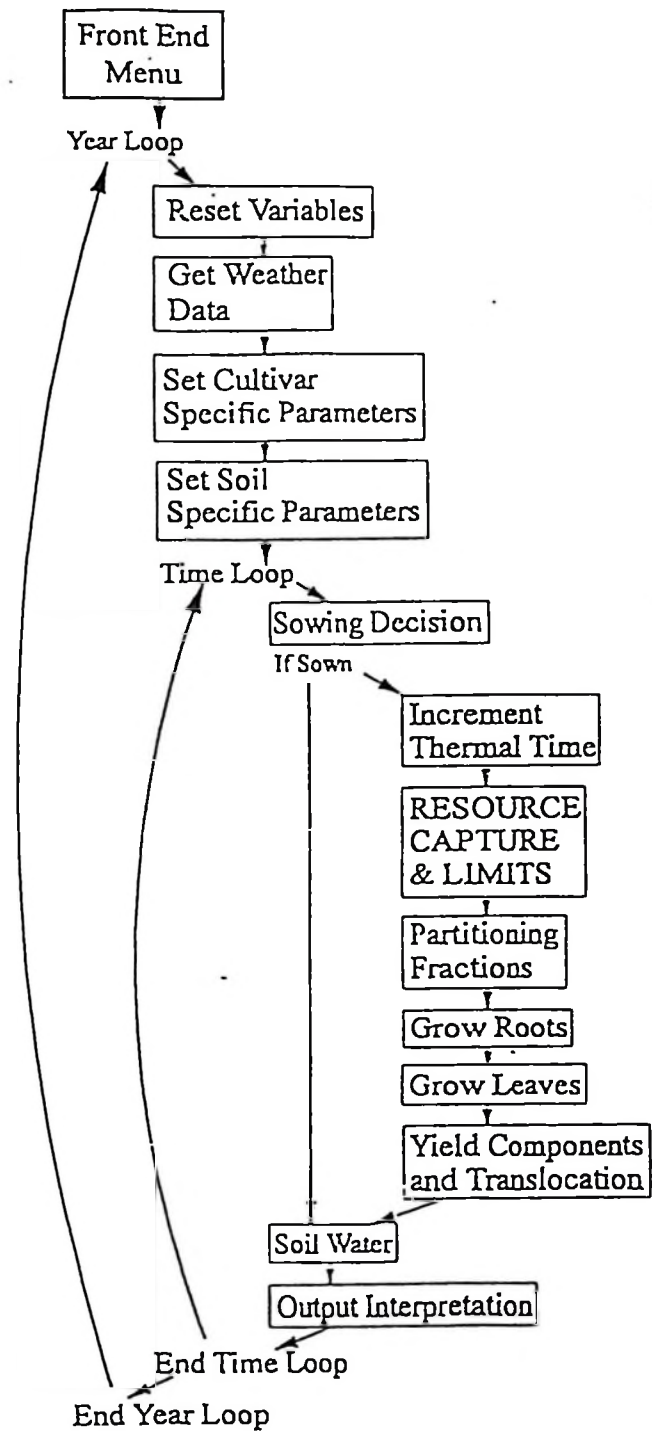


Figure 3.1 Flow chart showing the main subroutines used in PARCH [After Bradley and Crout (1992)]

For each time step, the potential carbon assimilated by photosynthesis, together with the consequent water demand of the crop are calculated. If water is limiting the carbon assimilation is reduced and the crop is considered to be stressed. The carbon assimilated is then partitioned between the various organs of the plant in a manner dependent upon the growth stage of the crop, calculated on the thermal time basis. This partitioning can be adjusted according to the level of stress. Roots, leaves, stem, and yield are then 'grown' by the model resulting in changes in the root system and leaf canopy which then feed back into calculations for next time step.

PARCH considers an unstressed crop to be one where growth proceeds at a rate limited only by the availability of light. Water, nutrients, and temperature are optimal. If water supply or temperature are such that growth is reduced then the crop is considered stressed. The model quantifies this by a stress index, SI. Two forms of stress are considered; water stress SI_w , and temperature stress, SI_t .

$$SI_w = \frac{\text{Light Limited Transpiration}}{\text{Potential Water Supply}} \times \frac{I}{ST_{index}} \quad (6)$$

- Where:
- ST_{index} is a crop specific parameter which reflects the tolerance of the specie to water stress (a value of around 5 is used for sorghum),
 - Light Limited Transpiration is the transpiration which would occur if light were the only limitation to growth,
 - Potential water supply is the maximum amount of water the roots can extract from the soil profile during the time step.

Therefore, as light limited transpiration exceeds water supply, so SI_w increases, inducing the various stress responses of the modelled crop.

Temperature stress is caused when peak daily temperature (T) rises above the optimum temperature for crop growth (T_{opt}), and increases towards the maximum non-lethal temperature (T_{max}).

$$SI_t = \frac{T - T_{opt}}{T_{max} - T_{opt}} \quad (0 < SI_t < 1) \quad (7)$$

SI_w and SI_t are compared and the overall crop stress index is set to the larger of the two. This then controls the crop stress responses for that time step (day).

$$SI = \max(SI_w, SI_t) \quad . \quad (8)$$

The variable stress is used throughout the model to control the following plant growth stages:

- phenological development,
- light capture and 'conversion',
- water capture and 'conversion',
- root and leaf growth,
- grain production.

The calculation of soil water available to plant uptake is vital component of PARCH, and a full water balance is incorporated within the program. This allows for:

- Evaporation,
- Infiltration,
- Redistribution by Darcy's law,
- Drainage,
- Macropore (crack or preferential) flow.

The inputs to the model include:

- . Climatic variables: rainfall(mm), pan evaporation(mm), maximum and minimum temperature(°C), saturated deficit(kPa), and irradiance (MJ). Under daily basis.
- . Soil characteristics: texture, bulk density.
- . Crop data: plant population, planting date.

The outputs include: total dry weight, grain weight, leaf weight, root weight, and daily Transpiration, Evaporation, and soil water content.

A total of 36 validation comparisons of actual growth data against PARCH predictions have been conducted in semi-arid areas (Bradley and Crout, 1992). For each, grain yield and total crop dry matter values have been produced. The 36 points for grain and dry matter thus calculated have been plotted against the actual recorded values to produce 1:1 comparison graphs. A linear regression analysis conducted on the pooled data gives $r^2 = 0.97$ with 70 df. This is a very encouraging result and has been the base for choosing it for use in this study.

3.3 Soil Water Balance Models

The processes of infiltration, evaporation, transpiration and percolation determine the soil water balance. The simplest type of model employs a budgeting or 'book keeping' approach, in which inflow and outflow of water in separate layers is simulated on a daily basis. Inflow into the first layer is from infiltration. An upper limit of storage is defined and any excess is assumed to drain into the next layer. Water is

extracted by evaporation and transpiration. Modifications are made to allow for macropore flow, hysteresis effects and delayed drainage (Parkes et al. 1989).

The alternative approach involve modelling vertical fluxes within the soil profile using a numerical approximation of Richards equation by the transient, one-dimensional finite difference approach is probably the most popular of the various methods for quantifying soil moisture changes spatially and temporally. In its various forms it has been used in SWATRER (Dierchx et al. 1986), PARCH (Bradley and Crout, 1992), WEPP (Nearing et al. 1989), etc. The explicit form of the finite difference scheme (as used in PARCH) is simple and flexible. The more stable but also more complex implicit scheme is used in SWATRER.

The relatively simple budgeting models require much less computational effort than the latter approach, but cannot be used when downward water flow is impeded or ground water is perched near the root zone. Under these circumstances upward capillary flux can be significant. This is accommodated by finite difference models. The relatively simple and flexible explicit form of finite difference scheme used in PARCH was adopted for this study.

3.4 Rain Water Harvesting Models

Few attempts to develop a complete model of rain water harvesting have been identified in the literature. Those that do exist (Boers et al 1986; Morin and Matlock, 1975, Hari Krishna, 1989, Oron and Enthoven, 1987, Namde 1987) have invariably been developed under temperate arid conditions with rainfall outside the growing season. Water harvesting models researched and developed in the temperate arid regions cannot be directly transferred to Semi arid Tropics (SAT) not least because of the greatly increased risk of erosion due to higher rainfall intensity. Also, whereas experiences and indigenous practices within SAT have been documented, there have been few attempts to carry out systematic analysis.

This study combined PARCH and THIRST models to simulate the soil plant water process in a micro-catchment rain water harvesting crop system. The simulation uses an upper catchment area (profile 1) to generate runoff for lower cropped basin (profile 2). The runoff is assumed to flow down slope to the cropped basin where it ponds and is then subjected to infiltration and evaporation. Different cropped to catchment area ratios are simulated by adding a multiplier to the amount of runoff passed to the cropped area.

4.0 MATERIALS AND METHODS

4.1 THIRST Component

Two sub-models from the THIRST model were used in this study; these are:

- . runoff sub-model [APPENDIX B-1]
- . rainfall disaggregator [APPENDIX B-2].

The runoff sub model was used to calculate runoff according to the Green and Ampt (1911) infiltration equation. The data input for running this model were:

- . soil characteristics (texture, bulk density, organic matter)
- . rainfall intensity
- . Initial moisture content
- . Vegetation cover and type
- . Initial random roughness and slope

The run-off sub-model calculates the amount of infiltration and run-off. The infiltration is passed directly into the top layers of the soil of the catchment area. The runoff was simulated to flow down slope to the cropped basin. The model was calibrated on a 10 x 20 m catchment. Runoff yield from other sizes was simulated simply by putting a multiplier to

the amount of runoff collected from a 10 x 20 m catchment.

The output is daily runoff intensity (as specified by the user) and duration. The rainfall disaggregator takes daily rainfall amounts and generates intensity data at intervals specified by the user. In this study intervals of thirty minutes was used.

4.2 PARCH Component

All PARCH sub model were used in this study to simulate plant growth stages as affected by water and light.

The data inputs for running the model were:

- . Daily climatic variables: rainfall(mm), pan evaporation (mm), maximum and minimum temperature (°C), saturated deficit (Kpa), and irradiance (MJ).
- . Soil characteristics: texture, bulk density, organic matter content.
- . Crop data: plant population, planting date.

The outputs include: total dry weight, grain weight, daily transpiration, evaporation and soil moisture content.

4.3 Soil Water Availability Model

A soil water availability model was developed to estimate the daily water availability for the sorghum crop. For days with water deficit the model estimates the water to be added to the crop in form of irrigation. When combined with PARCH the model was used to simulate RWH with storage. The data input for running the model were:

- . Daily crop transpiration
- . Daily soil moisture content
- . Root depth

The output is the daily water depth (mm) needed for days with water deficit.

4.4 Source of Data

This study used historical climatic and agronomic data from research experiments conducted by the Soil - Water Management Research Project of SUA (Hatibu et al., 1995). The data was collected from experimental fields planted with sorghum at Hombolo in Dodoma, Tanzania for three years. Hombolo is situated at latitude 5°45'S, longitude 35°57'E and at an altitude of 1020 meters above sea level.

4.5 Design Of Rain Water Harvesting System

In order to assess the suitability of the models from the design point of view, the three models were combined to simulate the soil-plant water process in a micro-catchment crop system. The model uses an upper catchment area (profile 1) to generate run-off for lower cropped basin (profile 2). Essentially it is the PARCH model with THIRST routines added so that it can calculate runoff. (Fig 4.1)

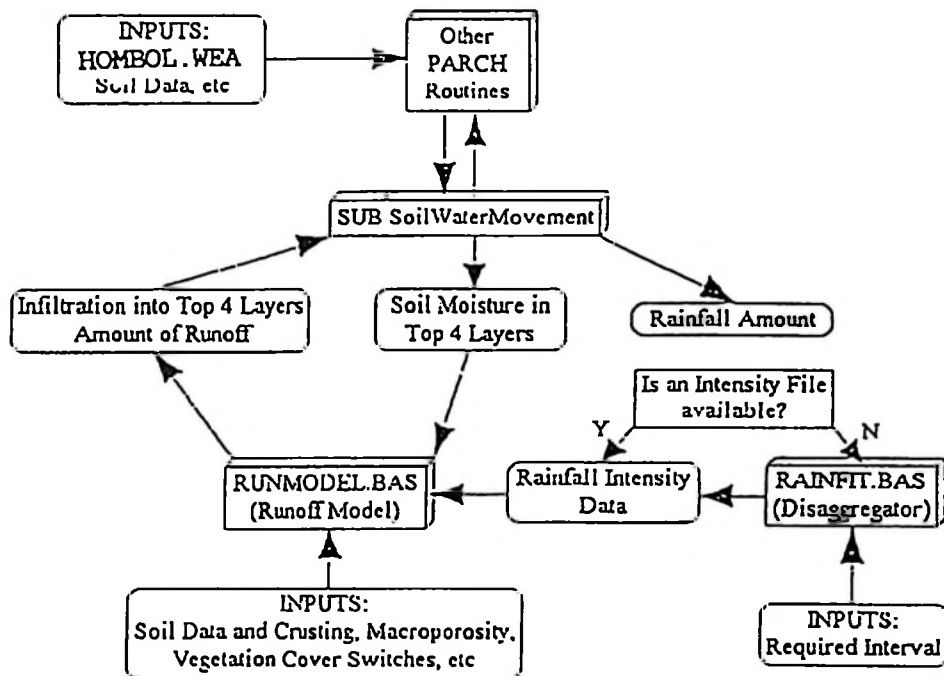


Figure 4.1 A Summary of THIRST-PARCH Interactions

Where the crop is grown the yield is shown by PARCH on the graphic screen in the usual way. The interaction between PARCH and THIRST models was at a fairly basic level. PARCH runs as normal except on the rainy days when the THIRST routines are called.

PARCH reads the weather file (HOMBOLXX.WEA) [APPENDIX C-2] and when it finds a value of greater than zero in the rainfall column, it looks for a rainfall intensity file for that day. If one is not present, then it calls SUB Disagregate to disagregate the daily rainfall and produce a rainfall intensity array. This is then passed to the runoff sub - model.

When simulating RWH with storage, PARCH model is run as usual. The output of the run is used as input to the soil water availability model to determine whether the soil moisture content is sufficient for crop requirement. For the days with water deficit the amount of water to be added as supplementaly irrigation is estimated and passed again to PARCH as an input irrigation file (HOMBOLOXX.IRR) [APPENDIX C-3].

A design procedure was established to come up with an optimal CBAR. A catchment of 5 x 20 m and a basin of 10 x 10 m size were used as standards. In designing systems with storage, days with water deficit were identified and the amount needed to alleviate the deficit was calculated. This amount was compared to the total amount produced by the catchment as runoff to judge whether the catchment size was enough to produce such amount. In case of a system without storage, the runoff produced was combined with rainfall as total water supply and the amount was tested whether it was enough to meet the crop water requirements. In case the supply was not sufficient, the PARCH-THIRST model was run again with bigger catchment size and the whole process was repeated.

The components of the design procedure were programmed in a computer using Turbo Pascal language and the soil moisture status for the three years was simulated continuously. The model was run using 0:1, 2:1, and 4:1 CBAR. The model chose the optimum CBAR as the one which can supply adequately the crop water requirement with minimum losses. A generalized flow chart of the soil moisture availability and irrigation prediction model is shown in Figure 4. The program and results for 1994/95 season are shown in Appendix B-2.

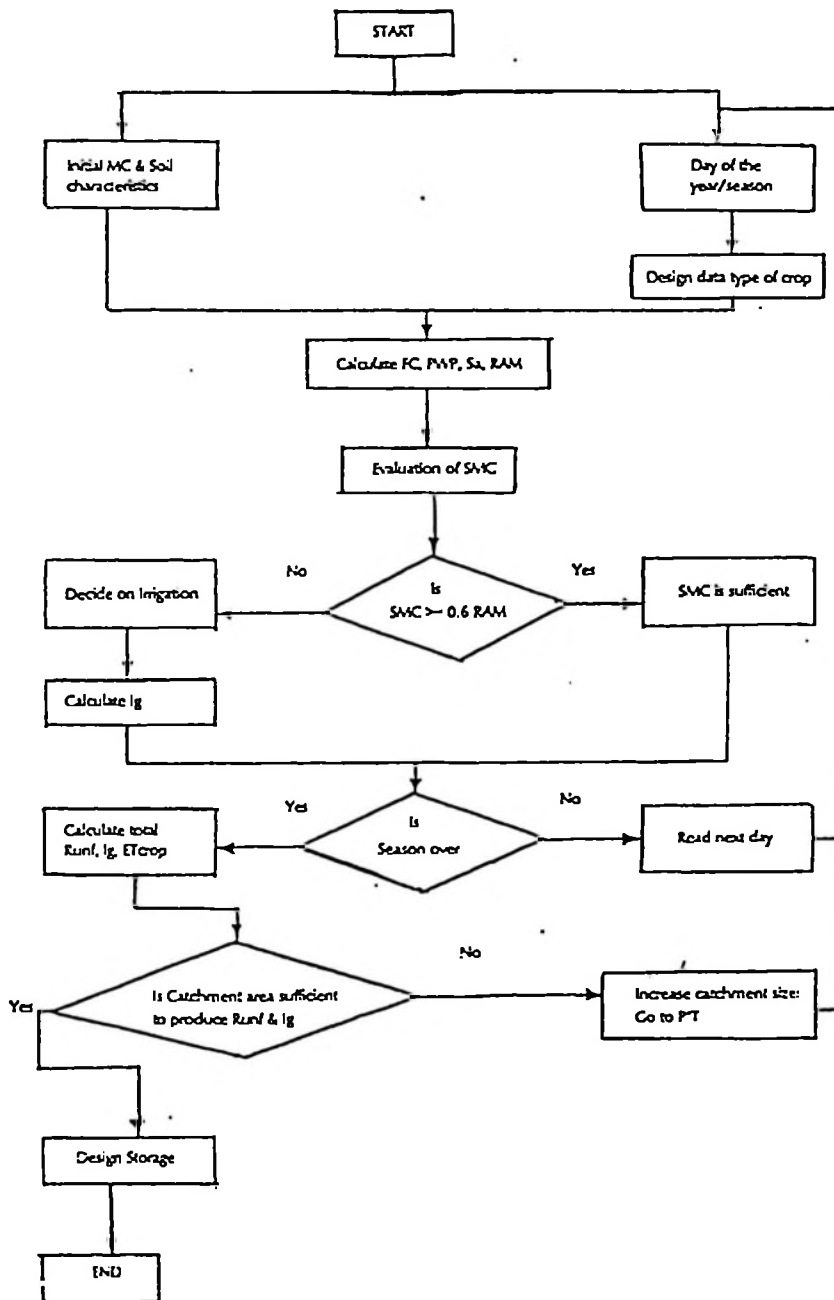


Figure 4.2 Catchment Design Flow Chart.

5.0 RESULTS AND DISCUSSION

5.1 Runoff Yield Estimation

The data used for comparison was runoff volumes collected from a bare and slightly compacted catchments of sizes 10 x 20 m (2:1 CBAR) and 10 x 40 m (4:1 CBAR) (with 1.2 % slope). This data was for one season (1994/95). The runoff intensities estimated by the run-off sub-model were also converted into run-off volumes per day (Table 5.1, Fig.5.1 (a) and Fig. 5.1 (b)).

A fairly good agreement is observed for a 10 x 20 m catchment. Under this catchment size the estimated runoff trend is the same as that of measured values but is slightly overpredicting the runoff amount (Fig. 5.1 (a)). This can be explained by the fact that the model was calibrated on this catchment size. This reveals that the model can best be used to estimate the runoff for the size on which the model is calibrated.

In order to simulate the runoff for a 10 x 40 m catchment the run-off volume was simulated simply as twice the runoff collected from the 10 x 20 m.

Fig. 5.1 (b) show that the results of the model for a 10 x 40 m catchment are so scattered that even if without forcing the regression through the origin, the correlation between the measured and estimated runoff is poor. There is also underprediction at the low and high runoff quantity. One of the probable reason for this under prediction is the simple multiplication factor used by the model assuming that runoff yield per unit area is constant thus runoff yield for a 10 x 40 m catchment is assumed to be twice the amount collected from that of 10 x 20 m. The work done by Mahoo et al (1994) at Kisangara and Morogoro on effects of catchment length on runoff yield concluded that runoff yield per unit area of catchment was not significantly different from 5 m and 10 m length plots. The 10 m length plots produced significantly different runoff yield (at $P = 0.05$). However, the total run-off yield from the 5 m length plots was 10 % higher than the total runoff from the 10 m length plots. This can partly explain the reason for the general overestimation of the simulated runoff.

Another reason is that, catchment characteristics (random roughness and slope) are assumed by the model to be constant. Surface micro relief or roughness provides surface depressions for temporary storage of water on the surface

thus providing more time for water infiltration and reducing the flow of water across the surface. The runoff sub-model contain a very simple routine for simulating surface depression storage and because of lack of data on depression storage on the plots this was set to zero. This may in part account for the general overestimation of the simulated runoff.

Another probable source of discrepancies between observed and predicted runoff is the use of a simplified rainfall disaggregator in producing rainfall intensities used by the runoff sub model. The other arguable component of the model are the pedotransfer functions which allow the estimation of complex soil physical properties from readily available data. Their validity for the Hombolo soils is not yet established. However, the overall results of the correlation analysis between the estimated and measured values gives the value of $r^2 = 0.804$ and 0.712 for 10×20 m and 10×40 m catchments, respectively. This performance is encouraging.

Table 5.1 Comparison of measured and estimated runoff 1994/95 season

Date	10 x 20 m		10 x 40 m	
	Measured	Simulated	Measured	Simulated
15/11/94	0.34	0.45	0.86	0.69
28/11/84	0.03	0.21	1.07	0.67
05/12/94	0.17	2.12	0.09	0.34
12/12/94	0.12	0.13	0.13	0.25
13/12/94	0.02	0.02	0.01	0.03
18/12/94	0.13	0.14	0.19	0.67
19/12/94	2.83	2.95	8.49	0.69
04/1/95	2.96	3.08	9.47	6.16
05/1/95	2.72	2.83	3.72	5.66
15/1/95	0.00	0.10	0.00	0.20
19/1/95	20.73	21.58	65.06	43.16
22/1/95	29.79	28.62	54.99	57.24
25/1/95	1.91	1.99	3.39	3.98
29/1/95	29.37	28.21	65.30	56.42
07/2/95	29.46	28.30	42.21	56.60
10/2/95	0.13	0.53	0.13	1.06
17/2/95	10.99	10.55	23.06	21.10
21/2/95	3.98	3.82	4.28	7.64
24/1/95	30.76	29.55	87.78	59.10
25/2/95	31.16	32.44	72.69	64.88
27/2/95	10.28	10.70	27.55	21.40
03/3/95	29.21	30.41	30.54	60.82
06/3/95	5.37	5.59	5.58	11.18
07/3/95	29.92	31.15	39.76	62.30
08/3/95	9.18	9.56	20.66	19.12
10/3/95	3.69	2.55	11.07	5.10
12/3/95	2.96	1.85	9.47	3.70
14/3/95	1.87	2.47	3.78	4.94
16/3/95	10.75	12.19	28.51	24.38
08/4/95	9.22	10.68	9.45	21.36
22/4/95	13.27	13.81	41.40	27.62

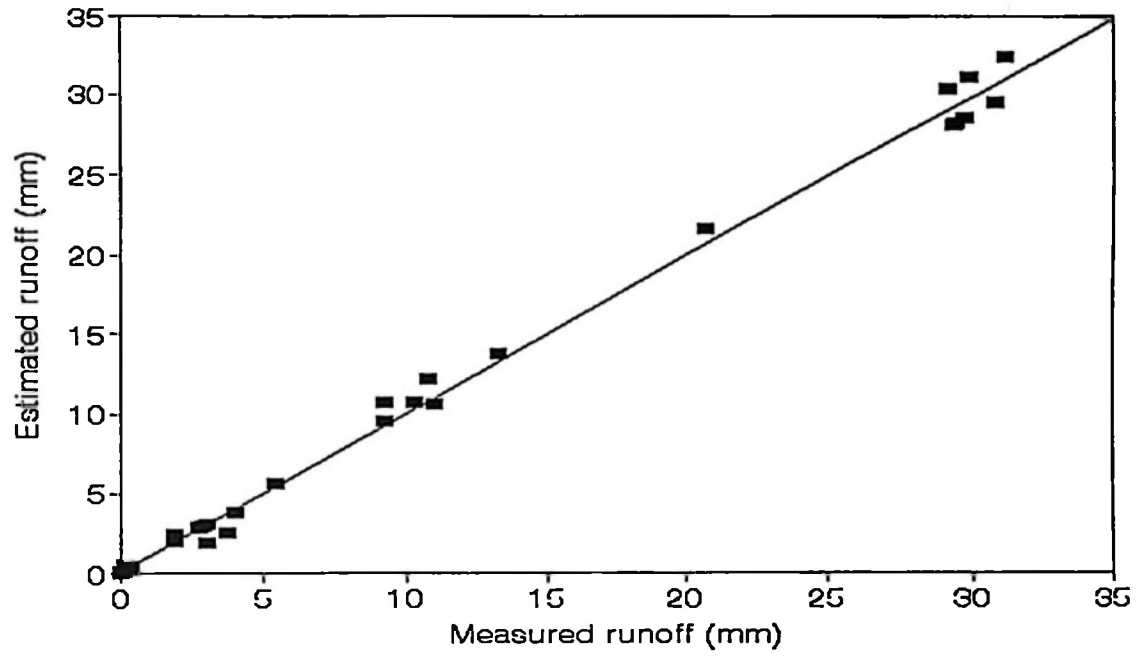


Figure 5.1(a) Runoff Yield for a 10 x 20 m Catchment

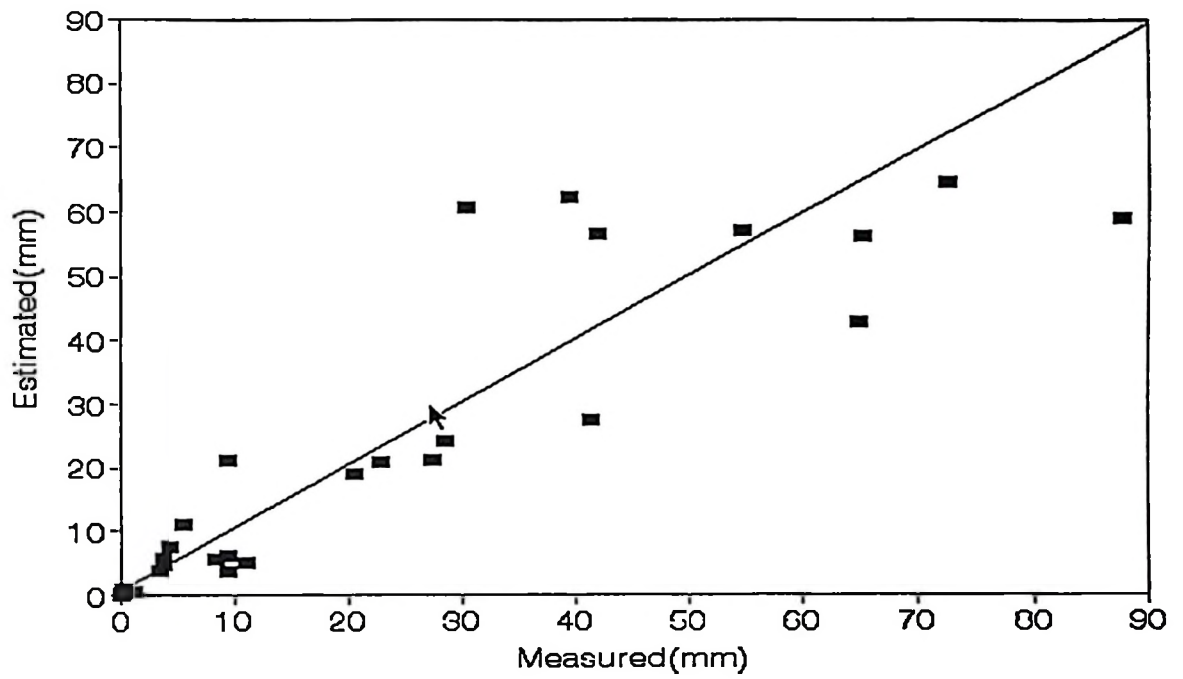


Figure 5.1 (b) Runoff yield for a 10 x 40 m catchment

5.2 Estimation of Soil Moisture Content

Soil moisture content was predicted using the models on daily basis. To make a simulation, one must know or assume a reference soil moisture on a first day and from there onwards, daily weather parameters which affect the soil moisture content are incorporated. The estimated soil moisture values were compared with the data obtained by a Neutron probe CPN 503 DR during the 1993/94 and 1994/95 seasons (Hatibu et al. 1995). The data was recorded on each rain day or once per week in absence of rainfall. The soil moisture was expressed as millimetres of water for a 100 cm depth (0 - 100 cm depth).

The results for soil moisture estimation are presented in Figures 5.2 (a) and 5.2 (b). The estimated moisture trend is the same when compared to the measured soil moisture. It is clear from figures, that the model tend to overpredict the soil moisture content. The explanation for overprediction likely involve several factors. Lateral soil water flows (which are not taken into account in the one dimensional model), pedotransfer functions which are still under validation, and change of bulk density of the top soil with time are some of these factors. Soil bulk density varies widely both spatially and temporally because of undisturbed

zones within the soil and solidification due to subsequent tillage and slumping of unstable soil aggregates as a result of precipitation. Bulk density, porosity and mechanical strength have been reported to have a major impact on soil water relationships and crop root development. For example work done in Botswana has shown that the elongation of roots in sandy loam soil can be halved by increase in the soil bulk density from 1.6 Mg/m^3 to 1.8 Mg/m^3 (DLFRS, 1985). Reduction in root elongation can affect very much the water uptake by the crop. Considering the changes in bulk density and their effects it could be logical to modify the model to take care of the changes.

Another important factor contributing to these high values is the simplified versions of modelling macropore flow, infiltration, and drainage which require minimum parameters and a fairly little knowledge of soils.

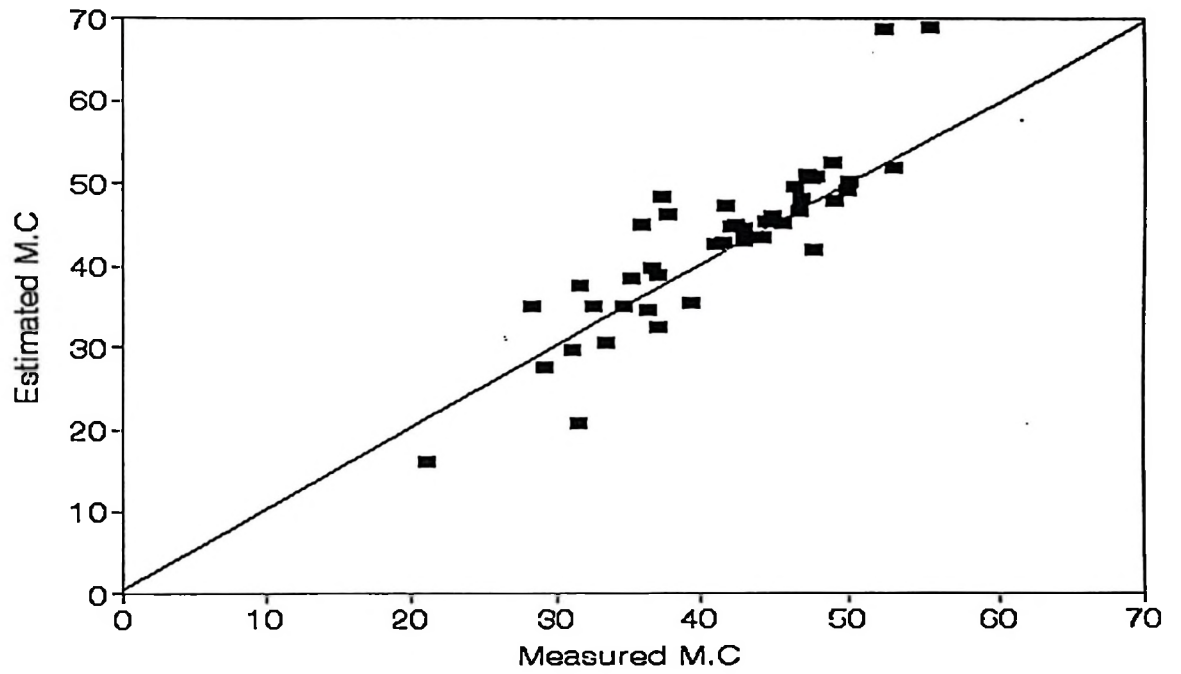


Figure 5.2 (a) Estimation of Soil Moisture in Catchment Basin

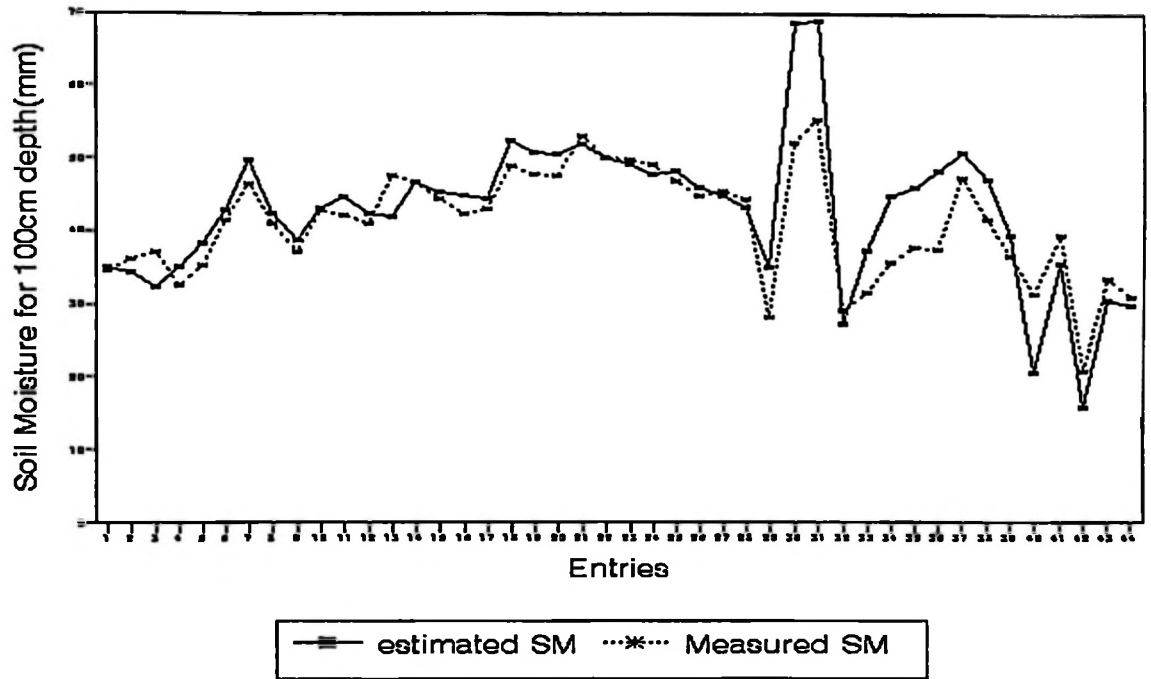


Figure 5.2 (b) Estimation of soil moisture in Catchment Basin

5.3 Simulation of Effect Of Rain Water Harvesting on Yield of Sorghum

The simulated yields were compared with the actual yields of sorghum for three seasons. The results are presented in Figures 5.3 (a) to (e).

The 4:1 CBAR field with storage treatment resulted into significantly higher yields followed closely by a 2:1 with storage. Actual yields results for 1993/94 season were, however not significantly influenced by RWH due to inadequacy of well distributed rainfall during critical crop growth months of January to March.

The trend of simulated yield shows that the yield is increased by increasing the water quantity and distribution. By adding more water to the crop, it increased the yield and furthermore when the water was supplied to the crop at a better distribution (rain water harvesting with storage) a better yield was realised. From the results the model show that one should expect to get more yield with bigger CBAR (Figure 5.3.2 (a) to Figure 5.3.2 (c)). The estimated yield show the direct relationship of increase in yield due to increase in water while the actual yield doesn't reveal this.

This can be explained by the fact that, since crop growth is modelled using only water and light variables, the reduction in water stress will result into higher yields. Water logging has some effects on crop yield as it can impair crop growth. Sorghum as other crops respire by gaseous exchange in the root zone - the process whereby roots absorb oxygen (O_2) from the soil atmosphere and release carbon dioxide (CO_2) back into it. Roots are also able to absorb O_2 dissolved in the soil water but this capacity is limited. In water logged soils, the air content of the soil is low, and anaerobic conditions in the soil may result in toxic concentrations of reduced iron, and manganese compounds, sulphides and organic gases. The indefinite increase in yield due to increase in water quantity contradict the effects of water logging. This show that the model is inadequate in predicting the upper limit of water input effects.

It is clear from the results that the model tend to over predict the yields this is seen mainly in a 10 x 20 catchment with storage, 10 x 40 m catchment and 10 x 40 m catchment with storage. This can be partly explain by the above mentioned reason since the PARCH model is sensitive to the increase of water.

The results of the correlation analysis between the simulated and the actual yield have the correlation coefficient $r^2 = 0.622$. The explanation for this relatively low correlation involves several factors. Some of the factors have already been mentioned but lack of enough agronomic data involved in determination of cultivar parameters which govern crop growth, and the assumed values of fertility, weeds, and Soil strength are additional factors.

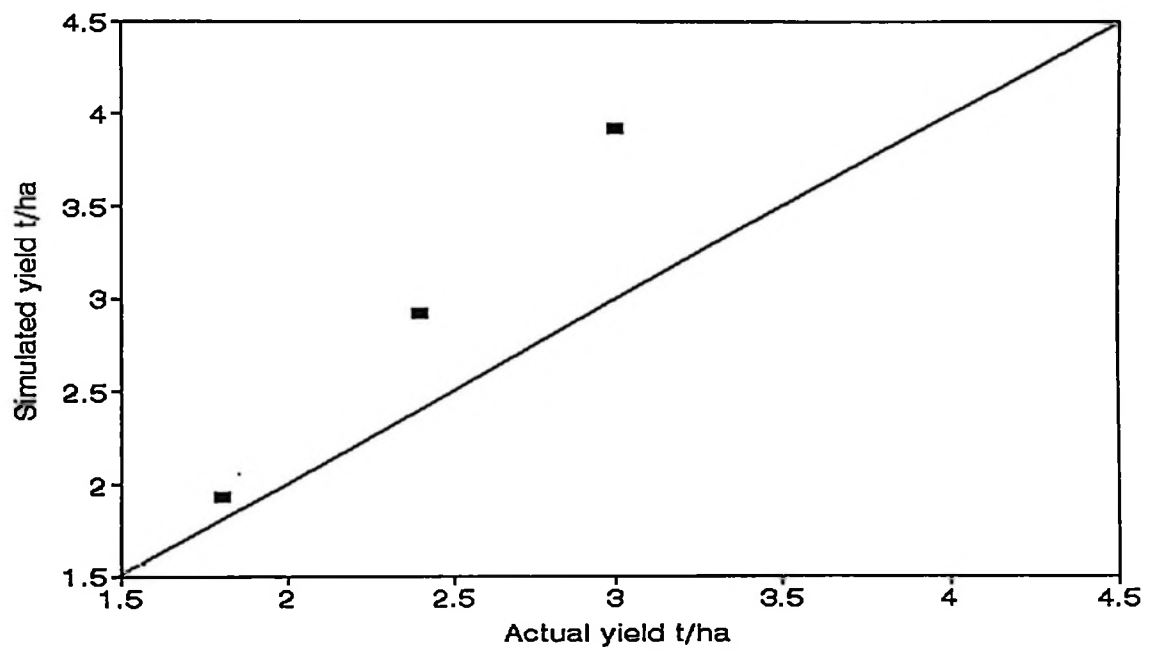


Figure 5.3.1 (a) Yields for 0:1 Catchment

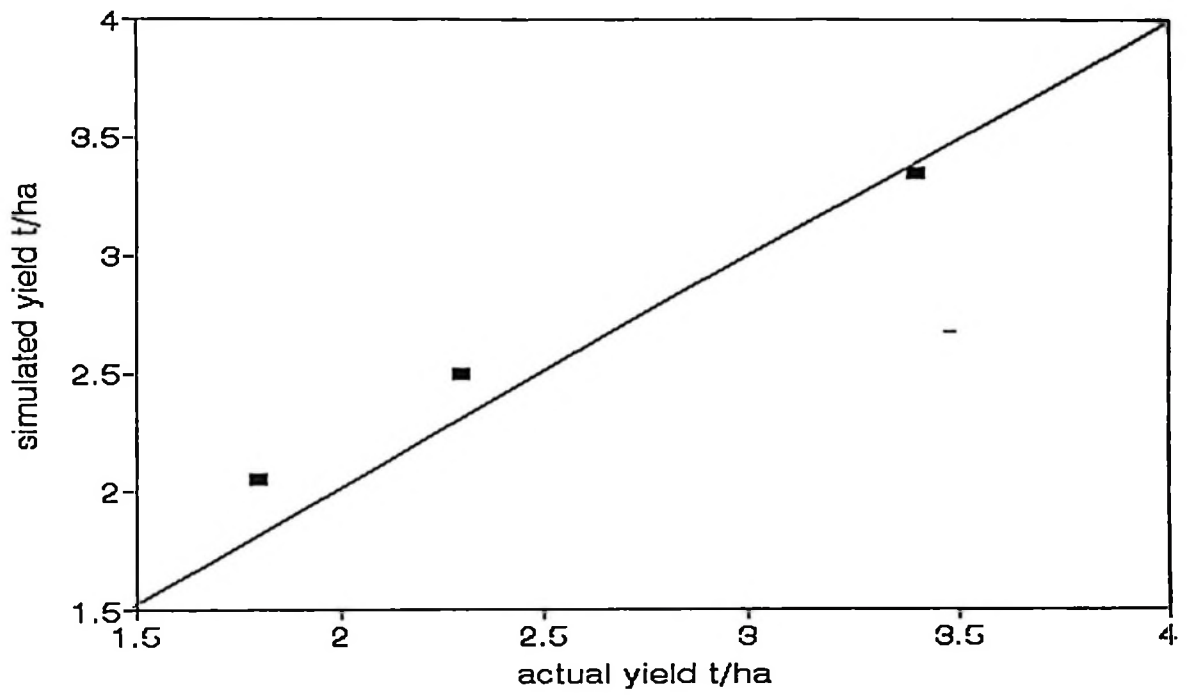


Figure 5.3.1 (b) Yield for 2:1 Catchment

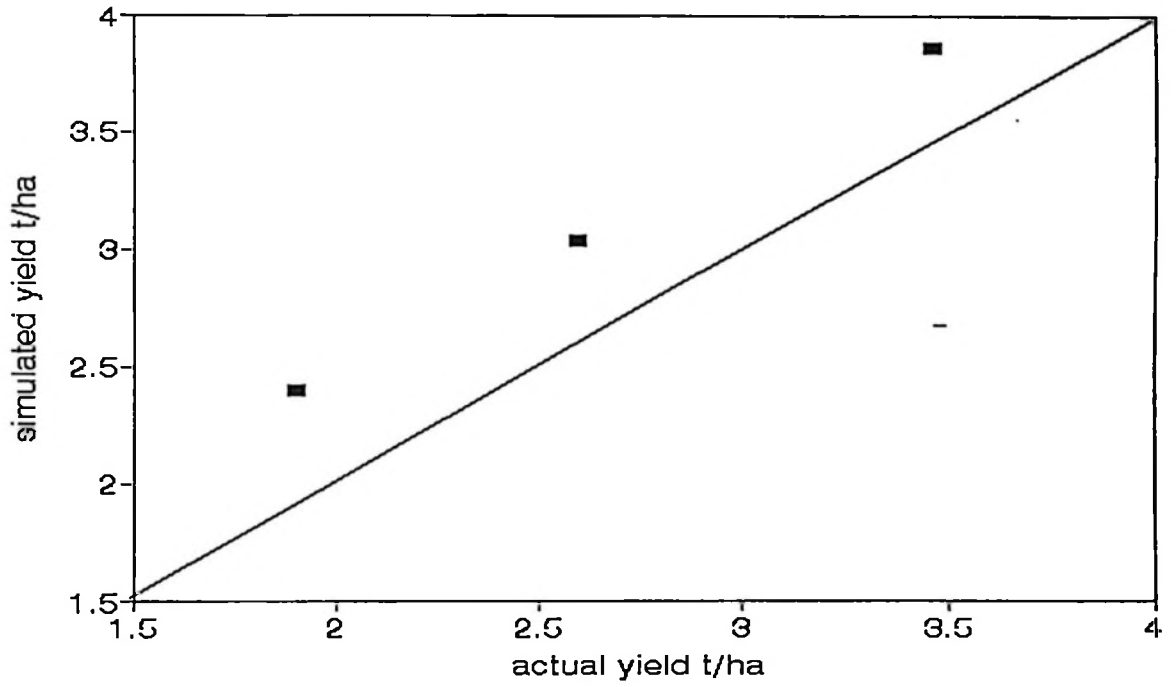


Figure 5.3.1 (c) Yield for 2:1 Catchment with storage

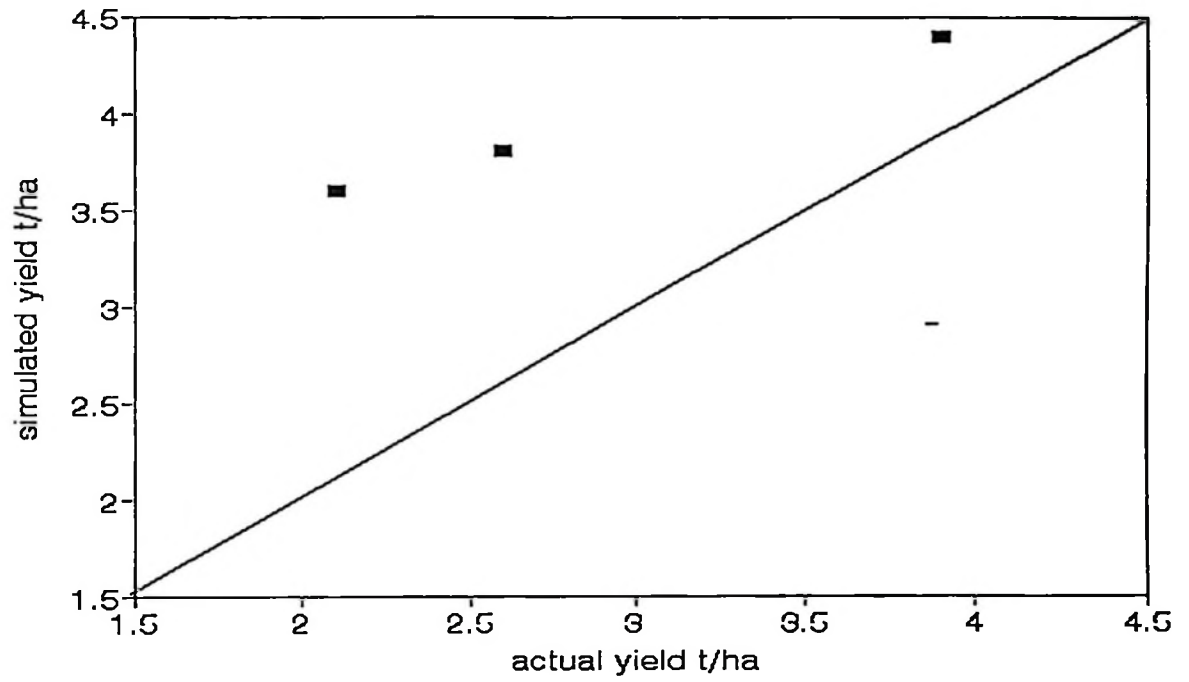


Figure 5.3.1(d) Yield for 4:1 Catchment

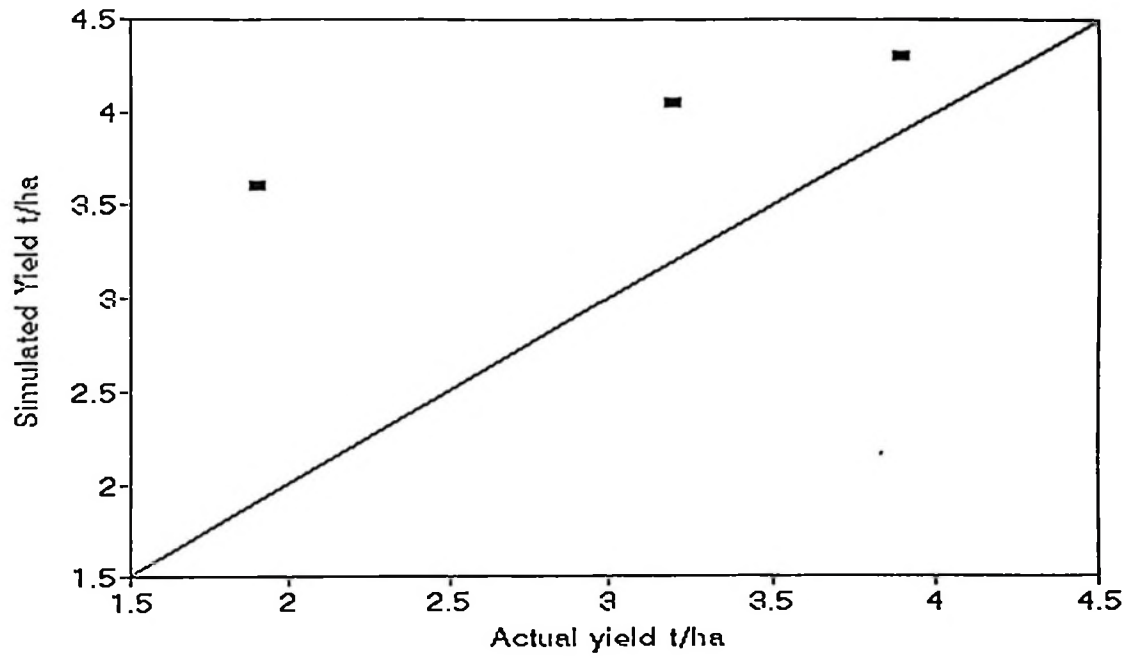


Figure 5.3.1 (e) Yield for 4:1 with storage

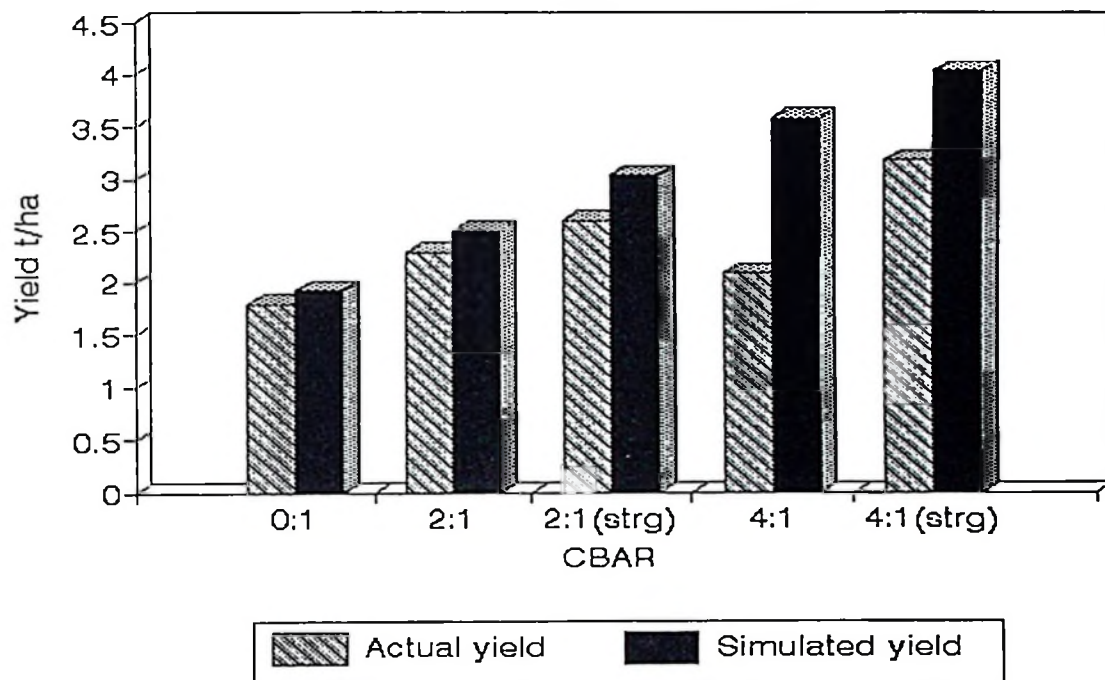


Figure 5.3.2 (a) Yield for 1992/93 season

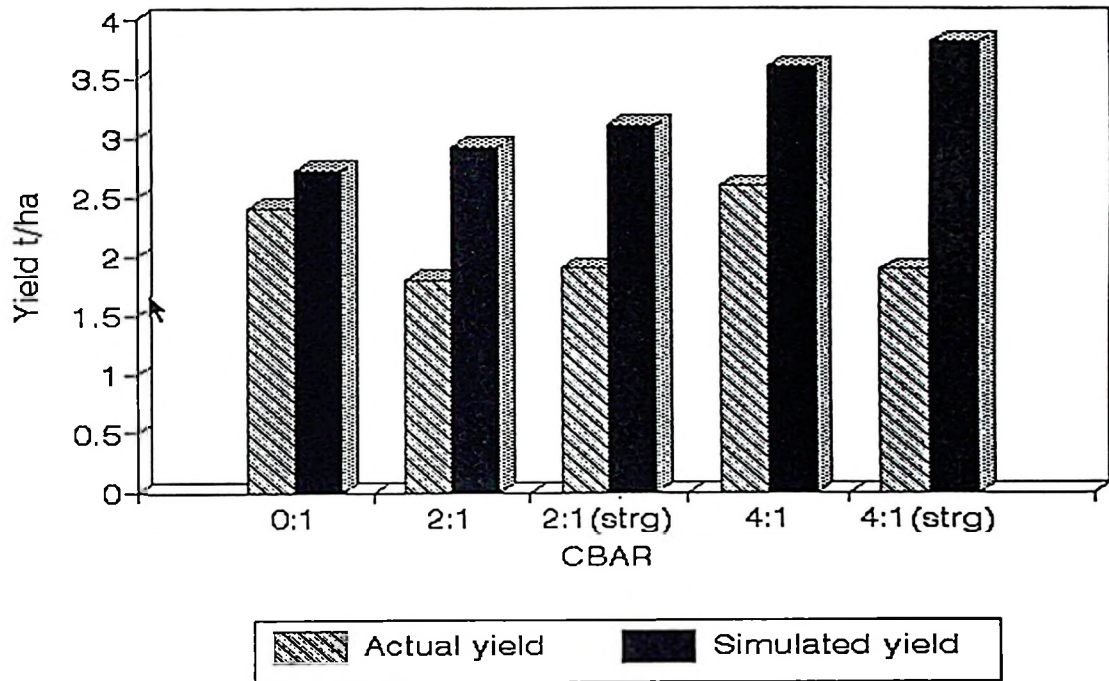


Figure 5.3.2 (b) Yield for 1993/94

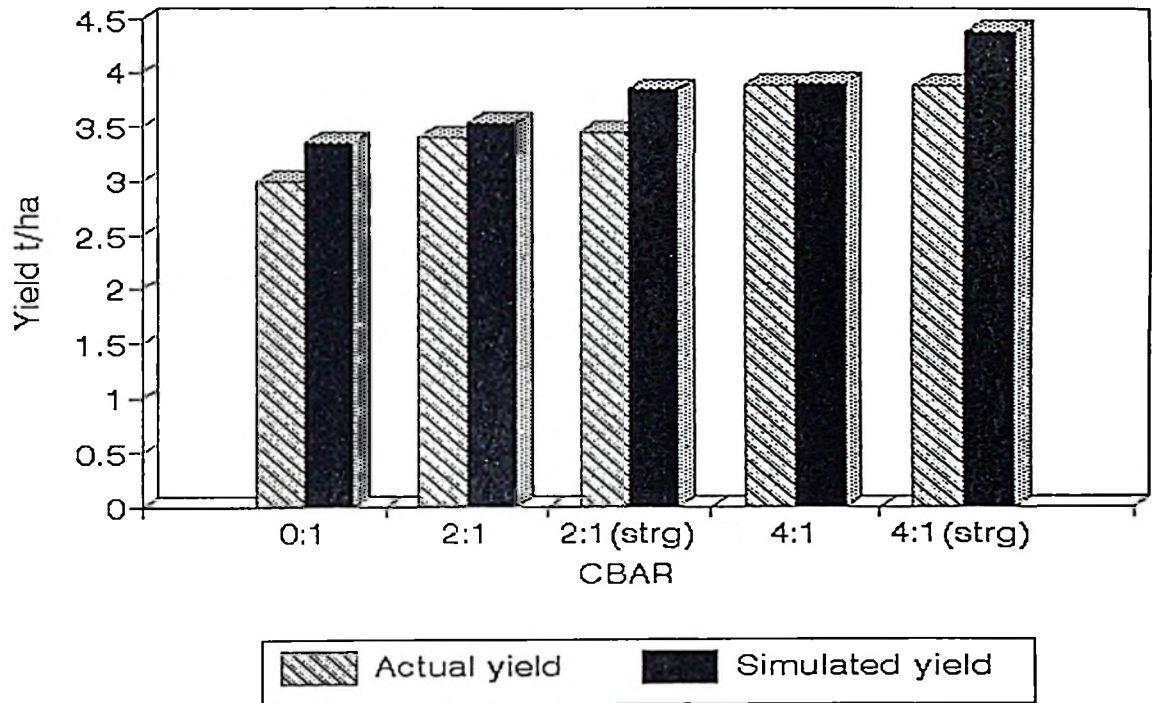


Figure 5.3.2(c) Yield for 1994/95 Season

5.4 Selection of Planting Dates

In selecting proper planting dates PARCH and THIRST models were run using three years data. First by using two dates of planting, December 1 and January 1, it was found out the number of years that have a planting opportunity of 10 days either side of these dates (planting opportunity means a day with soil moisture of at least 10 mm). Second by choosing two definitions of 10 mm, and 20 mm soil moisture it was found out the number of years that achieved these values in the second month after planting i.e in January and February. The probability of 10 mm soil moisture in day 1 being followed by 20 mm soil moisture after a month was calculated using Bayesian decision theory which allows the probability of an event to be revised in the light of new information. It can be best explained by an example.

Example:

The probability of having 10mm in day 1 around January 1st is 0.23 and the probability of these being 20mm in Feb is 0.33 Therefore the Prio probability of having 10mm in day1 is 0.23 and of not having it 0.67.

The next question to ask is how many years which have 20mm in Feb are preceded by a planting opportunity of 10mm in day 1. For this case 0.75 are preceded by a planting opportunity. Similarly how many years that have 10mm in day1 are not followed by 20mm in Feb. The value for this is 0.2. These two values, 0.75 and 0.2 are known as the likelihood or conditional probabilities.

The joint probabilities are found by multiplying the prior probabilities eg: $0.23 \times 0.75 = 0.17$. The posterior probability values are found by dividing each joint probability by the total probability eg: $0.17 / (0.75 + 0.13)$. The results are presented on table 5.2.

Table: 5.2 Planting opportunities assuming 10mm planting soil water followed by 20mm of soil water after a month

MONTH		Prior	Conditional	Joint	Posterior
NOV	Plant +	0.10	0.72	0.10	0.33
	Plant -	0.90	0.23	0.20	0.67
DEC	Plant +	0.22	0.81	0.18	0.62
	Plant -	0.78	0.14	0.11	0.38
JAN	Plant +	0.23	0.75	0.17	0.56
	Plant -	0.67	0.20	0.13	0.44
FEB	Plant +	0.20	0.70	0.14	0.45
	Plant -	0.80	0.21	0.17	0.55
MARCH	Plant +	0.17	0.40	0.07	0.17
	Plant -	0.83	0.42	0.35	0.83

5.5 Selection of optimal CBAR

Results of the design procedure for rain water harvesting with and without storage for two seasons found that the catchment area can supply rain water satisfactorily a cropped basin of half its size planted with sorghum. This was interpreted as a 2:1 CBAR which conform with the results obtained earlier in the area (Lameck, 1993).

6.0 CONCLUSIONS AND RECOMENDATIONS

1. There is a fairly good agreement between observed and simulated runoff for a 10 x 20 m catchment with correlation coefficient (r^2) of 0.804. For a 10 x 40 m catchment the correlation between measured and estimated runoff is relatively low with a value of $r^2 = 0.712$. The disagreement between simulated and measured runoff was caused by several factors including keeping catchment characteristics (random roughness and slope) constant, using a simplified rainfall disaggregator in producing rainfall intensities, and use of the Raws and Brakensiek (1989) pedotransfer functions to estimate complex soil physical properties.
2. The relationship between runoff yield and catchment length, and a routine for simulating surface depression storage should be incorporated in the runoff sub-model.
3. The simulated moisture trend is the same when compared to the measured soil moisture with correlation coefficient (r^2) of 0.607, however the model tend to overpredict the soil moisture content. The reasons for overprediction likely involve lateral soil water flow (not taken into account by the model), use of Raws and Brakensiek (1989) pedotransfer function, assumption of

constant bulk density over the season, and simplified versions of modelling infiltration and drainage which require minimum parameters with fairly little knowledge of soils.

4. The soil moisture balance sub-model of PARCH should be modified to simulate the lateral soil water flows, infiltration and drainage with greater perfection.
5. The trend of simulated sorghum yield show direct relationship of increase in yield due to increase in water quantity and distribution with a correlation coefficient (r^2) = 0.622. The model show inadequacy in predicting the upper limit of water input and hence the effects of water logging on crop yield. The explanation for the relatively low correlation involves lack of sufficient agronomic data (cultivar parameters), assumed values of fertility, weed, soil strength and due to imperfections in the soil water model on water logging.
6. The PARCH model should develop the ability to simulate the effects of anaerobis in the root zone with greater perfection. This can be achieved by either reducing establishment during early growth, or by reducing root uptake of water during later growth stages. Use of variable bulk density values is also recommended.

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8.0 APPENDICES

APPENDIX A-1

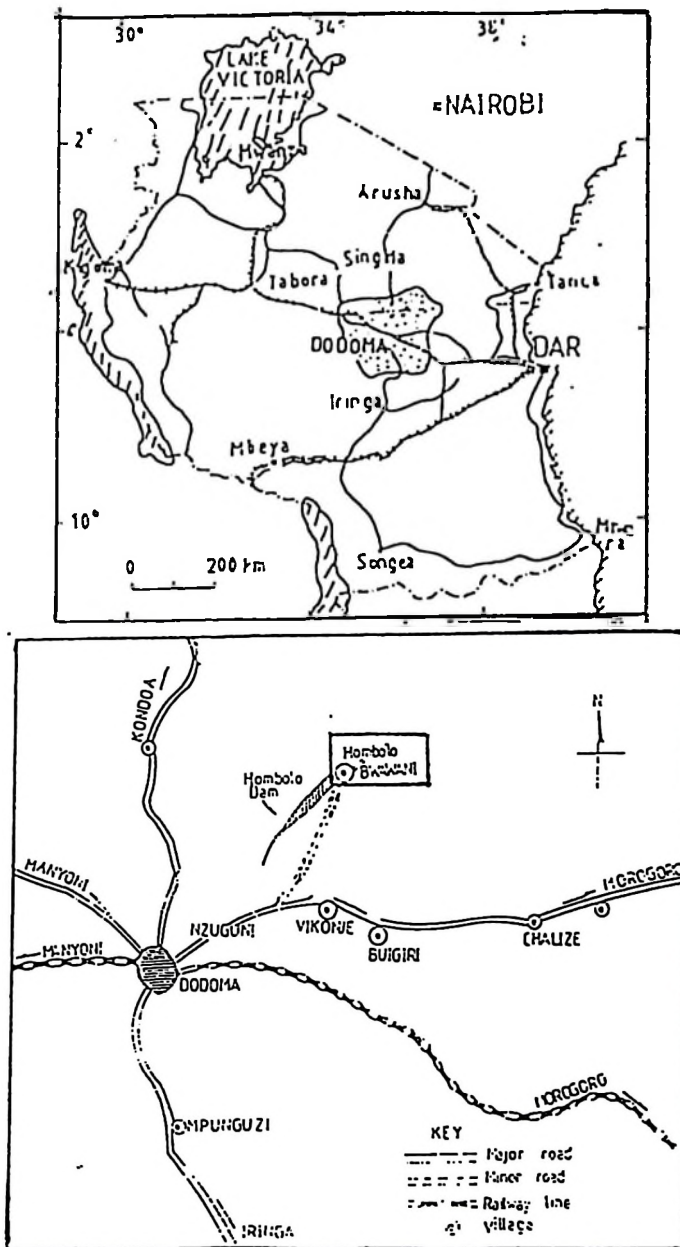


Figure A 1: Location of the study area.

APPENDIX A-2

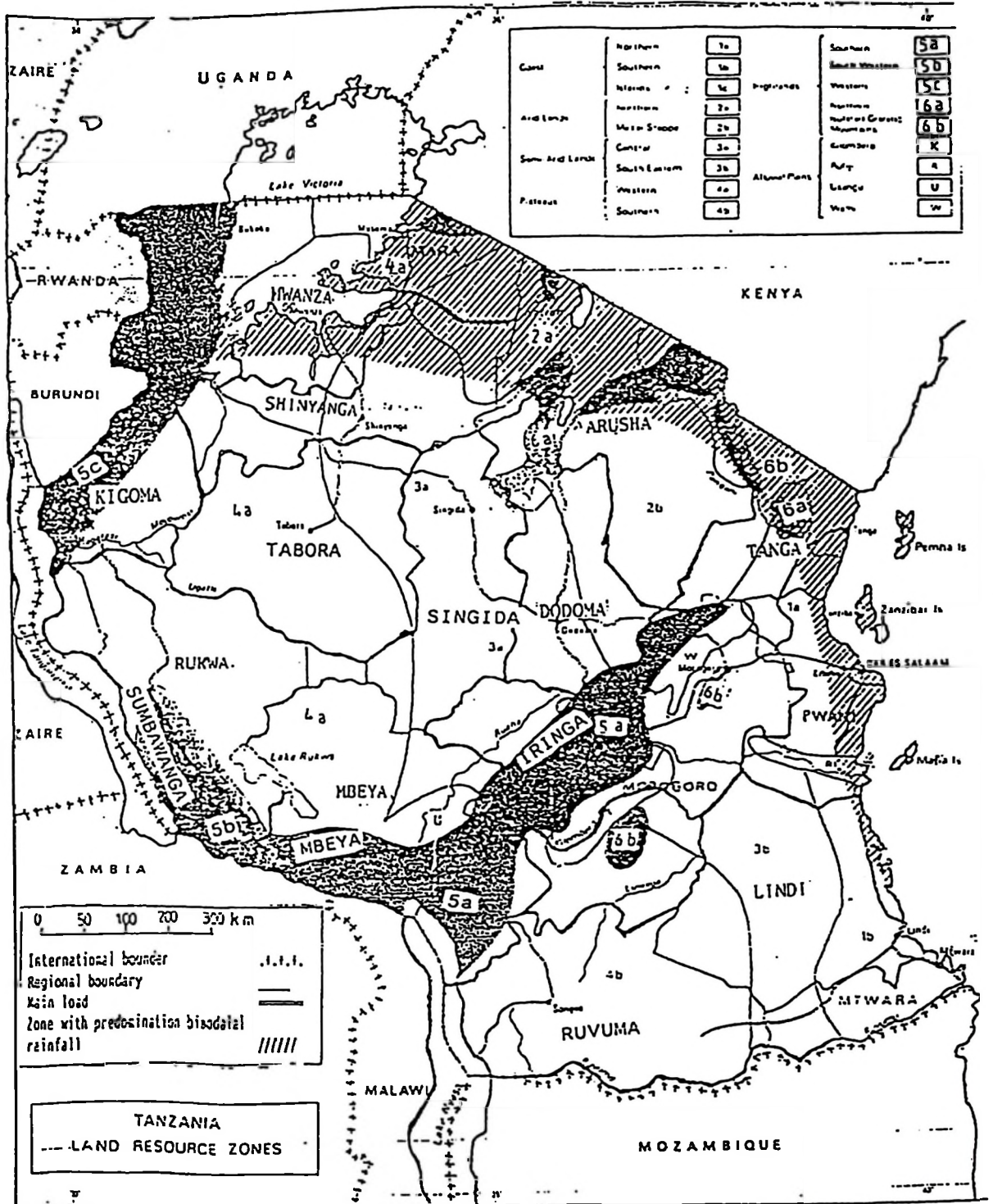


Figure A 2: Agro-ecological zones of Tanzania.

APPENDIX B-1 Runoff Sub-model (THIRST)

```

'*****
'***** GAMLSIMP.BAS*****
'***** 11/1/94 *****
'*****
'** This is the runoff generator based upon the Green and '**
'** Ampt equation and calculated simply using the old-value**
'** method. It is important to note that the accuracy of '**
'** the approach depends upon the length of the dTime! '**
'** steps (inversely proportionate) as does the time to '**
'** run the model (inversely proportionate). Further '**
'** information is given in the text. '**
'*****

DECLARE SUB NoRain ()
DECLARE SUB Paramin (thetares!, WetFronSuc!, HydrConfs!)

'***** Handles parameter input **

DECLARE SUB NoPond (Disagg!(), TMult!, HydrConfs!, MoistDef!,
WetFronSuc!, Runoff!(), CumInf!(), Inf!(), CumRunoff!(),
Tincrement%, DepStorage!())

```

```

*****          Handles infiltration without ponding      **
DECLARE SUB Pond (Disagg!(), CumInf!(), Inf!(), Runoff!(),
                  CumRunoff!(), CumInf2!, HydrConfs!, MoistDef!,
                  WetFronSuc!, DepStorage!(), Tincrement%, TMult!)

*****          Handles infiltration during ponding        **
DECLARE FUNCTION POTINF! (F!, HydrConfs!, MoistDef!,
                          WetFronSuc!)

*****          Calculates potential infiltration rate      **
DECLARE SUB RunoffModel (Disagg!(), Runoff!(), IterVar!,
                        Thetafs!, Thetainit!, HydrConfs!, WetFronSuc!,
                        MinRunStep, RunDay, TMult!, MoistDef!, CumInf!(),
                        Inf!(), InfRate!(), CumRunoff!(), Tincrement%,
                        DepStorage!())

DIM Runoff!(IterVar! + 1)
*****
*****          Arrays dimensioned dynamically              **

DIM Inf!(IterVar! + 1)
*****          by IterVar! to allow for variable time     **
DIM CumInf!(IterVar! + 1)

```

```

*****      steps                                     **
DIM      DepStorage!(IterVar! + 1)
*****

DIM InRate!(IterVar! + 1)
DIM CumRunoff!(IterVar! + 1)

*****

*****      SUBROUTINE NoPond                          **
*****
***** This subroutine calculates infiltration and runoff **
***** during unponded conditions.                      **
*****

SUB NoPond (Disagg!(), TMult!, HydrConfs!, MoistDef!,
WetFronSuc!, Runoff!(), CumInf!(), Inf!(), CumRunoff!(),
Tincrement%, DepStorage!())
SHARED CumInf1!, CumInf2!, InRate1!, InRate2!, dTime!,
      dTimeMax! ', TMult!
SHARED Depstor!, DepStorMax!, Runof!, SUM, dCumInf!, AppVol!
SHARED InRate!()
CumInf1! = CumInf!(Tincrement%) + Disagg!(Tincrement%) *
      TMult!

```

```

InfRate1! = POTINF(CumInf1!, HydrConfs!, MoistDef!,
                  WetFronSuc!)

```

```

IF InfRate1! > Disagg!(Tincrement%) THEN

```

```

    InfRate1! = Disagg!(Tincrement%)

```

```

    CumInf(Tincrement%) = CumInf1!

```

```

    IF Tincrement% > 1 THEN

```

```

        Inf!(Tincrement%) = CumInf!(Tincrement%) - CumInf!(
Tincrement% - 1)

```

```

        CumRunoff!(Tincrement%) = CumRunoff!(Tincrement% - 1)

```

```

        Runoff!(Tincrement%) = 0

```

```

    ELSE

```

```

        Inf!(Tincrement%) = CumInf!(Tincrement%)

```

```

        CumRunoff!(Tincrement%) = 0

```

```

        Runoff!(Tincrement%) = 0

```

```

    END IF

```

```

    Tincrement% = Tincrement% + 1

```

```

    CumInf!(Tincrement%) = CumInf(Tincrement% - 1)

```

```

    IF CumInf!(Tincrement%) < .0000000001# THEN

```

```

        CumInf!(Tincrement%) = .0000000001#

```

```

ELSE

```

```

    SUM = 0!

```

```

    CumInf1! = CumInf!(Tincrement%)

```

```
CALL Pond(Disagg!(), CumInf!(), Inf!(), Runoff!(),
CumRunoff!(), CumInf2!, HydrConfs!, MoistDef!,
WetFronSuc!, DepStorage!(), Tincrement%, TMult!)
END IF
END SUB
SUB Paramin (thetares!, WetFronSuc!, HydrConfs!)
    persand! = 79    '** Change
    perclay! = 16
    persilt! = 5
    perom! = 1.03
    CEC! = .05
    bd0! = 1.54
    AllowCr% = 0
    AllowMa% = 0
    AllowCa% = 0
    percover! = 1
    CanopyArea! = 1
    CanopyBare! = 1
    OpenArea! = 99
    OpenBare! = 99
    CrustThick! = .5
IF CEC! < .1 THEN
    porosity! = (2.65 - bd0!) / 2.65
    thetafs! = porosity!
```

$$\begin{aligned} \text{thetares!} = & -.0182482\# + (.00087269\# * \text{persand!}) + \\ & (.00513488\# * \text{perclay!}) + (.02939286\# * \text{porosity!}) - \\ & (.00015395\# * \text{perclay!}^2) - (.0010827 * \text{persand!} * \\ & \text{porosity!}) - (.00018233\# * \text{perclay!}^2 * \text{porosity!}^2) \\ & + (.00030703\# * \text{perclay!}^2 * - \text{porosity!}) - (.0023584 \\ & * \text{porosity}^2 * \text{perclay!}) \end{aligned}$$

$$\begin{aligned} \text{HydrConfs!} = & \text{EXP}((19.52348 * \text{porosity!}) - 8.96847 - \\ & (.028212 * \text{perclay!}) + (.00018107\# * \text{persand!}^2) - \\ & (.0094125 * \text{perclay!}^2) - (8.395215 * \text{porosity!}^2) \\ & + (.077718 * \text{persand!} * \text{porosity!}) - (.00298 * \text{persand!} \\ & ^2 * \text{porosity!}^2) - (.019492 * \text{perclay!}^2 * \\ & \text{porosity!}^2) + (.0000173 * \text{persand!}^2 * \text{perclay!}) + \\ & (.02733 * \text{perclay!}^2 * \text{porosity!}) + (.001434 * \\ & \text{persand!}^2 * \text{porosity!}) - (.0000035 * \text{perclay!}^2 * \\ & \text{persand!})) \end{aligned}$$

$$\text{HydrConfs!} = \text{HydrConfs!} / 100$$

$$\begin{aligned} \text{WetFronSuc!} = & \text{EXP}((6.5309 - (7.32561 * \text{Thetafs!}) + \\ & (.001583 * (\text{perclay!}^2)) + (3.809479 * (\text{Thetafs!}^2)) \\ & + (.000344 * \text{persand!} * \text{perclay!}) - (.049837 * \text{persand!} \\ & * \text{Thetafs!}) + (.001608 * (\text{persand!}^2 * \text{Thetafs!}^2)) \\ & + (.001602 * (\text{perclay!}^2 * \text{Thetafs!}^2)) - (.0000136 \\ & * (\text{persand!}^2 * \text{perclay!})) - (.003479 * (\text{perclay!}^2 \\ & * \text{Thetafs!})) - (.000799 * (\text{persand!}^2 * \text{Thetafs!})))) \end{aligned}$$

$$\text{WetFronSuc!} = \text{WetFronSuc!} / 100$$

ELSEIF CEC! >= .1 THEN

$$\text{porosity!} = (2.65 - \text{bd0!}) / 2.65$$

$$\begin{aligned} \text{EntrapAir!} = & (1! - (3.8 + (.00019 * \text{perclay!} ^ 2) \\ & - (.337 * \text{persand!}) + (.126 * \text{CEC!} * \text{perclay!}) \\ & + (\text{perom!} * ((\text{persand!} / 200) ^ 2)))) / 100 \end{aligned}$$

$$\text{Thetafs!} = \text{porosity!} - (\text{EntrapAir!} * \text{porosity!})$$

'**** Water content at field saturation - needs CEC ****'

$$\begin{aligned} \text{thetares!} = & (.2 + (.1 * \text{perom!}) + (.25 * \text{perclay!} \\ & * (\text{CEC!} ^ .45))) * \text{bd0!} / 100 \end{aligned}$$

$$\begin{aligned} \text{C!} = & .17 + (.181 * \text{perclay!}) - (6.9\text{E-}07 * \text{persand!} ^ 2 \\ & * \text{perclay!} ^ 2) - (4.1\text{E-}07 * \text{persand!} ^ 2 * (100 - \\ & \text{persand!} - \text{perclay!}) ^ 2) + (.000118 * \text{persand!} ^ 2 * \\ & \text{bd0!} ^ 2) + (.00069 * \text{perclay!} ^ 2 * \text{bd0!} ^ 2) + \\ & (.000049 * \text{persand!} ^ 2 * \text{perclay!}) - (.000085 * (100 - \\ & \text{persand!} - \text{perclay!}) * \text{perclay!} ^ 2) \end{aligned}$$

$$\begin{aligned} \text{HydrConfs!} = & .00035 * (((\text{Thetafs!} - \text{thetares!}) ^ 3) / \\ & ((1 - \text{Thetafs!}) ^ 2)) * ((\text{bd0!} / \text{thetares!}) ^ 2) * \text{C!}^2 \end{aligned}$$

$$\text{HydrConfs!} = \text{HydrConfs!} / 100$$

$$\begin{aligned} \text{WetFronSuc!} = & \text{EXP}((6.5309 - (7.32561 * \text{Thetafs!}) + \\ & (.001583 * (\text{perclay!} ^ 2)) + (3.809479 * (\text{Thetafs!} ^ 2)) \\ & + (.000344 * \text{persand!} * \text{perclay!}) - (.049837 * \text{persand!} \\ & * \text{Thetafs!}) + (.001608 * (\text{persand!} ^ 2 * \text{Thetafs!} ^ 2)) \\ & + (.001602 * (\text{perclay!} ^ 2 * \text{Thetafs!} ^ 2)) - (.0000136 \\ & * (\text{persand!} ^ 2 * \text{perclay!})) - (.003479 * (\text{perclay!} ^ 2 \end{aligned}$$

```

* Thetafs!)) - (.000799 * (persand! ^ 2 * Thetafs!)))
WetFronSuc! = WetFronSuc! / 100
END IF

'***** Rawls and Brakensiek (1989) *****
'***** Crust factors *****

WetDepth! = 14.7 - (.0015 * persand! ^ 2) - (.3 *
perclay! * bd0!)
IF WetDepth! < CrustThick! THEN WetDepth! = 1
SC! = .736 + (.0019 * persand!)
b! = .0099 + (.0721 * CrustThick!) + (.0000068 *
persand! ^ 2) + (.000021 * persand! ^ 2 * CrustThick!)
- (.000315 * persand! * CrustThick! ^ 2)
CrustF! = WetDepth! / (((WetDepth! - CrustThick!) / SC!)
+ (CrustThick! / b!))
CanopyF! = 1 + (percover! / 100)
MacroporeF! = EXP(.96 - (.032 * persand!) + (.04 *
perclay!) - (.032 * bd0!))
IF MacroporeF! < .2 THEN MacroporeF! = .2
IF AllowCr% = 1 THEN
IF AllowMa% = 1 THEN
IF AllowCa% = 1 THEN
EffHydrConfsO! = (((OpenBare! / OpenArea!) *

```

CrustF!) + (MacroporeF! * (1 - (OpenBare! /
OpenArea!)))) * HydrConfs!

EffHydrConfsC! = CanopyF! * (((CanopyBare! /
CanopyArea!) * CrustF!) + (MacroporeF! * (1 -
(CanopyBare! / CanopyArea!)))) * HydrConfs!

EffHydrConfs! = (CanopyArea! / 100 * EffHydrConfsC!)
+ (OpenArea! / 100 * EffHydrConfsO!)

ELSE

EffHydrConfs! = MacroporeF! * CrustF! * HydrConfs!

END IF

ELSE

IF AllowCa% = 1 THEN

EffHydrConfsO! = (((OpenBare! / OpenArea!) * CrustF!) +
((1 - (OpenBare! / OpenArea!)))) * HydrConfs!

EffHydrConfsC! = CanopyF! * (((CanopyBare! /
CanopyArea!) * CrustF!) + ((1 - (CanopyBare! /
CanopyArea!)))) * HydrConfs!

EffHydrConfs! = (CanopyArea! / 100 * EffHydrConfsC!) +
(OpenArea! / 100 * EffHydrConfsO!)

ELSE

EffHydrConfs! = CrustF! * HydrConfs!

END IF

END IF

```

ELSE
  IF AllowMa% = 1 THEN
    IF AllowCa% = 1 THEN
      EffHydrConfsO! = (((OpenBare! / OpenArea!)) +
        (MacroporeF! * (1 - (OpenBare! / OpenArea!)))) *
        HydrConfs!
      EffHydrConfsC! = CanopyF! * (((CanopyBare! /
        CanopyArea!)) + (MacroporeF! * (1 - (CanopyBare! /
        CanopyArea!)))) * HydrConfs!
      EffHydrConfs! = (CanopyArea! * EffHydrConfsC!) +
        (OpenArea! * EffHydrConfsO!)
    ELSE
      EffHydrConfs! = MacroporeF! * HydrConfs!
    END IF
  ELSE
    IF AllowCa% = 1 THEN
      EffHydrConfs! = HydrConfs!
    ELSE
      EffHydrConfs! = HydrConfs!
    END IF
  END IF
END IF
HydrConfs! = EffHydrConfs!
END SUB

```

```

'*****
'***** SUBROUTINE Pond *****
'*****
' ** This subroutine deals with infiltration under ponded **
' ** conditions (when rainfall rate > infiltration rate or **
' ** when depression storage > 0). This is done using the **
' ** old value method. The time-step is sub-divided into **
' ** a number of smaller subimesteps (of length Dtime!). **
' ** The greater the number of these, the greater will be **
' ** the accuracy of the final result. **
'*****
SUB Pond (Disagg!(), CumInf!(), Inf!(), Runoff!(), CumRunof
f!(), CumInf2!, HydrConfs!, MoistDef!, WetFronSuc!,
DepStorage!(), Tincrement%, Tmult!)

SHARED CumInf1!, InfRate1!, InfRate2!, Dtime!, Dtimemax!
SHARED Depstor!, DepStorMax!, Runof!, SUM, Dcuminf!, AppVol!
SHARED InfRate!()

BEGIN: Dcuminf! = InfRate1! * Dtime!
      CumInf2! = CumInf1! + Dcuminf!
      InfRate2! = POTINF(CumInf2!, HydrConfs!, MoistDef!,
      WetFronSuc!)

```

```

IF Depstor! <= 0! THEN
  IF InfRate2! > Disagg!(Tincrement%) THEN
    InfRate2! = Disagg!(Tincrement%)
  ELSE
    END IF
ELSE
  END IF

  Dcuminf! = .5 * (InfRate1! + InfRate2!) * Dtime!
  AppVol! = Depstor! + Disagg!(Tincrement%) * Dtime!
  IF Dcuminf! > AppVol! THEN Dcuminf! = AppVol!
  CumInf1! = CumInf1! + Dcuminf!

  SUM! = SUM! + Dtime!
  InfRate1! = POTINF(CumInf1!, HydrConfs!, MoistDef!,
  WetFronSuc!)
  IF Depstor! <= 0! THEN
    IF InfRate1! > Disagg!(Tincrement%) THEN
      InfRate1! = Disagg!(Tincrement%)
    ELSE
      END IF
  ELSE
    END IF

  Depstor! = Depstor! + Disagg!(Tincrement%) * Dtime! -

```

```

Dcuminf!
IF Depstor! > DepStorMax! THEN
  Depstor! = DepStorMax!
ELSE
END IF
IF SUM >= Dtimemax! THEN
  CumInf!(Tincrement%) = CumInf1!
IF Tincrement% > 1 THEN
  Inf!(Tincrement%) = CumInf!(Tincrement%) -
  CumInf!(Tincrement% - 1)
IF Inf!(Tincrement%) > (Disagg!(Tincrement%) * Tmult!) THEN
  Inf!(Tincrement%) = (Disagg!(Tincrement%) * Tmult!)
  Runoff!(Tincrement%) = 0
ELSE
  Runoff!(Tincrement%) = (Disagg!(Tincrement%) * Tmult!)
  - Inf!(Tincrement%) - Depstor!
END IF
CumRunoff!(Tincrement%) = CumRunoff!(Tincrement% - 1) +
Runoff!(Tincrement%)
  DepStorage!(Tincrement%) = Depstor!
ELSE
  Inf!(Tincrement%) = CumInf!(Tincrement%)
  IF Inf!(Tincrement%) > (Disagg!(Tincrement%) *
  Tmult!) THEN

```

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Inf!(Tincrement%) = (Disagg!(Tincrement%) * Tmult!)

Runoff!(Tincrement%) = 0

ELSE

Runoff!(Tincrement%) = (Disagg!(Tincrement%) * Tmult!)

- Inf!(Tincrement%) - Depstor!

END IF

CumRunoff!(Tincrement%) = Runoff!(Tincrement%)

DepStorage!(Tincrement%) = Depstor!

END IF

Tincrement% = Tincrement% + 1

CumInf!(Tincrement%) = CumInf!(Tincrement% - 1)

IF CumInf!(Tincrement%) < .0000000001# THEN

CumInf!(Tincrement%) = .0000000001#

ELSE

GOTO BEGIN

END IF

END SUB

```

'*****
'***** FUNCTION POTINF () *****
'*****
'** This function very simply calculates a potential **
'** infiltration rate based upon a value of cumulative **
'** infiltration which is passed to it. **
'*****
FUNCTION POTINF (F, HydrConfs!, MoistDef!, WetFronSuc!)
POTINF = HydrConfs! * (1 + ((MoistDef! * WetFronSuc!) / F))
END FUNCTION

SUB RunoffModel (Disagg!(), Runoff!(), IterVar!, Thetafs!,
  Thetainit!, HydrConfs!, WetFronSuc!, MinRunStep, RunDay,
  Tmult!, MoistDef!, CumInf!(), Inf!(), InfRate!(),
  CumRunoff!(), Tincrement%, DepStorage!())

SHARED CumInf1!, CumInf2!, InfRate1!, InfRate2!, Dtime!,
  Dtimemax!

SHARED Depstor!, DepStorMax!, Runof!, SUM, Dcuminf!, AppVol!

'*****
'** The next piece of code is concerned with the **
'** initialisation of the **
'** various variables used in this module. NOTE: Coeff! **
'** is the coefficient **
'** of the negative exponential used to decrease **

```

```

** "cumulative infiltration" **
** between rainfall events. The higher its value the **
** faster will be the decrease. **
*****
'NoRainPMax% = 300
** Exponential water balance turned off **
'Coeff! = .000005
Tincrement% = (RunDay + MinRunStep) / MinRunStep
*****
*****      Initialising variables      **
      DepStorMax! =0
*****
      Dtime! = .05
      Dtimemax! = Tmult! - .01 * Dtime!
*****
** The next lines of code control the calling of SUBs **
** Pond, NoPond and NoRain. It is run through once for **
** every time-step (Tincrement%) until the end of the **
** rainfall data (IterVar!). NOTE: NoRainP% is a variable **
** which counts the number of consecutive days with no **
** rainfall. If its value exceeds NoRainPMax%, then SUB **
** NoRain is called to decrease the apparent cum. **
** infiltration. This simulates the soil's gradual **

```

```

*** increase in infiltration capacity during dry periods **
*** (Through redistribution, evaporation, etc. **
*****
IF CumInf!(Tincrement%) <= 0 THEN CumInf!(Tincrement%) =
    0.0000000001#
    InfRate!(Tincrement%) = POTINF(CumInf!(Tincrement%),
    HydrConfs!, MoistDef!, WetFronSuc!)
IF Depstor! > 0 THEN
    InfRate1! = InfRate!(Tincrement%)
    SUM = 0!
    CumInf1! = CumInf!(Tincrement%)
    CALL Pond(Disagg!(), CumInf!(), Inf!(), Runoff!(),
    CumRunoff!(), CumInf2!, HydrConfs!, MoistDef!,
    WetFronSuc!, DepStorage!(), Tincrement%, Tmult!)
    NoRainP% = 0
ELSE
    IF InfRate!(Tincrement%) > Disagg!(Tincrement%) THEN
        IF Disagg!(Tincrement%) <= 0 THEN
            NoRainP% = NoRainP% + 1
            IF NoRainP% > NoRainPMax% THEN
                CALL NoRain
            ELSE
                CALL NoPond(Disagg!(), Tmult!, HydrConfs!, MoistDef!,
                WetFronSuc!, Runoff!(), CumInf!(), Inf!(),

```

```
        CumRunoff!(), Tincrement%, DepStorage!())
    END IF
ELSE
    CALL NoPond(Disagg!())
    NoRainP% = 0
END IF
ELSE
    InfRate1! = InfRate!(Tincrement%)
    SUM = 0!
    CumInf1! = CumInf!(Tincrement%)

    CALL Pond(Disagg!(), CumInf!(), Inf!(), Runoff!(),
        CumRunoff!(), CumInf2!, HydrConfs!, MoistDef!,
        WetFronSuc!, DepStorage!(), Tincrement%, Tmult!)
    NoRainP% = 0
END IF
END IF
END SUB
```

APPENDIX B-2 Rainfall Dissaggregator

```
DECLARE FUNCTION Func! (C!, IA45#, D#, R2#)
```

```
DECLARE SUB NewtRaph (IA45#, D#, R2#, Coeff#)
```

```
DECLARE FUNCTION Diffunc! (C!, IA45#, D#)
```

```
DECLARE SUB Disaggregate (P, Disagg!(), D#)
```

```
'*****          FUNCTION Diffunc          *****
'*****
'** This function is the differential of the function in **
'** FUNCTION Func It is called by SUB NewtRaph and forms **
'** part of the Newton-Raphson method for solving the    **
'** implicit equation for Cumulative infiltration (C)
'*****
FUNCTION Diffunc (C, IA45#, D#)
    Diffunc = -((-IA45# / (C ^ 2)) * (EXP(-C * (D# - .75))
    - 1) + (IA45# / C * (-(D# - .75) * EXP(-C * (D# -
    .75))))))
END FUNCTION
```

SUB Disaggregate (P, Disagg!(), D#)

```

'*****
' ** Input information below **
'*****

      R# = P

      Rainint# = .083333333333333#

      I30# = 1.6177567# + .8805255# * R#

'*****      invents storm I30      **

      IF I30# >= R# * 1.5 THEN I30# = R# * 1.5
      D# = (2.8483079# * (R# / I30#)) '-.594259

      IF D# <= 1 THEN D# = 1.001

'*****      invents storm duration      **

      IMax# = (I30# / (22.5 / 60)) * .5

'*****      calculates max intensity      **

      IA45# = (I30# / (22.5 / 60)) * .25

'*****      calculates intensity at 45 mins      **

'*****
' ** R# is the total rainfall for the day. R1# is the      **
' ** total rainfall from      **
' ** 0 to 45 mins (the area under the graph of intensity      **
' ** against time from      **
' ** 0 to 45 mins) and R2# is the total rainfall from 45      **
' ** mins to the end of      **
' ** the entered duration (D#) (the area under the      **

```

```

    '** exponential curve).                                **
    '*****
      R1# = ((IMax# * .5) / 2) + (((IMax# - IA45#) * .25) / 2)
      + (IA45# * .25)
      R2# = R# - R1#
      CALL NewtRaph(IA45#, D#, R2#, Coeff#)
    '*****
    '** The next piece of code deals with an input interval **
    '** which does not divide into the input duration to give**
    '** an integer                                          **
    '*****
      IterVar% = INT(D# / Rainint#)
      IF IterVar% = 0 THEN
        IterVar% = 1
      ELSEIF D# / IterVar% <> Rainint# THEN
        IterVar% = IterVar% + 1
        Remainder$ = "YES"
      ELSE
      END IF
      DIM ExpArea#(IterVar%)
      DIM Intensity#(IterVar%)
      DIM Avintensity#(IterVar%)
      DIM Avintensity!(IterVar%)
      Counter% = 0

```

90

```
FOR Count1% = 1 TO IterVar%
  rtime# = Count1% * Rainint#
  SELECT CASE rtime#
    CASE IS <= .5
      '***** linear rising portion of distribution **
        IF Count1% = 1 THEN
          Intensity#(1) = (I30# / (22.2 / 60)) * rtime#
          Avintensity#(1) = Intensity#(1) / 2
        ELSE
          Intensity#(Count1%) = (I30# / (22.2 / 60)) * rtime#
          Avintensity#(Count1%) = (Intensity#(Count1%) +
            Intensity#(Count1% - 1)) / 2

          END IF
        CASE IS <= .75
          '***** linear falling portion of distribution **
            IF (Count1% - 1) * Rainint# < .5 THEN
              Intensity1# = (Intensity#(Count1% - 1) + IMax#) / 2
              Intensity2# = (IMax# + (IMax# + ((IA45# - IMax#) / .25) *
                ((rtime# - .5)))) / 2
              Avintensity#(Count1%) = (Intensity1# + Intensity2#) / 2
              Intensity#(Count1%) = IMax# + ((IA45# - IMax#) / .25)
                ((rtime# - .5))
            ELSE
```

```

Intensity#(Count1%) = IMax# + ((IA45# - IMax#) / .25)
* ((rtime# - .5))
Avintensity#(Count1%) = (Intensity#(Count1%) +
Intensity#(Count1% - 1)) / 2
END IF

CASE ELSE

' ** exponential portion of distribution **
IF Count1% = IterVar% AND Remainder$ = "YES" THEN
  rtime# = D#
  ExpArea#(Count1%) = IA45# / Coeff# * (1 -
(EXP(-(Coeff# * (rtime# - .75))))))
ELSE
  ExpArea#(Count1%) = IA45# / Coeff# * (1 -
(EXP(-(Coeff# * (rtime# - .75))))))
END IF

IF Counter% = 0 THEN
  Counter% = Counter% + 1
  IF (Count1% - 1) * Rainint# < .75 THEN
    PrevIntensity# = (IMax# + ((IA45# - IMax#) / .25) *
((.75 - .5)) + Intensity#(Count1% - 1)) / 2
    Avintensity#(Count1%) = (((ExpArea#(Count1%) * (1 /
(rtime# - .75))) / Rainint#) * (rtime# - .75)) +
((PrevIntensity# / Rainint#) * (.75 - (Rainint# *
(Count1% - 1))))

```

```

ELSE
    Avintensity#(Count1%) = ExpArea#(Count1%)
    * (1 / rtime# - .75)
END IF

ELSE
    Avintensity#(Count1%) = (ExpArea#(Count1%) -
    ExpArea#(Count1% - 1)) * (1 / Rainint#)
END IF

END SELECT

NEXT Count1%

' ** Output of data to file **

FileNum = FREEFILE

OPEN "Disagg.out" FOR OUTPUT AS #FileNum

FOR Count3% = 1 TO (IterVar% - 1)
    Disagg!(Count3%) = Avintensity#(Count3%)
    Disagg!(Count3%) = Disagg!(Count3%) / 1000' **D
    (Converting m to mm)
    PRINT #FileNum, Disagg!(Count3%)
NEXT Count3%

CLOSE #FileNum

END SUB

' *****FUNCTION Func *****
' **This function is used by SUB NewtRaph to solve the **
' **implicit equation to get cumulative infiltration with **

```

```

**time.                                                                 **
*****
FUNCTION Func (C, IA45#, D#, R2#)
Func = IA45# / C * (1 - (EXP(-(C * (D# - .75))))) - R2#
END FUNCTION

SUB NewtRaph (IA45#, D#, R2#, Coeff#)
    C2 = .0001
    CONST Tol = .00000001#
    DO: C1 = C2
    N% = N% + 1
    C2 = C1 - Func(C1, IA45#, D#, R2#) / Diffunc(C1, IA45#,
D#)
    'PRINT N%; "C ="; C2
    output to screen **
LOOP WHILE ABS((C2 - C1) / (C2 + C1)) > Tol AND N% < 100
    IF N% >= 99 THEN PRINT "The Newton-Raphson Equation has
no solution"
Coeff# = C2
END SUB

```

APPENDIX B-3 Computer programme: TP V 6.0 For predicting the soil water availability to meet the crop water requirements.

```
PROGRAM Design_RWH (input,output);
```

```
{This program reads the water reserves in the soil(as soil moisture content), and on daily bases decides wether this amount is sufficient to meet that day's crop water requirement. If not so it calculates the amount of water to be supplied as supplementary irrigation.It calculates size of storage and includes a decision on whether the Catchment area is sufficient. It uses the PARCH-THIRST output data as its input data}
```

```
USES CRT;
```

```
CONST
```

```
MaxD=3; {Max days of season:should be changed according to the crop}
```

```
TYPE
```

```
IRR = ARRAY[1..MaxD] OF real;
```

```
VAR
```

```
Ra,RUNF,ET,SMC,SWATER,AMOUNT:IRR;BD,RaT,D,FC,MinAW,RAM
```

```
,SUM,TOT,STORG,WATS:real;
```

```
result:text;
```

```
value_in:text;
```

```
PROCEDURE pause;
  VAR
    Proceed:char;
  BEGIN
    Writeln;
    Writeln('THIS IS PROGRAM WAS WRITTEN BY KAMUGISHA
            S.S');
    Write('PRESS ENTER KEY TO CONTINUE');
    Readln;
  END;

PROCEDURE calc_RAM(VAR RAM,BD,FC,MinAw:real);
  BEGIN
    Writeln('ENTER SOIL BULK DENSITY IN G/CUB CM');
    Readln(BD);
    Writeln('ENTER CROP ROOT DEPTH IN M');
    Readln(M)
    FC:=(1-2.6/BD)*0.5;
    MinAw:=FC/3;
    RAM:=0.6*D*(FC-MinAw);
  END;

PROCEDURE Calc_SWATER(VARSWATER,Ra,RUNF,ET,SMC:IRR);
                                {calc:daily soil moisture}

  VAR
    Day:integer;
```

```

BEGIN
    SWATER[Day] := 0 ;
    BEGIN
        FOR Day := 2 To MaxD DO
            SWATER[Day] := SWATER [Day] + SMC [Day-1] + Ra
                [Day] + RUNF [Day] - ET [Day] ;
        END;
    END;
PROCEDURE Calc_Amount (VAR Amount, SMC, RUNF, ET, SWATER :
    IRR ; RAM:Real); {calc:water for irrigation}
    VAR
        Day:Integer;
    BEGIN
        AMOUNT [Day] :=0;
        BEGIN
            FOR Day:= 1 TO MaxD DO
                AMOUNT [Day] := (ET [Day] -Ra [Day] -RUNF [Day] + ((0.6*RAM) -
                    (SMC [Day] ))) /0.8;
            END;
        BEGIN
            FOR Day:=1 TO MaxD DO
                IF (AMOUNT [Day] <0) THEN
                    AMOUNT [Day] :=0
                ELSE

```

```
        AMOUNT [Day] :=AMOUNT [Day]
    END;
END;
PROCEDURE Calc_STORG ( VAR STORG: real; AMOUNT:IRR);
    VAR
    Day:integer;
    BEGIN
        STORG:=0;
        BEGIN
            FOR Day:=1 To (MaxD) DO
                STORG:=STORG + AMOUNT [Day];
            END;
        END;
END;
PROCEDURE Calc_TOT(VAR TOT:real;RUNF,AMOUNT:IRR);
    {calc:total water harvested}
    VAR
    Day:integer;
    BEGIN
        TOT:=0;
        BEGIN
            FOR Day:=1 to (MaxD) DO
                TOT:= TOT + RUNF [Day] + AMOUNT [Day];
            END;
        END;
END;
```

```
PROCEDURE Calc_SUM(VAR SUM:Real;ET:IRR);{calc:total
                                ETcrop}
```

```
VAR
```

```
Day:integer;
```

```
BEGIN
```

```
    SUM:=0;
```

```
    BEGIN
```

```
        FOR Day:=1 TO MaxD DO
```

```
            SUM:=SUM + ET[Day];
```

```
        END;
```

```
    END;
```

```
PROCEDURE Calc_Rat(VAR RaT:real;Ra:IRR);{calc:total rain}
```

```
VAR
```

```
Day:integer;
```

```
BEGIN
```

```
    RaT:=0;
```

```
    BEGIN
```

```
        FOR Day:=1 TO MaxD DO
```

```
            RaT:=RaT + Ra[Day];
```

```
        END;
```

```
    END;
```

```
PROCEDURE calc_WATS (VAR WATS, RaT, TOT: real);
    BEGIN
        WATS := Rat + TOT
    END;

PROCEDURE Read_data (VAR Ra, RUNF, ET, SMC: IRR);
    VAR
        Day: integer;
        Value_in: text;
    BEGIN
        ASSIGN(Value_in, 'a:\Value.Pas');
        RESET(Value_in);
        FOR Day := 1 TO MaxD DO
            Read value_in, Ra[Day], RUNF[Day], ET[Day], SMC[Day];
        CLOSE(Value_in)
    END;

PROCEDURE Write_Result (Ra, RUNF, ET, SMC, SWATER,
    AMOUNT: IRR; RaT, TOT, STORG, WATS: real);
    VAR
        Day: integer;
        Result: text;
    BEGIN
        Window (6, 10, 75, 40);
        ASSIGN(result, 'a:\output1.pas');
        REWRITE(result);
```

```

        Writeln(result,' SUMMARY OF THE DESIGN');
Writeln(result,'=====');
        Writeln(result,'day','Ra (mm) ':14,'RUNF (mm) ':14,'SWATER
        (mm) ':15,'AMOUNT (mm) ':17{,'TOT (mm) ':12});
Writeln(result,'=====');
        Writeln(result); FOR Day:=1 TO MaxD DO
        Writeln(result,Day, Ra [Day]:14:2, RUNF [Day]:14:2,
        SWATER [Day]:15:2, AMOUNT [Day]:17:2{,TOT [day]:13:2});
        Writeln(result);
Writeln(result,'=====');
        Writeln(result);
        Writeln(result,'TOTAL RAIN WATER IS-----',RaT:6:2);
        Writeln(result,'TOTAL WATER HARVESTED IS---',TOT:6:2);
        Writeln(result,'TOTAL EVAPOTRANSPIRATION IS',SUM:6:2);
        Writeln(result,'WATER FOR STORAGE IS-----',STORG:6:2);
        writeln(result,'TOTAL WATER SUPPLY IS---',WATS:6:2);
        Writeln(result,'IF TOTAL EVAPOTRANSPIRATION IS GREATER
        THAN TOTAL WATERSUPPLY');
        Writeln(result,'INCREASE CATCHMENT SIZE AND GO BACK
        TO PARCH-THIRST MODEL');
        CLOSE(result)
    END;
PROCEDURE alert;
    BEGIN

```

```

clrscr;

writeln;writeln;

writeln('1.':10,'    PROGRAM EXECUTION HAS BEGUN');

writeln;

writeln('2.':10,'BE SURE TO HAVE MADE THE
FOLLOWING:');

writeln;

writeln('a)':12,' TO HAVE DATA IN DATA FILE CALLED
data');

writeln;

        writeln('b)':12,' TO HAVE ARRANGED DATA AS          FOLL
                                                OWS:
                                                ');

writeln('          ',' Ra          ','RUNF          ','ET
','SMC          ');

writeln;

writeln('c)':12,' TO HAVE ENTERED MAXIMUM SEASON DAYS
(MaxD)');

writeln;

        writeln('3.':10,' THE RESULTS ARE IN FILE OUTPUT1');

writeln;

pause

END;

BEGIN

```

```
alert;
read_data (Ra, RUNF, ET, SMC);
calc_swater (swater, Ra, RUNF, ET, SMC);
calc_RAM (Ram, BD, FC, MinAw);
calc_amount (Amount, Ra, RUNF, ET, SMC, RAM);
calc_TOT (TOT, RUNF, AMOUNT);
calc_SUM (SUM, ET);
calc_RaT (RaT, Ra);
Calc_STORG (STORG, AMOUNT);
calc_WATS (WATS, RaT, TOT);
write_result ( Ra, RUNF, ET, SMC, SWATER, AMOUNT, RaT,
              TOT, STORG, WATS);
PAUSE;
END.
```

APPENDIX B 4: Summary of the output of the soil water
availability programm

Predicted soil moisture , Amount of water to be applied to
the crop, and size of storage.

Ra(mm) = Rainfall, RUNF(mm) = Runoff, Etcrop(mm) = Crop
evapotranspiration, Amount(mm) = Amount of water to be
applied.

SUMMARY OF THE OUTPUT

day	Ra (mm)	RUNF (mm)	Etcrop (mm)	AMOUNT (mm)
1	0.00	0.00	2.60	0.00
2	0.00	0.00	2.22	1.70
3	0.00	0.00	2.70	0.00
4	11.70	0.40	1.80	0.00
5	2.10	0.00	1.80	0.00
6	0.00	0.00	2.30	0.00
7	0.00	0.00	2.10	0.00
8	21.40	0.20	1.90	0.00
9	1.10	0.00	1.70	0.00
10	4.70	0.60	1.80	0.00
11	19.20	1.20	1.80	0.00
12	4.10	0.40	1.80	0.00
13	0.00	0.00	1.60	0.00
14	0.10	0.00	2.20	0.00
15	0.70	0.00	2.10	0.00
16	3.40	0.10	1.30	0.00
17	2.40	0.10	1.40	0.00
18	26.50	1.00	1.60	0.00
19	0.00	0.00	2.10	0.00
20	0.70	0.00	2.90	0.00
21	0.00	0.00	5.30	0.00
22	0.00	0.00	4.60	0.00
23	0.00	0.00	5.30	0.00
24	0.00	0.00	4.20	0.00
25	0.00	0.00	5.00	0.00
26	20.80	1.60	3.40	0.00
27	0.20	0.00	5.80	0.00
28	0.00	0.00	4.30	0.00
29	0.00	0.00	4.30	0.00

30	0.00	0.00	4.80	0.00
31	0.00	0.00	4.80	0.00
32	0.00	0.00	4.70	0.00
33	0.10	0.00	5.00	0.00
34	0.00	0.00	4.20	0.00
35	0.00	0.00	3.90	3.50
36	8.50	0.70	3.00	0.00
37	0.00	0.00	2.80	0.00
38	3.60	0.00	3.20	0.00
39	21.00	1.20	3.30	0.00
40	0.50	0.00	3.00	0.00
41	1.40	0.10	3.60	0.00
42	5.30	0.10	3.10	0.00
43	12.40	0.50	3.00	0.00
44	5.80	0.30	2.10	0.00
45	0.00	0.00	2.80	0.00
46	5.30	0.90	2.90	0.00
47	0.60	0.00	2.80	0.00
48	10.80	0.00	2.80	0.00
49	2.80	0.80	3.20	0.00
50	7.00	1.00	2.70	0.00
51	2.10	0.00	4.00	0.00
52	0.00	0.00	5.30	0.00
53	8.90	1.10	4.60	0.00
54	1.00	0.00	5.10	0.00
55	0.00	0.00	4.80	0.00
56	0.00	0.00	4.30	0.00
57	0.00	0.00	4.40	0.00
58	0.00	0.00	5.80	0.00
59	0.70	0.10	4.70	0.00
60	8.10	0.30	5.40	0.00
61	0.30	0.00	5.30	0.00
62	7.50	0.00	4.20	0.00
63	14.20	0.70	3.70	0.00
64	1.10	8.00	3.50	0.00
65	1.70	0.20	4.70	0.00
66	13.00	1.10	4.00	0.00
67	0.30	0.00	4.70	0.00
68	0.00	0.00	4.30	0.00
69	0.00	0.00	5.40	0.00
70	0.00	0.00	5.70	0.00
71	0.00	0.00	5.70	0.00
72	0.00	0.00	5.40	0.00
73	3.00	0.00	4.80	0.00
74	0.00	0.00	5.00	0.00
75	0.00	0.00	5.00	0.00
76	0.00	0.00	4.90	0.00
77	11.80	0.20	4.40	0.00

78	0.00	0.00	4.80	0.00
79	0.00	0.00	4.10	0.00
80	0.50	0.00	4.50	0.00
81	0.00	0.00	4.30	0.00
82	0.30	1.00	3.40	0.00
83	1.10	0.00	3.80	0.00
84	0.00	0.00	4.80	0.00
85	0.20	0.00	5.10	0.00
86	5.30	0.00	4.80	0.00
87	0.00	0.00	6.00	0.00
88	0.00	0.00	5.30	4.90
89	1.30	0.00	5.40	3.90
90	0.10	0.00	4.80	4.40
91	1.60	0.10	3.80	2.00
92	0.00	0.00	5.30	5.10
93	0.00	0.00	5.10	5.00
94	0.00	0.00	4.50	4.30
95	1.80	0.00	4.30	2.40
96	0.00	0.00	4.80	4.70
97	0.00	0.00	4.50	4.30
98	0.00	0.00	5.90	6.00
99	0.00	0.00	4.70	4.50
100	0.00	0.00	5.00	5.00
101	4.00	0.00	4.20	6.90
102	2.50	0.00	4.10	9.00
103	5.20	7.90	5.80	0.00
104	5.90	0.60	5.40	0.00
105	2.50	0.50	5.00	0.00
106	0.20	0.00	5.10	0.00
107	0.00	0.00	5.60	0.00
108	0.90	0.00	5.40	0.00
109	0.10	0.00	5.30	0.00
110	0.10	0.00	5.20	0.00
111	2.80	0.00	3.70	0.00
112	0.70	0.00	5.30	0.00
113	0.70	0.90	5.40	0.00
114	21.30	0.00	3.50	0.00
115	6.00	0.00	4.00	0.00
116	4.60	0.30	7.80	0.00
117	27.00	0.10	3.80	0.00
118	0.50	0.00	4.70	0.00
119	0.00	0.00	3.70	0.00
120	0.00	0.00	3.80	0.00
121	0.00	0.00	3.50	0.00

=====
TOTAL RAIN WATER (mm) -----375.10
TOTAL WATER HARVESTED (mm) ----- 98.10

TOTAL EVAPOTRANSPIRATION (mm)-----492.00
TOTAL WATER SUPPLY (mm)-----473.20

IF TOTAL EVAPOTRANSPIRATION IS GREATER THAN TOTAL WATER
SUPPLY
INCREASE CATCHMENT SIZE AND GO BACK TO PARCH-THIRST MODEL
=====

APPENDIX C-1: Calculation of Saturated deficit(Kpa) and the Irradiance(MJ)

Saturation deficit (SD) data is one of the most difficult data to obtain at a site, but is also very important for calculations of water limitation within PARCH. Below is the formula used to obtain an estimate of saturation deficit using maximum and minimum Temperatures.

$$SD(K) = 0.75 * (VX - VN) / 10 \text{ 'MBar} \Rightarrow \text{'Convert temperature to Sat. Def.}$$

$$VN = 6.107 * EXP(17.269 * MinTemp(K) / (273.3 + MinTemp(K)))$$

$$VX = 6.107 * EXP(17.269 * MinTemp(K) / (273.3 + MinTemp(K)))$$

Light energy within PARCH is treated as total radiation. The expected unit of input for irradiance is MJm⁻²day⁻¹. Only sunshine hours were available for Hombolo and the following equation was used:

$$Rs = Ra (a1 + a2 * n/N)$$

Where: Ra is the extra-terrestrial radiation or Angot value,

a1 and a2 are site specific Angstrong

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coefficients,

n is the recorded number of sunshine hours, and
 N is the site specific maximum sunshine hours.

For Hombolo the following formula was used:

$$S(MJ) = 37 * (.25 + (.5 * S(Hours)/11.5))$$

APPENDIX C-2: Example of a Weather file

Rainfall (mm)	PANevap (mm)	TempMax (°C)	TempMin (°C)	Sat.Deficit (Kpa)	Irrad. (MJ)
0.0	12.5	35.5	21.5	1.7	28.1
0.0	10.0	35.8	22.9	1.6	25.0
0.0	11.6	35.2	22.0	1.6	23.3
35.1	6.2	35.0	18.6	0.6	23.6
6.2	3.0	25.7	18.6	0.6	10.8
0.0	5.5	30.0	20.9	1.0	17.9
0.0	6.5	30.1	21.1	1.0	13.7
63.0	3.2	25.6	18.5	0.6	11.4
3.2	2.8	25.0	20.9	0.4	11.1
13.8	4.1	20.9	21.1	0.1	9.3
57.1	3.7	28.5	18.5	1.0	15.6
12.2	4.0	29.5	18.5	1.7	28.4
0.0	5.7	32.0	20.0	1.3	25.7
0.2	9.5	33.8	18.5	1.7	28.4
0.0	5.1	32.4	19.0	1.4	26.1
10.1	1.4	23.3	20.0	0.3	9.3
6.4	4.0	26.7	19.5	0.7	10.3
24.0	5.0	30.4	20.5	1.1	24.5
0.0	8.0	30.7	19.1	1.2	26.4
0.0	6.5	31.0	19.1	1.3	27.4
0.0	10.0	31.9	18.9	1.4	27.8
0.0	8.0	31.7	19.5	1.3	27.3
0.0	9.5	30.8	20.0	1.1	27.9
0.0	5.0	31.7	19.9	1.3	24.4
0.0	9.9	30.9	19.2	1.2	24.2
62.4	6.5	29.0	20.0	0.9	26.1
0.0	13.0	30.0	20.5	1.0	25.6
0.0	2.0	26.5	19.4	0.7	9.3
0.0	4.0	28.7	19.0	1.0	15.9
7.0	10.0	29.5	19.5	1.0	24.1
,	,	,	,	,	,
,	,	,	,	,	,
,	,	,	,	,	,
,	,	,	,	,	,

up to the end of the year.

APPENDIX C-3 Example of an irrigation file.

HOMBOLO 1995 Cult. 65D RWH - Irrigated

26	
2	01.70
22	01.00
35	03.50
26	02.01
57	00.50
70	02.60
73	06.40
81	04.02
88	04.90
89	03.90
90	04.40
91	02.00
92	05.10
93	05.00
94	04.30
95	02.40
96	04.70
97	04.30
98	06.00
99	04.50
100	05.00
101	06.90
102	09.00
109	03.60
112	03.02
121	00.12

Irrigation File

=====

The above consists of Title & Irrigation.

The actual data is :-

NIRRigations followed by :

Days After Planting, IRRigation in mm.