SOKOINE UNIVERSITY OF AGRICULTURE

FACULTY OF AGRICULTURE

DEPARTMENT OF AGRICULTURAL ENGINEERING

AND LAND PLANNING

ADOPTION OF MODIFIED PANDEY BIOECONOMIC MODEL FOR EVALUATING THE ECONOMIC FEASIBILITY OF RAIN WATER HARVESTING (RWH) FOR SUPPLEMENTARY IRRIGATION IN SEMI-ARID AREAS OF TANZANIA

By

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ABSTRACT

A weather driven simulation model was developed to evaluate the economic feasibility of rain water harvesting (RWH) in the farming system. The biophysical parameters were incorporated with the economic parameters to determine the net benefits of RWH system to a farmer.

The model is composed of the biophysical component which consists of the following submodels, rainfall-runoff , soil water balance, evapotranspiration ,and the economic submodel which consists of the input-output prices relationship component. When the two components were incorporated, they facilitated decision making regarding the prospects of RWH technology of reference.

The model was calibrated using historical climatic data obtained from meteorological stations at experimental site.The data collected were for three seasons (1991/92-1994/95). The model validation was performed by correlating observed and predicted data. The observed data were obtained from the field trials and historical data, while the predicted data were estimated using the simulation model.

A regression analysis was applied to test the performance of the model. A 1:1 graph was produced in which a straight line passing through the origin was fitted to the data. A perfect prediction would lead all points lying along 45^0 line passing through the origin to a correlation coefficient of 1. The slope of the regression line was taken as a correlation factor for calibrating the predicted data.

The model revealed that, the returns accrued to the resources invested could be recovered, particularly in years proceeding the initial year of investment. This is because the storage tank is a long term asset which generates a stream of benefits for several years in future. This can be reflected by the high yield harvested under RWH storage, comparing with the yield produced without RWH storage. Whereas the yields produced under catchment area ratio (CA:CF) of 4:1 and 2:1 with RWH storage were 3.92 and 2.53 t/ha respectively, the yields produced under catchment area ratio (CA:CF) of 4:1 and 2:1 without RWH storage were 1.92 and 2.4 t/ha respectively.

Basing on the findings of one growing season data, it is shown that RWH system could be a break through to the long term problem of erratic and unreliable rainfall in semi–arid areas of Tanzania. In view of this, it is recommended that RWH techniques be advocated for adopting by a smallholder farmers in Tanzania.

DECLARATION

I, **THEOBALD NYATANYI MASHINGA**, 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 at any other University.

Signature...

Date 4/11/1996

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DEDICATION

This dissertation is dedicated to my beloved wife Dianna, our son Alphonce Rugamba, nephews, nieces, advocate S.K. Safari and V. Ndyetabula and family. May God bless you.

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INTRODUCTION

1.1 Background

Tanzania which has a population estimated at 23.2 million people, and a land area of 886,000 km^2 is and will probably continue to depend on rainfed agriculture for the foreseeable future given the pace of development of her economy (LDC,1987).

Agriculture accounts for half of the country's gross national product, about 80 percent of recorded export earnings, and 90 percent of rural employment. (Msambichaka, et al.,1983). However, agriculture in Tanzania is greatly dependent on climatic conditions which vary enormously within the country (Fig.1). This aspect is reflected by the fact that land with a combination of adequate soil fertility and adequate rainfall is limited to less than 10% of the total area of Tanzania. About 80 percent of Tanzania receives less than 100mm of seasonal and unreliable rainfall. Further to this, only 22 percent of the land receives 570mm, or more in 9 years out of 10 years, and nearly throughout the country, potential evapotranspiration exceeds rainfall during more than nine months of the year. It is also estimated that, only 5 percent (7 million ha) of the total land area is under cultivation of which 14 percent is occupied by permanent crops (Hatibu et al., 1993).

Thus, the agricultural potential limitation can be largely attributed to the combination of low soil fertility, low and erratic rainfall, as well as low level of technology. Consequently the potential for lateral agriculture expansion to meet the food security needs of a population growing at 3 percent annually has become unattainable. Msambichaka et al. (1983) underscore the effect of these constraints in their report which indicates that agriculture grew rapidly in the 1960s, stagnated in the 1970s and early 1980s, leading to an inability for the country to sustain food self sufficiency and increased foreign exchange earnings. Although these shortfalls may be attributed to many factors in addition to the ones mentioned above, the erratic and unreliable rainfall has been singled out to be the most outstanding obstacle to agricultural production, especially in the semi-arid areas of Tanzania (Ngana, 1983; Hatibu et al., 1993)

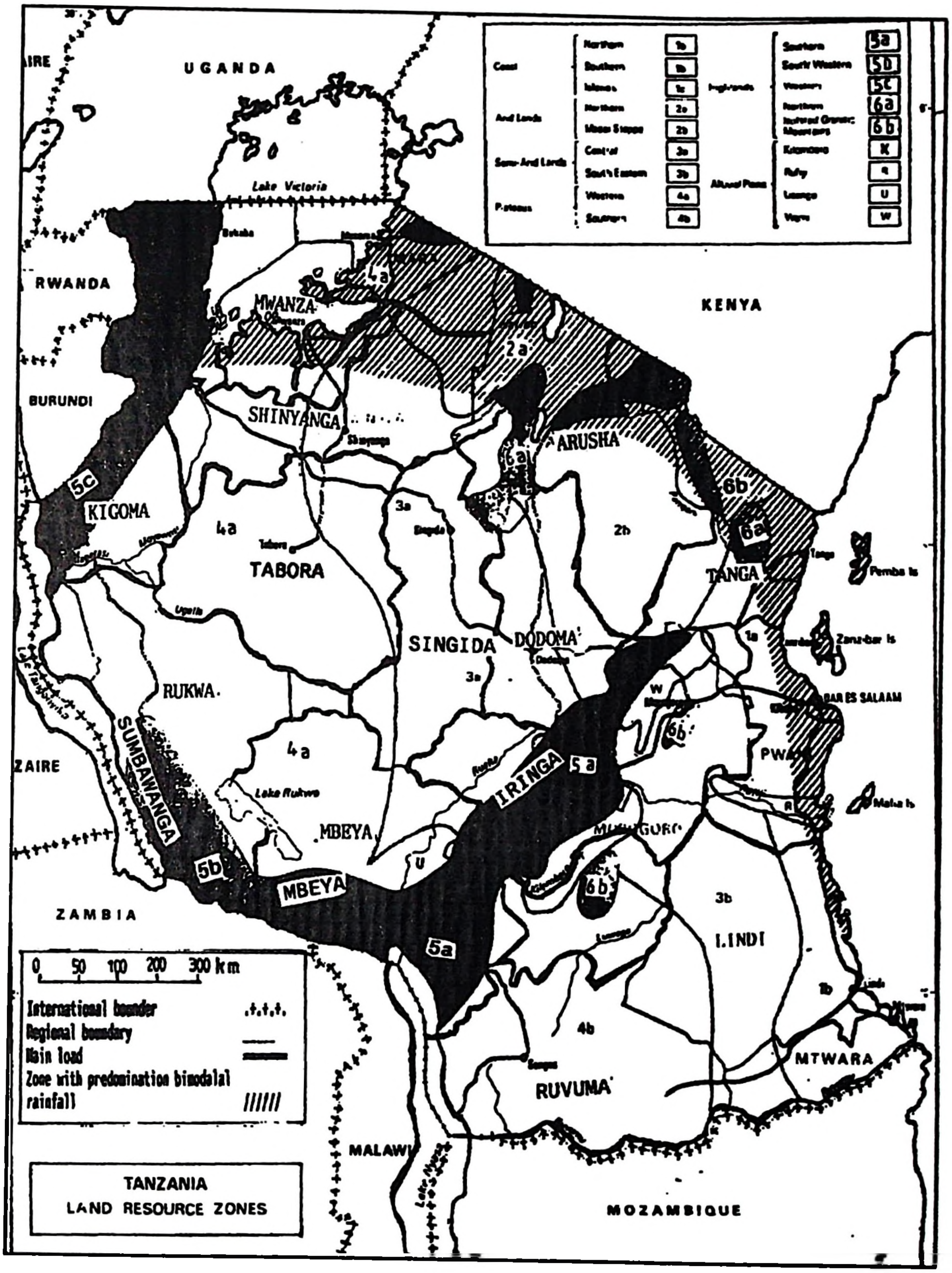

Figure 1: Tanzania, classification of agro-ecological zones.

Source: Land Resources Development (1987)

The semi-arid areas are characterised by low but highly variable rainfall patterns. Pandey (1991) reported that due to high variabilities of rainfall in semi-arid tropics, rainfall figures are of little use for crop planning purposes. A high variability means that there can be a prolonged dry spell even during the rainy season, which is the characteristic of semi-arid areas of Tanzania. Another characteristics of rainfall in the semi-arid areas is that most of it, is received in a few high intensity storms.

Rainfall intensities of 20 to 60 mm/hr are common but intensities as high as 160mm/hr have been reported (Pandey, 1991). If the threshold value at which rainfall becomes erosive is 25mm/hr (Hudson, 1981a),these high intensity rainfalls means substantial soil erosion and the loss of much water as surface run-off.

Thus, since rainfall is a constraint to successful agricultural production, it is crucial that every effort be made to conserve and efficiently utilise the scarce rain water. This requires improved soil water management techniques that maximises holding capacity of water in the soil, coupled with cultural practices which ensure the most optimum use of the available soil water by crops.

A great deal of intervention techniques geared towards these harsh agroclimatic situations have been developed in Tanzania and indeed in the world at large. Irrigation, which has been seen in the past as a universal panacea against unreliable rainfall, has however proved unworkable in semi-arid areas. Its applicability has been limited mainly by non availability of perennial sources of water. Besides, the cost of development of an irrigation project which ranges between 15,000 - 20,000 U$/ha is out of reach for most farmers in semi-arid areas of Tanzania (Hatibu et al., 1993). Field bunds have been used to keep run-off within bounded fields and this is mostly done on trial and error basis (Mwakalila,1992). Recently, improved RWH technique trials have been conducted in Hombolo (Dodoma district), Kisangara (Mwanga district), Shinyanga, and Mwanza regions. Majority of these intervention techniques have shown to be promising.

The potentiality of the RWH technique is supported by the report of Von oppen and Ryan (1975).The report indicates that, one of the elements in the design of improved soil water management technologies for the semi-arid tropics (SAT) is the concept of harvesting excess run-off from small agricultural watershed.The run-off is collected into water storage reservoir, for subsequent use during critical growth stages of crops, in years with poorly distributed rainfall. This fact highlights the growing interest and importance attached to this technique in other parts of the world.

Rain water harvesting (RWH) technique offer several advantages among which are; maximises soil water availability to the crops as a result of each rainfall event; optimises crop yield per unit of this available soil water resource; maximises yields in the normal rainfall years; and stabilizes crop production (Hatibu et al.,1993).

Better management of rain water where it falls does not only enhance crop production, but also protect the environment. This is because poor management allows wasteful run-off to occur causing erosion, downstream flooding and siltation. Soil water management in semi-arid areas, is therefore not only vital in enhancing plant production,but also a generator of households income of resource poor inhabitants of these areas and protecting the land against degradation caused by erosion.

Thus, successful application of RWH technique in areas prone to erratic and unreliable rainfall may be an important technological break through to the long standing problem of trial and error planting period in the semi-arid areas of Tanzania.

1.2 Definition and classification

Rainwater harvesting has been defined by various authors as the process of collecting water from prepared catchments for beneficial use (Fraiser, 1975; Pandey, 1991; Laryea, 1992). Although there have been several other definitions, all of them indicate two common components:

(a) Collection of water from catchment where run-off is induced and collected.

(b) Storage of water for future use,where water will be collected and used in cropped field (CF).

Run-off may also be applied directly to the cropped field and thus stored in the root zone. Run-off from catchment may be induced either by changing the configuration of the surface of catchment or by physical and chemical treatment of the soil. RWH is therefore restricted to induction, collection, storage, and usage of run-off from local rainfall (Fraiser, 1975; Matlock and Dutt, 1986; Pandey, 1991). Critchley et al. (1992) reported that, RWH for crop production can be classified into about 8 categories as shown in Figure. 1.1.

Although RWH technology in the agrosystems of Tanzania is still in its infancy stage, the technology is becoming familiar to the local community. There is therefore a great need to justify its feasibility in the country. The best way to do that is through economic evaluation. The essence of economic evaluation among others, looks at the additional returns on invested resources to determine if the prospective investment is attractive for adoption by the beneficiaries.

Thus, if the technology of RWH is to be adopted as a tool to manage the scarce rainfall in Tanzania, there is therefore a need to evaluate the economics of RWH technology to determine its expected net benefit.

Similar studies have been conducted in India (Fig.1.2 and Fig.1.3). One of the outstanding studies, is the study by Pandey (1991) in

Raisen district, Madhya Pradesh, India. He applied a modelling approach technique to evaluate the economic feasibility of water harvesting and supplementary irrigation technique in the semi-arid tropics of India. This weather-driven based bioeconomic simulation model is structured around the biophysical and economic components. The biophysical component consists of submodels describing the rainfall - runoff relationship, the soil water balance, yield response and the rainfall and pan evaporation predictor. The economic component consists of submodels for the determination of the economic feasibility of RWH technology.

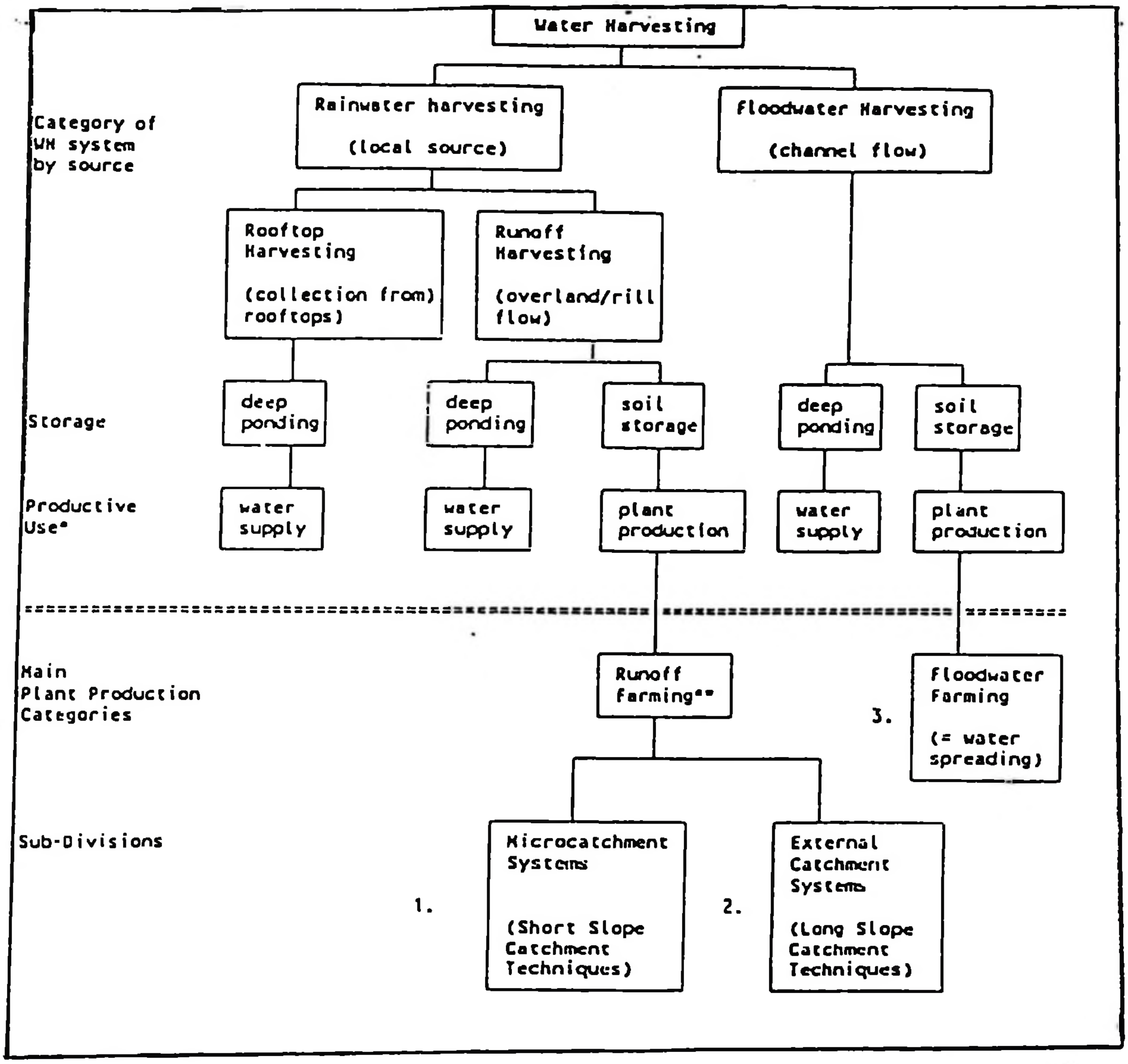

Figure 1.1: Classification of rain water harvesting techniques

Source: Reij et al.(1988)

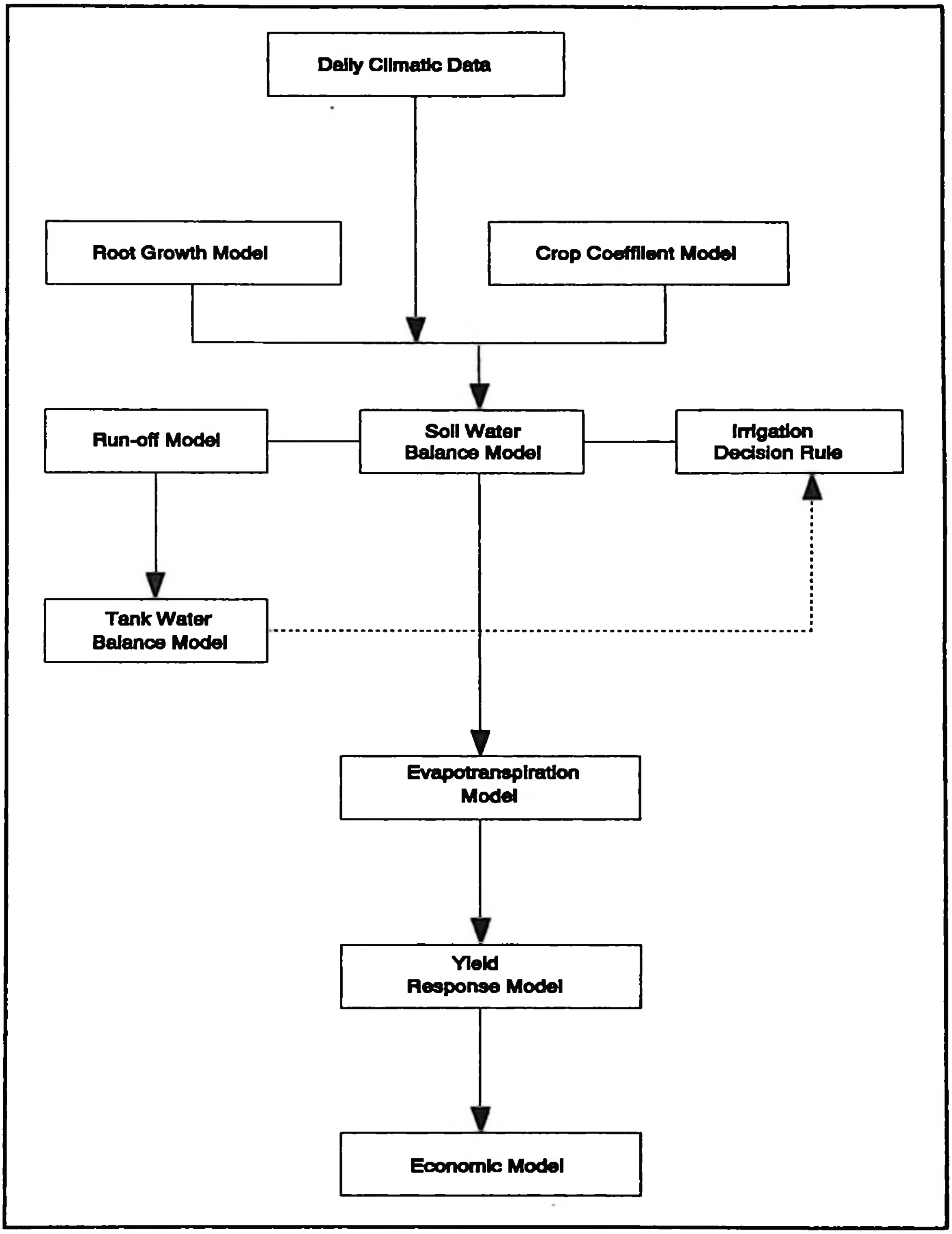

Figure 1.2: Schematic flow diagram of the simulation model

Source: Pandey (1991)

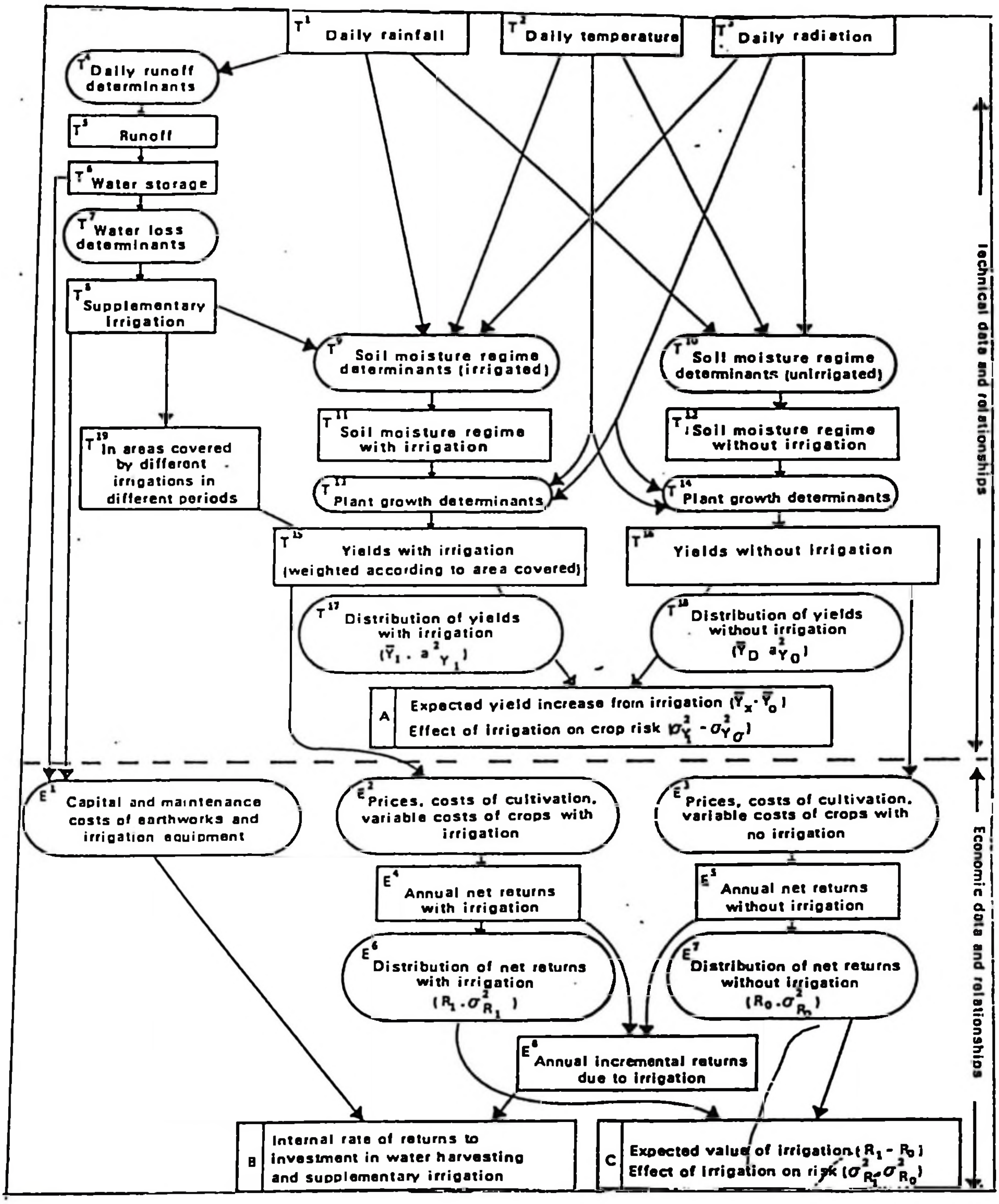

Figure 1.3: Simulation model of returns from water harvesting and supplementary irrigation.

Source: Ryan and Pereira(1978)

Using the systems approach the critical parameters identified were the probability of a successful dry season crop without irrigation and the seepage rate.

The RWH system visualised in this study (Fig. 1.4) is based on the above model, however, there are slight modifications necessitated by both time and resource factors. The differences are found in the number of parameters. The model used in this study is subdivided into five distinct parts:

(a) Climatic variables submodel
(b) Runoff submodel
(c) Soil moisture submodel
(d) Crop growth and yield submodel
(e) Economic Submodel

The main aim of RWH is to improve the reliability of yield in semi-arid areas, and therefore to assess the long-term effects of RWH, long sequences of weather data are needed. These climatic variables are used to drive the bio-physical simulation model.

Regarding the run-off submodel, it accounts for the generated amount of water from catchment area which subsequently is used in the corresponding cropped field during the critical growth stages in years with poorly distributed rainfall.

With respect to soil moisture balance submodel, this is necessary for predicting evapotranspiration, because evapotranspiration is a function among others of the soil moisture content. The soil water balance submodel quantifies both the amount of soil moisture storage available in the cropped area and the rate of its availability to the crop . Consequently this determines the amount of run-off to be irrigated. The soil moisture content must, therefore, be updated daily.

The crop growth and yield submodel provides the information regarding the effect of moisture stress on yield during the growth cycle of the plant. Hence, the crop growth and yield submodel is used to simulate crop growth as affected by water. This involves estimating the actual evapotranspiration and potential evapotranspiration for each growth phase (or irrigation interval) and the resultant yield. The moisture stress during various growth phases are estimated by simulating the soil water balance.

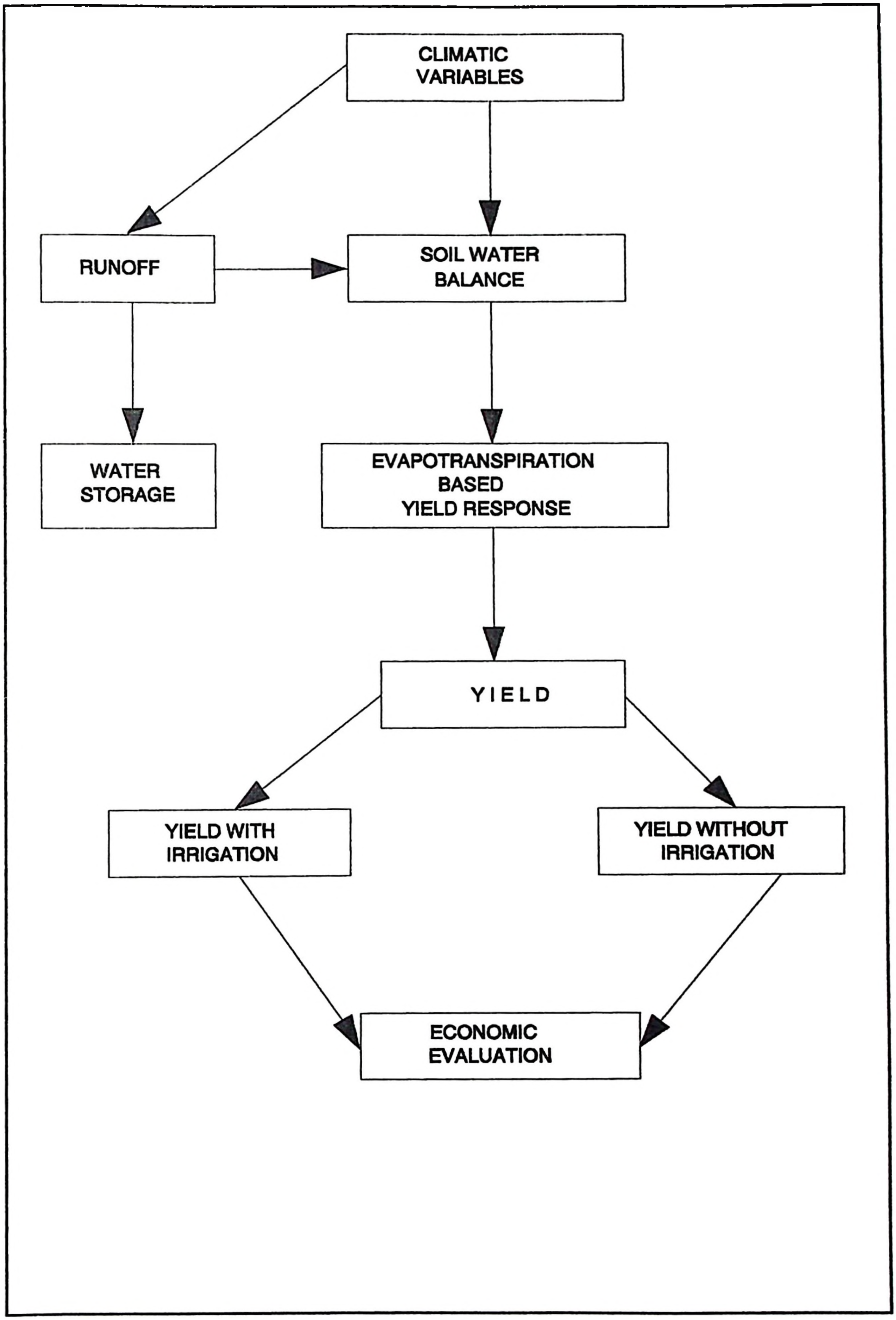

Figure 1.4: Simulation model of returns from RWH system.

The rainfall – runoff relationship submodel linked with soil water balance and crop growth and yield submodel, form the biophysical component of the overall model.

In an experimental undertaking, the biophysical simulation model driven by stochastic climatic variables is developed to predict additional gains derived from water application (irrigation), while the economic submodel is used to estimate benefits of with and without RWH storage situations. This involves calculating net benefits with and without storage situation for each year. These values are then discounted at an appropriate rate to obtain a measure of net worth of the investment activity in present value terms.

Thus, the economic results are incorporated with biophysical component in a decision making model for estimating the economic feasibility of RWH system under consideration.

1.3 Importance of assessment of technology

New technologies are designed with the objective of contributing to social goals. Hence evaluation is necessary to judge whether the effects of a new technology is consistent with social objectives. Bearing this in mind, the evaluation of economic feasibility of RWH conducted in this study is aimed at assessing the prospective technology on experimental cropped fields under consideration. Studies on RWH farming system otherwise known as run-off farming have been conducted in various parts of the world, including Tanzania though at rudimentary level (Mwakalila, 1992). Their overall objective is to ameliorate the effects of drought and aim at improving plant production (Critchley et al.,1991; Laryea,1992; Hatibu and Simalenga, 1993). Similarly, studies on the evaluation of economic feasibility of RWH through systems modelling approach have been conducted in India (Ryan and Pereira, 1980; Pandey, 1991).

The rationale for a system approach lies in the fact that, whenever various components are interacting, the behaviour of the system cannot be deduced by simply aggregating the behaviour of various components. Instead, the whole of the collection of components must be studied as a system (Pandey, 1991).

Tanzania seems to have not paid much attention to this kind of study. RWH system is being adopted as an agrosystem and that, it is geared to alleviate the long term harsh agroclimatic problem in semi-arid areas in the country. The promoters of the technology need not only to convince the would be beneficiaries the advantages that can be accrued to the adaptation of the promising technology, but also to the policy makers, so as to integrate the technology into the national agricultural development policy. The conviction can be achieved through establishing economic viability of this technology. It is for this reason that the present study was undertaken.

1.4 Objectives

The main objective of this study, was to assess the applicability of a modified weather driven bioeconomic model developed in India and to determine its adaptability to the local condition in semi-arid areas of Tanzania. The specific objectives were:

(i) To develop predictive model based on climatic variables and soil type capable of predicting run-off, soil moisture, and hence be able to determine evapotranspiration based yield response to water.

(ii) To validate the structured model for evaluating the economic feasibility of RWH.

(iii) To determine the net benefits expected from RWH system under consideration.

2. LITERATURE REVIEW

Reports on rain water harvesting for agricultural and livestock purposes and human consumption covering areas in semi-arid regions date as far back as the first half of bronze age (Von Oppen,1975). Archaeological evidence shows that rain water harvesting systems were used in the Middle East by the ancient Israelites, Nabaleans, Romans and Byzantines (Evanari et al., 1971).
It is currently practised in different forms in semi-arid regions of Middle East, India, Australia, Central and North America, and sub-Saharan Africa, (Pandey, 1991).

Some parts of the semi-arid area, particularly semi-arid tropics of India have long history of rain-water harvesting. The reconstruction of ancient water harvesting systems in the northern Negev since the late 1950's, gave rise to intensive agro-hydrological and agronomic studies of mainly micro-catchments and their optimization during the last decades. This work has provided an enormous impetus to rain water harvesting research in the USA, India, and other countries, particularly in sub-Saharan Africa, where the method called macro-catchments water harvesting was developed at the beginning of the early 1980s (Evanari et al., 1971).

In the drought-prone areas of India, the traditional solution has been to collect run-off in reservoirs called tanks. Large bunds were built as early as the 15th century in India, to store run-off from the rocky catchments in Jaisalmer district of west Rajastan, located in the Thar desert and receives an average rainfall of only 167mm.

Since 1975, considerable research on rain water harvesting has been undertaken in India, notably at the Centre for arid zone studies in Jodpur and by International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Hyderabad. While the research in Jodpur focused on the size and shape of the catchments and yield of run-off, ICRISAT's farming systems research programme aimed at the development of improved method of soil, water and crop management (Von Oppen and Ryan, 1987). In Australia, collection systems of greatest importance are those in which run-off from one or more of a variety of catchment types is stored in an excavated earth tank. These farm "dams" or reservoirs are of similar design and construction to those used in reservoirs for subsequent use by either sheep or cattle.

Early efforts in water harvesting at the US Water Conservation laboratory were directed primarily at supplying water for livestock on rangelands. The research, however, was further extended to crop production (Fink and Ehrler, 1980). Various researches on water harvesting techniques have been conducted in U.S.A among which are; evaluation of various type of treatments for catchments and storage reservoirs; reduction of seepage and evaporation from reservoirs.

Early research in Mexico, used a run-off area to root area ratio to determine the optimum size of micro-basins. However, the ratio was based on empirical assumptions about the best ratio, not on scientifically generated data (Evanari et al., 1971). A study done in Mexico in 1977/78 season on in-situ water harvesting led to the formation of an equation for estimating the size of microbasins based on root size, run-off coefficient, crop consumptive use, and precipitation during the vegetative cycle (Anaya , 1981) :

$$D = D_r + \frac{(C-P)\,D_r}{kP} \qquad (2)$$

where:

D = Micro-basin area (equals the distance between rows in cm).

Dr = Root area(corresponds to the diameter in cm of planting zone for row crops).

K = Soil run-off coefficient.

C = Consumptive use.

P = Precipitation based on 50% probability.

In Africa, a number of climate related projects established in the 1980s have included a rain water harvesting component, underlying the growing interest and realization of the importance of the technology.

In West Africa, the drop in annual rainfall since the late 1960s have caused emphasis to shift from simple soil conservation towards moisture conservation and water harvesting. In Burkina Faso, in the Yatenga province, an agro-forest project has developed and popularized contour stone bunding for water harvesting, the Hausa in Niger use rock bunds and small weirs using sticks, stalks and earth to direct water to cropped fields (Reij, 1988; Lameck, 1994).

Sudan has probably the most extensive and diverse heritage of traditional water harvesting and water spreading of any country in Sub-Saharan Africa. The system range from the utilization of" Wadi" flow by bunding within flood plains, variation of which can be seen throughout the semi-desert areas, to small scale, "tras" construction in the eastern plains (Pacey et al., 1986).

In Southern Africa, little or no traditional small-scale RWH system for plant production is known. It is only recently that the department of research and specialist services in Zimbabwe have begun experimentation with various techniques. At Matopos, the research station trials on RWH treatments for rangelands rehabilitation, and at Chiredzi research station, small scale water concentration techniques based on ridging are being tested (Lameck,1994).

In Eastern Africa, reports indicate that, semi-circular hoops water harvesting techniques were used in Turkana, Baringo and Kitui districts in Kenya, for improving regeneration of grass or fodder species in dry areas. These hoops were semi-octagon in shape, bund length was 46m impounding an area of approximately 300m^2,and the slope ranged from 0.5% to 2% (Finkel, 1984; Lameck, 1994). Mwakalila (1992) reported that, in Tanzania, farmers are practising rain water harvesting in the north-west parts of Tanzania comprising of Tabora, Shinyanga and Mwanza regions. There are no records to show how the system started, but farmers have been developing it on a trial and error basis since early 1940s for paddy production. Rain water collected from catchment is being stored in bounded fields which are mostly rectangular in shape with earth bunds. However, the research done by Mwakalila (1992) in Shinyanga region showed that, the current rain water harvesting was inefficient due to low control and inadequate management of the catchment area. Rain water harvesting trials are also being conducted in Hombolo (Dodoma district), and Kisangara (Mwanga district). (Hatibu and Simalenga, 1993).

2.1 Agricultural modelling

Suitable and successful crop production strategies have evolved from conventional agronomy and agriculture. Then, these strategies are adopted to local environment. The strategies generally result from observation over long period of time. Their stability and success is dependent upon selecting the proper long term production practices (eg. sowing date, genotype; water application schedules etc). Strategies normally are chosen based on qualitative information or trial and error experiences. In some instances, strategies developed in this manner are unattractive because of the time and expenses required or the difficulty of adopting them to other regions.

Choosing crop production strategies using a simulation model has the potential for providing useful quantitative information for decision making and eliminating much of the repetitive trial and error of selecting production strategies. 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.

A model of a farming system is a model of its various interacting subsystems and of the linkages from the environment. Hence, a model of farming system may consist of a crop growth model, a soil model, a farm model, a climate model, and an economic model for prices of farm inputs and outputs.

In studying such phenomena, a systems approach is considered appropriate. This is because the subsystems are in dynamic relation with other interacting phenomena. Pandey (1991) adopted a modelling approach in the evaluation of economic feasibility of RWH system.

A system approach is preferred to other approaches due to the fact that it:

- permits evaluation of the system's performance over a wide range of stochastic regimes and;
- Identifies critical parameters determining the systems feasibility without requiring a considerably long period of real experimentation.

Based on the above facts (Pandey,1991) conducted a study in India based on the overall model which consist of the biophysical and economic submodels. This model was applied in Raisen district, Madhya Pradesh, India. The biophysical component include submodels describing the rainfall-run-off relationship, the soil water balance, yield response to water, while the economic component consist of submodels for price of inputs and outputs of the system.

2.1.1 Biophysical submodels

The biophysical submodels examine how a set of inputs in the form of land, labour, seeds, machinery, fertiliser etc, is converted into biomass part of which the saleable output produces a revenue for the producer. The biophysical transformation of the inputs into a crop output may be represented by:

$$Y = f\ (\bar{x}) \qquad (2.1)$$

Where: Y = Fraction of the total yield which can be sold

$\bar{x}$ = (x1,x2, x3.....xn)= Quantity of resources used for growing

f = Production function that transform input/output process into quantitative relationships.

2.1.1.1 Run-off

A number of studies have been conducted in India, to asses the economic of RWH (Ryan and Pereira, 1980; Pandey, 1991).
Pandey (1991) predicted surface run-off using a modified USDA run-off curve model (USDA,1972). This was due to the fact that,the original USDA model was based on the prediction of discrete run-off curve number. The advantage of the modified model is that, it allows for a continuous change in the run-off generation potential depending on the antecedent soil moisture condition. In addition the model includes an empirical adjustments for; land smoothness effect caused by earlier rainfall; the formation of micro-cracks on the surface of drying soils causing reduced run-off; and the formation of deep cracks in very dry soils. The prediction equation is of the following form:

$$Ro = \frac{(Ra - 0.2\ S)^2}{(Ra + 0.8s)} \qquad (2.11)$$

where: Ro = surface runoff depth in mm

Ra = rainfall in mm

S = potential maximum difference between rainfall and runoff

The value of the parameter "S" depends on the soil type, crop cover, antecedent soil moisture conditions and land management practices. It can be calculated by using the following relationship (Schwab et al., 1981).

$$S = \left(\frac{25400}{CN} \right) - 254 \qquad (2.12)$$

Where: CN = an arbitrary curve number ranging from 0 to 100

Boers et al. (1986) showed that, the rainfall-runoff relationship can be described by a linear regression model, though the model does not take into account the effect of rainfall intensity on run-off prediction. The model has been applied to annual rainfall-runoff data from small watersheds, large basins, and to separate storms. For separate storm the model can be written as:

(2.13)

$$R = 0 \text{ for } 0 < P \leq \delta$$

$$R = \varpi\ (p - \delta) \text{ for } p > \delta$$

Where:

P = storm depth

R = runoff depth over run-off area from one storm

ω = coefficient of run-off

Ù= Threshold value for run-off

Ritchie (1989) predicted run-off using the curve number technique as described in the USDA-soil conservation service (USDA-Scs). It uses total precipitation occurring in a calendar day to estimate run-off. Run-off curves are specified by numbers which vary from 0 (no run-off) to 100 (all run-off). The USDA-Scs technique considers the wetness of the soil calculated from the antecedent rainfall amounts, as an additional variable in determining run-off amount.

Ryan and Pereira (1979) used a multiple regression model to predict run-off. The latter is regressed on rainfall and other independent variables representing: rainfall intensity; antecedent rainfall; vegetative cover; method of cultivation; soil type; etc. The model is of the following form:

$$RO = f(RF, Xi, \Psi) \tag{2.14}$$

Where:

RO = run-off

RF = rainfall

Xi = other independent variables

Ψ = random error assumed to satisfy the least squares properties of residual.

This model has been calibrated for the ICRISAT centre and Shalapur, Maharastra, using run-off data from experimental watersheds. The model predicted the amount of daily runoff and is reported to have a good statistical fit with accuracy increasing as daily predictions are cumulated over longer periods.

The important application for a derived rainfall-run-off model lies in the conversion of rainfall data into effective rainfall for use in the various water balance models.It is worth noting that, as the mechanism of runoff generation is likely to be site specific due to variation in topography, vegetation and climate, there is probably no such thing as a universal run-off model. The selection of any particular model should be guided by the nature of available data and relevance of particular model with reference to agro-climatic environment and the objectives of the study.

2.1.1.2 Soil water balance

Chang (1968); Hillel (1971) and Simalenga (1989) defined water balance as a merely detailed statement of the law of conservation of matter, which states that matter can neither be created nor destroyed but can only change from one state or location to another. Thus, in its simplest form, the water balance is the difference between the amount of water added (Win) and the amount of water withdrawn (Wout) during a certain period and is given as:

$$\Delta W = Win - Wout \qquad (2.15)$$

Pandey (1991) described soil water balance model as consisting of an accounting identity – i.e. effective rainfall and irrigation added to the soil moisture while evapotranspiration and percolation beyond root zone deplete the soil moisture.

Soil water balance models are necessary for predicting evapotranspiration because evapotranspiration is a function, among others of soil moisture content and must be updated daily. The soil moisture content (St) at the end of the day "t" is given by the following equation:

Where:

$$S_t = S_{t-1} + R_{t-1} + I_{t-1} - ET_{t-1} - D_{t-1} - Ro_{t-1} \qquad (2.16)$$

S_t = soil moisture content at the end of the day "t"

S_{t-1} = antecedent soil moisture content (on previous day)

R_{t-1} = antecedent rainfall (on previous day)

I = irrigation

E_t = evapotranspiration

D = drainage

Ro = surface run-off

Boers et al. (1986) applied a linear regression model combined with soil water balance model to design micro-catchment for water harvesting (MCWH) in the northern Negev desert, Israel. The simulation model used consists of linear regression model for the rainfall-run off process combined with a transient one – dimensional finite difference model for the water balance of the soil profile in the infiltration basin. For a given time period, the water balance equation of the basin can be written as:

$$T = P + Ro + Ei - Ew - E - D - \Delta W \qquad \textbf{(2.17)}$$

where:

T = Transpiration

P = Precipitation on the basin

Ro = Surface run-off into basin

Ei = Evaporation of intercepted water

Ew = Open water evaporation

E = Soil evaporation

D = Deep percolation

ΔW = Increase of water storage in the soil profile

The intercepted losses which consists of deep percolation, evaporation and water evaporation process were neglected.

Thus combining precipitation and run-off as a total infiltration(I) becomes:

$$I = P + Ro \tag{2.18}$$

When the evaporation and deep percolation are combined as losses (L), the equation is written as:

$$L = E + D \tag{2.19}$$

If the annual water balance (ΔW) can be assumed zero, then the equation (2.17) reduces to:

$$T = I - L \tag{2.20}$$

Given the above situations, the equation (2.20) was used as the design equation (Boers,1986).

Witney et al.(1982) also modified the soil moisture balance equation (2.17). The modified equation was reported elsewhere (Simalenga, 1989), and is written in the following form:

$$M = MP + P - R - D - E \tag{2.21}$$

where: M = soil moisture status on the present day

Mp = soil moisture status on the previous day

P = precipitation

R = Run-off

D = Drainage

E = Evaporation

All existing soil moisture balance models are based on general balance equation (2.21) and they differ only in the calculation of the individual elements of the basic equation, i.e. evaporation, drainage and run-off (Simalenga, 1989).

In conclusion water balance models developed to date have been empirical and site specific. The reason is that, several models which have been developed to describe the flow of water in the soil-plant-atmosphere continuum (SPAC), as gorvened by the difference in water potential involves complex water flow equations. Instead of fiddling with water flow equations, it was therefore, suggested (Knight et al., 1975) to rely on empiricism and simple conceptual models. This is because these simple models can produce comparable results at relatively low cost. However, the process of choosing among them must be guided by their relative predictive power, since empirical water balance models are of various complexities and generalities (Pandey, 1991).

Of the various components of the soil water balance model, evapotranspiration is the most important. This is because relative evapotranspiration has been consensusly accepted to be a function of soil moisture content and plant type.
Almost all budgeting techniques make use of well known concept of Potential evapotranspiration (PET) as an indicator of the possible maximum loss of water from the soil under conditions where soil water supply is not limiting.

Potential evapotranspiration depends primarily on the energy supplied to the surface by solar radiation, which is a climatic characteristic of each location (depending on latitude, season, slope, cloudiness etc) and varies very little from year to year

(Linden, 1982; Pandey, 1991).

PET is generally estimated from standard class A pan evaporimeter due to the fact that, other methods are time consuming and, or expensive (Pierce, 1960; Dejong et al., 1987; Simalenga, 1989).

Actual evapotranspiration (ETcrop) is generally a fraction of PET depending on the degree and density of plant canopy coverage of the surface as well as on soil water stress conditions.

Pandey (1991) reported that, evapotranspiration involves transpiration by plant of stored soil moisture and evaporation of moisture from the soil surface. Both components of evapotranspiration are believed to occur in two phases. In the first phase, evapotranspiration is at the potential rate (PET) and is independent of soil or plant factors. In the second phase in which actual evapotranspiration (ETcrop) falls short of Potential value, relative evaporation from the soil is a decreasing function of time and the plant transpiration in the declining phase and is a function of soil moisture and atmospheric demand. This shows that, the variation depends on water supply.

As regards to the prediction of the two components.

Transpiration was predicted using the model developed by Slabbers (1980) and described by Pandey (1991) as follows:

(a) The critical moisture content at which actual transpiration falls short of the potential value was predicted using the following equation;

$$a = 0.94 - (2.6/PT) \qquad (2.22)$$

Where:

a = critical soil moisture content as a proportion of total available moisture content

PT = Potential transpiration in mm.

(b) Then actual transpiration was predicted on the basis of the potential transpiration and soil moisture content in the root zone, using the following equations;

$$T = PT\text{, if } SM \geq a(ASM) \qquad (2.23)$$

$$T = \frac{SM \times PT}{a(ASM)}\text{, When } SM \leq a(ASM) \qquad (2.24)$$

Where:

T = actual Transpiration

SM = current soil moisture content in the root zone

ASM = maximum available soil moisture content

(c) Potential transpiration was predicted by using basal crop coefficient, which is defined as the ratio of crop transpiration to potential evapotranspiration, when the soil surface is dry such that evaporation is minimal, but the soil water availability does not limit plant growth or transpiration.

Pandey (1991) showed the relationship between conventional crop coefficient (Kc) and the basal crop coefficient (K_{cb}) as:

$$Kc = K_{cb} + K_s \tag{2.25}$$

where: Ks = adjustment factor for soil evaporation.

Usually basal crop coefficients are estimated with alfalfa as the reference surface, hence not applicable to other reference surfaces. If the evaporation data to be used are from an open water surface or class A pan, conversion factors are applied to convert evaporation from these surfaces to evaporation from alfalfa, in order to be able to use basal crop coefficient, and this method was applied by Pandey (1991) to separate potential transpiration and potential evaporation, which were used in the determination of evapotranspiration.

Thus given that, evaporation from the reference surface is denoted by (EP), Potential transpiration (PT) and Potential evaporation (PE).

The relationship between these aspects is expressed as :

$$PE = kc * EP \tag{2.26}$$

$$PT = k_{cb} * EP \tag{2.27}$$

2.1.1.3 Yield response to water

Yield response to water (irrigation) model provides information on the effect of moisture stress on yield. Two types of water allocation problems at the farm level are the determination of:

a) The optimal total quantity of water to be applied, and

b) The optimal intra-seasonal distribution of this total seasonal quantity.

Numerous yield response to water models have been proposed and reported by Hanks and Rasmussen (1982); Vaux and Pruitt (1983) and Pandey (1991). They range from the fixed water requirement approach, water production function, indirect production functions with soil moisture stress as the intermediate variable; indirect response function based on an index of plant water stress to physiologically based models. Lack of adequate theory and deficient data do not permit conclusive favouring of one form of yield response function over the other. The choice must ultimately be based on empirical matters such as data availability and predictive power.

However, models based on indirect response function based on an index of plant water stress are relatively commonly used.
This approach is based on the introduction of evapotranspiration as the intermediate variable between yield and soil moisture. This means that yield response is estimated only with respect to evapotranspiration. This is then related to soil moisture through a soil-moisture availability curve, and the soil moisture is finally related to irrigation. Such a piecemeal approach helps to analyse the effect of a limited number of variables more thoroughly than

would otherwise be possible (Pandey, 1991).

Jensen (1968) proposed a yield response function in which the ratio of actual to potential evapotranspiration (ETcrop/PET) in various stages interact multiplicatively to determine yield. The model is of the following form:

$$Ya/Ym = \text{Ò}i(ETcrop/PET)i \qquad (2.28)$$

where:

ET_{crop} = actual evapotranspiration

PET = potential evapotranspiration

Ya = actual yield

Ym = yield in the absence of moisture stress

Òi = Parameter (relative sensitivity of the crop to water stress)

i = growth stage indices

He reported that, this model has the desirable property of diminishing marginal product of increased evapotranspiration (ETcrop) as the relative ETcrop approaches unity. This means that as the demand for water in a growth stage is increasingly satisfied, its marginal contribution to final yield decreases.

Several types of response models using evapotranspiration as the moisture stress variable have been formulated. In all of these models, simulation is necessary to link soil moisture content and evapotranspiration to irrigation.

Based on a study by Denmead and Shaw (1960), Flinn (1968) assumed the plant growth to cease whenever actual evapotranspiration fell short of potential evapotranspiration value. In this model, the effects of various growth stages were assumed to be additive. This means that, the amount of growth achieved in each stage is accumulated to obtain the final yield. This implies that, the potential growth at a later stage is independent of moisture stresses in the previous stages.

Stewart (1972), Stewart et al.(1975) and Doorenbos and Kassam (1979) have used models in which yield deficit was linearly related to the seasonal evapotranspiration deficit. The model is written as:

$$1 - Ya/Ym = Ky(1-ET_{crop}/\ PET) \qquad (2.29)$$

where:

Ky = parameter of the model (i.e yield reduction ratio).

Stewart et al. (1975) pointed that, the latter model assumes that, if this condition is not satisfied, there will be a secondary loss in yield in addition to that predicted by the latter equation. He further reported that, it has been shown empirically that, in the case of maize, moisture stress in the vegetative growth period increases the tolerance to moisture stress in the critical periods of pollination. The implication of such conditioning effects is that,the yield response to ETcrop deficits are not additive but interactive.

Yield models described above are of two types namely, additive and multiplicative. In the additive models, the amount of growth achieved in each stage is accumulated to obtain the final yield. Hence in the additive models, the potential growth at a later stage is independent of moisture stress in the previous stages. In the case of multiplicative models, a certain percentage loss in growth in one stage is assumed to reduce the final yield by at least the same percentage. Thus, a multiplicative model is more appealing because it recognizes(although crudely) the interdependencies among growth stages (Pandey, 1991).

2.1.2 Economic sub-model

One of the two components used by Pandey(1991) to evaluate the economic feasibility of RWH system is the economic sub-model. It consists of sub-models describing the input and output prices. When the two major components namely, economic and biophysical are incorporated, decision making can be made as to whether RWH technology is feasible or not.

Economic evaluation was carried out at two levels. At the first level the concept of optimality was applied in the stochastic analysis, while at the second level, the net present value decision criteria was applied to evaluate the benefits accrued from irrigation tank.

The optimality was measured in terms of maximising utility of expected value. Net present value decision criteria was considered as suitable evaluation technique, because tank irrigation is a durable asset providing a stream of benefits for several years.

Kiome et al.(1993) used the same technique in his studies conducted in semi-arid parts of Kenya. He reported that, when the analysis is carried out at farm level using prices actually faced by farmers, a positive NPV estimate for a given conservation measure would be interpreted as, option of that measure would profit the farmers. Hence, farmers should in principle be willing to adopt the measure voluntarily.

He further suggested that, the main criteria for measuring short term benefits for soil and water conservation are; gross margins, net benefits and marginal rate of returns, while for long term benefits,net present value (NPV) over a specified period of time is appropriate.

Despite that NPV is widely accepted as decision criterion worth taking investment, however it is not the only reliable decision criterion.

Pandey (1991) and Kiome et al. (1993) share the same opinion in this regard. Pandey (1991) suggest that, NPV criterion is necessary but not sufficient criterion for adopting a new production system. Kiome et al.(1993) noted that, even if the NPV estimate is positive, other factors might prevent a house hold from adopting a new system.

Accurate determination of the financial cost and benefits is essential for a reliable economic evaluation. In each soil and water conservation based crop production system, costs are incurred on various items. At farm level these are in ; labour, implements, farm inputs, and construction of soil and water conservation measures. Loss of nutrients is also often mentioned as a cost, and conversely the retention of nutrients by soil and water conservation as benefits. However, such benefits are reflected in the increase in yield and they are, therefore invalid in the analyses.

The main direct benefits from soil and water conservation-based crop production systems are the grain yield and biomass. Grain yield is directly marketable, as long as markets are operational, the value of yield is convertible to money.

Biomass may be used to make trashlines, thereby improving soil structure and fertility, or used as animal fodder, thus reducing the cost of livestock production. These are indirect benefits which are realized eventually in increased production.

Pandey (1991) reported that, the pay off from a system of water harvesting depends on the various parameters namely; amount of run-off available, plant response to water and prices of various inputs and outputs. He used these parameters to evaluate the economic returns of RWH systems as follows:

The system consists of catchment area (CA) from which run-off is collected into reservoir (tank), cropped field (CF) which is irrigated by water collected into reservoir. The sum of CA, CF and the area occupied by the reservoir is the area of watershed (WA).

Total quantity of water (TW) stored in the reservoir at time 't' is given as:

$$TW = f\,(CA, TV, TG, PWTDR, RF, Eo, LM, SR, u) \quad (2.30)$$

where:

TW = Total quantity of stored water
CA = catchment Area
TV = Tank (Reservoir) volume
TG = Tank (reservoir) geometry
PWTDR = Previous withdrawal of water from the tank
RF = Rainfall pattern
Eo = Evaporation
LM = Land Management factors
SR = Seepage rate
u = Random error term

The water availability in the cropped field is given as:

$$W = TW/CF \quad (2.31)$$

where: W = water availability per unit area in the cropped field.

Yield response to water (irrigation) was another important parameter used in the evaluation of returns from the RWH system. It was considered as a function of irrigation depth, exogenous factors which include all other factors determining yield. It is written in the following form:

$$Y = g\,(ID< \text{exogenous factors}, e) \qquad \textbf{(2.32)}$$

where:

Y = yield

ID = irrigation depth

e = random error term

The total cost of irrigation was calculated in terms of cost of water stored, cost of reservoir (tank) and associated land management costs, cost of labour, and cost of water application, given as:

$$TC = \psi(TW) + \text{Þ}(ID)CF \qquad \textbf{(2.33)}$$

where:

TC = Total costs

ψ = function for calculating the cost of water stored

Þ = function representing cost of water application

Thus,the net return from the RWH system was calculated from the following equation:

$$NR = P_y Y - \text{Þ}(W)CF - \Psi(TW) \tag{2.34}$$

where:

NR = net return

P_y = price of the output from the cropped field,

other functions are explained as above.

Ellis- Jones and Mbiha (1993) suggested the steps to be followed in the identification of the costs and benefits of RWH system, when carrying out an economic evaluation.

Basing on the data collected from the farm households in Hombolo (Dodoma district) and Kisangara (Mwanga district), they suggested a number of techniques that can be used, ranging from simple partial budgets to a more comprehensive discounted cash flow investment appraisal techniques. However, the technique to be applied depends on specified period of time the investment takes to mature.

According to their suggestions, economic evaluation for RWH technology can be evaluated based on the partial budgets which allows the calculation of the average annual increased revenue and cost . Also breakeven analysis which follows a similar approach as the latter.

Investment appraisal is another suggested technique. This requires quantification of costs and benefits over a period of time These can be discounted to net present value (NPV) and internal rate of return (IRR) and benefits costs ratios (B:C ratio) determined.

Ernst et al. (1994) pointed out that, cost benefit analysis technique provide a coherent framework for integrating information on the biophysical and economic environments faced by farmers. Variants of these techniques have been used to examine soil conservation cases, Veloz et al. (1985) in Dominican republic, Magrth (1989) in India indicated that, although various methods were applied to try to establish the nature and rate of degradation of future productivity, and the effect of conservation practices, only modelling approach was found to be more suitable to evaluate the biophysical environmental data.

Crop production budget technique was also considered appropriate technique, however its efficiency would be contributed by:

- Its ability to reflect practices and prices in the area of interest.
- Inputs provided by the house holds themselves such as family labour are priced at their cost in the nearest market.

Output and input prices used in the analysis have to represent long-run real price trends, and assessing discount rate is also very crucial given the pertaining nature of the problem.

Assessment of discount rate is furnished through the internal rate of returns (IRR) technique which is used to test discount rate. If the discount rate is smaller than the IRR, the proposed conservation measures would be profitable.

From the discussion above it has been shown that, the feasibility of rain water harvesting systems depend critically on the run–off generation potential of the watershed under consideration. It has also been revealed that water balance models developed to date have been empirical and site specific. Hence the process of choosing from among them must be guided by their relative power. Furthermore the importance of allowing for stochasticity in the farming systems has been emphasised. In the context of modelling, the intrinsic stochasticity in the farming systems as well as the uncertainty about the model itself has to be accounted for. Thus ,adequate treatment of stochasticity and the complexities of the bio–economic systems calls for a simulation type approach to systems modelling.

It can therefore be concluded that,the review of the models of rainfall–run–off relationship, soil water balance and yield response to water indicates that physically based models for these sub–systems are yet to be achieved. Hence a modeller must rely on empiricism at some stage thereby reducing the transferability of the model. A proper compromise between cost and accuracy can be defined only in relation to the objectives of the study.

3. MATERIALS AND METHODS

3.1 Location

The experimental work was conducted at Hombolo Research Station, Dodoma. It is located at about 58 Km North East of Dodoma municipality at latitude 5°54' S; longitude 35°57'E and 1020 m above mean sea level (Fig. 3.1).

3.1.1 Selection of the study area

Dodoma region was selected as a study area, because rainfall in Dodoma is quite erratic and sometimes of high intensity, and often lasts for short duration. Ngana (1983) reported that, in most months the rains are unevenly distributed and very uncertain, and this makes farming uncertain.

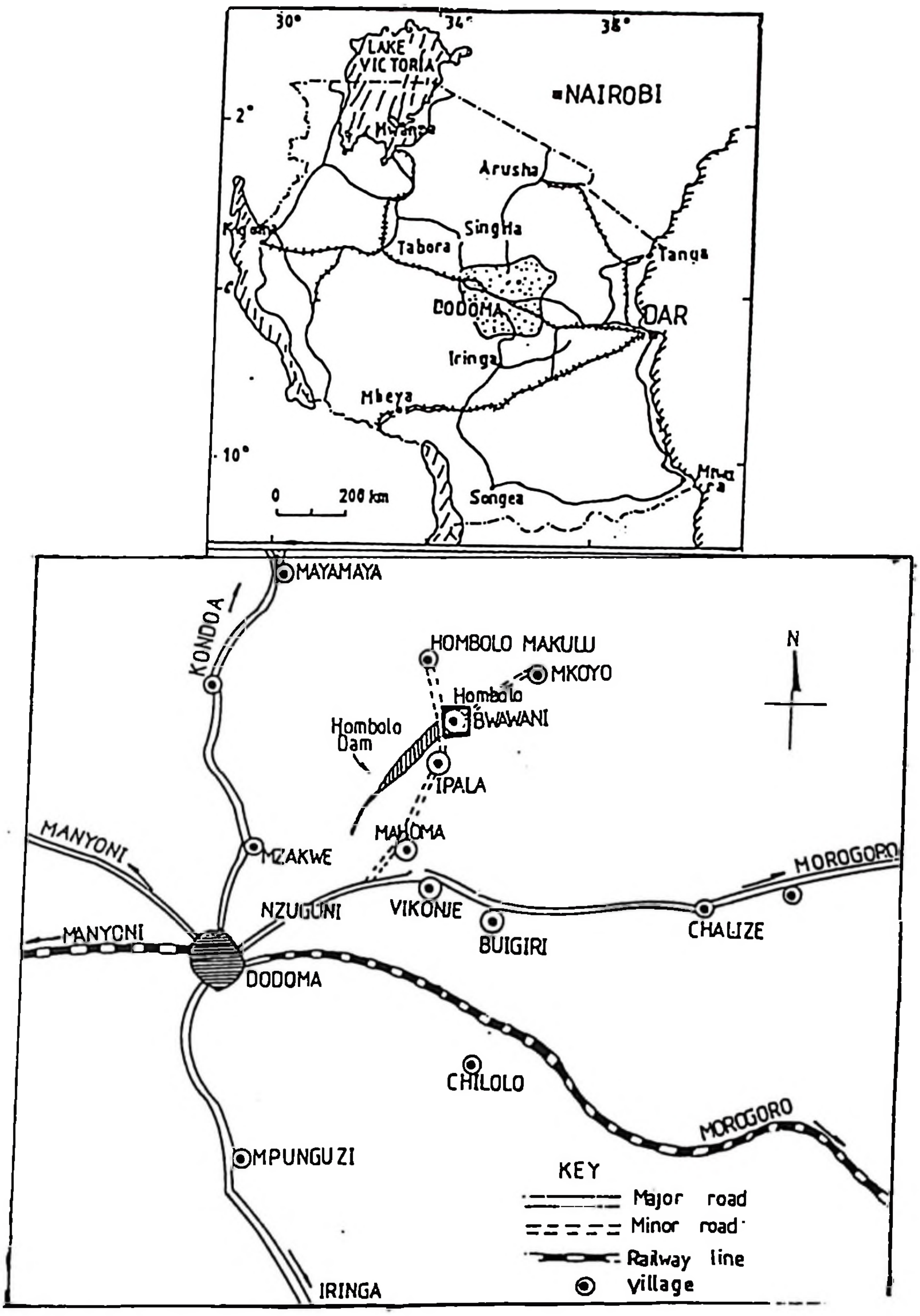

Figure 3.1: Location of the study area.

Source : Hatibu et al.(1993)

3.1.2 Soils

The soils of the experimental site are fairly uniform based on the colour and texture of the surface soil. The soils are generally not very fertile and frequently show signs of erosion resulting from overgrazing and poor farming practices.

Mahoo and Kaaya (1993) classified the soils at the site as Typic Untorthent in the US Soil Taxonomy, and as Dystric Regosol in the FAO–UNESCO system. The soils were morphologically characterised as having a profile which is fairly deep (>100cm) with texture, ranging from sandy to sandy clay on the surface, and loam subsoil. The structure of the surface horizon is weakly developed, while the sand fraction of nearly the whole profile is dominated by quartz minerals. The profile is characterized by an Ochric epipedon and no other diagnostic horizon is recognized. The moisture and temperature regimes of the soils were ustic and thermic respectively .

The soil reaction of the profile ranged from strongly acidic (pH 5.1) to medium acidic (pH 6.0), and varies irregularly with depth, with surface horizon having pH of 5.4, while the deepest horizon has a pH of 5.3.

3.1.3 Rainfall

The historical annual rainfall records indicate that rainfall in Hombolo varies between 350mm and 814mm, with a mean of 588mm. The analysis done on the basis of 17 years (1974–91) revealed that, 12 years had above average annual rainfall (Hatibu et al.,1993).

Rain in Hombolo falls in the months of October to April. However, most of the rains are received between December and March, with mean monthly rainfall of above 100mm, and the mean number of rain days per month above 10 days (Hatibu et al., 1993).

At the experimental site, daily rainfall data for the growing season 1994/95, were recorded using Dines tilting Siphon recording rain gauge. Rainfall data were summarised in 10–day totals, after which the monthly data were obtained.

The mean monthly weather data for the experimental site are shown in Table 3.1 below.

Table 3.1 Mean monthly weather data for Hombolo 1994/95 season.

Month	Maximum Temp(°c)	Min Temp(°c)	Wind Run (Km/hr)	Evap o(mm)	Rainfll
Nov. 94	33.6	19.5	295.9	9.4	17.7
Dec. 94	31.3	20.2	264.5	8.0	95.1
Jan. 95	30.2	19.7	154.0	6.0	116.3
Feb. 95	29.4	19.2	117.1	5.5	181.6
Mar. 95	29.4	19.0	111.1	5.5	198.7
Apr. 95	29.6	18.8	142.3	5.5	46.2
May. 95	28.3	17.4	178.4	4.7	10.3
Seasonal				44.6	665.9

3.1.4 Farming system

The major occupation for more than a half of the households is agriculture. However, the major income earning activities are both on farm and off farm activities, with relative high contribution from farm.

Hatibu et al. (1993) conducted a survey on socio–economic aspects in four villages in Dodoma namely, Hombolo, Ipala, Chamwino and Msanga (Fig. 3.1) and reported that 54% of the respondents, derived their income from on farm activities, while about 46% depended on off farm activities. Agricultural production is characterized by low inputs use, with hand hoe as the major tool used. Farm tools owned by farmers are mainly hand tools. The survey further indicated that, among the major constraints affecting crop and livestock production includes, non reliability of rainfall, inadequate inputs use and availability, declining soil fertility, absence of credits , diseases, and pests problems mainly on livestock. Rainfall appears to be a crucial element limiting agricultural production, as has been underscored elsewhere (Niewolt, 1973; Ngana, 1983, 1991).

3.2 Experimental design and treatments

3.2.1 Rain water haversting (RWH) experiment

The experiment consisted of eight treatments with two replicates. The treatments were a factorial combination of one crop (maize), five levels of rain water harvesting (RWH), and two levels of surface characteristics. The plots were 5x10m and laid lengthwise up slope 1–2%, and were arranged in a completely randomized block design. The five levels of RWH were:

Treatment T1: CA:CF ratio of 0:1 i.e cropped field not receiving run- off
Treatment T2: CA:CF ratio of 2:1 i.e with run–off storage
Treatment T3: CA:CF ratio of 2:1 i.e without run–off storage
Treatment T4: CA:CF ratio of 4:1 i.e with run–off storage
Treatment T5: CA:CF ratio of 4:1 i.e without run–off storage

Where:
CA = Catchment area
CF = Cropped field

3.2.2 Catchment area design

The experiment layout consisted of two parts referred to as Catchment Area (CA), and Cropped Field (CF) respectively. The catchment area were located above the cropped plot where run-off was generated and added to the cropped plot (Fig.3.2). The levels of RWH regime were determined by CA:CF ratio and whether storage is used or not. One type of catchment area configuration was 40m long by 5m wide treated as CA:CF ratio of 4:1, while the other type was 20m long by 5m wide treated as CA:CF ratio of 2:1 respectively. The catchment area of ratio 2:1 were slashed and burnt, while that of ratio of 4:1 were slashed only. The catchments were surrounded by compacted earthned bunds of 40cm height and 75cm base width, to allow collection of run-off, thus increasing the rainfall on the cropped plots. The lower end of CA:CF ratio of 4:1 and 2:1 without storage were left open for the corresponding cropped plots to receive run-off generated within the catchment, while the CA:CF ratio of 4:1 and 2:1 with storage had a concrete aprons at run-off entering point to the storage. The purpose of these aprons was to maximise the collection of harvested water into the storage tank. The silt traps were constructed slightly up slope of the storage tank in order to trap the sediment from entering the storage, thus enhancing storage capacity . Storage was intended to improve distribution, by allowing the run-off to collect into the storage tank located between the catchment area and cropped field (Plate 1)

Plate 1: Storage tank with an apron and silt trap.

The collected run-off was applied to the cropped fields at 7 days interval during the water requirement deficit, unless rainfall event occurred in between dry spells. The volume of water to be supplied was calculated using the following formula:

$$V = Id \times A \tag{3.1}$$

Where:

V = Volume of water to be supplied (m^3)

Id = Water application depth (mm)

A = Area(cropped Field) (m^2)

Regarding the irrigation tank capacity, there were two larger tanks and two small tanks respectively, randomized within the blocks. The larger tanks were of about 2m^3 (2000 litres) capacity,

while the smaller tanks were of about 1.5m^3 (1500 litres) capacity.

The calculation of the catchment and cultivated area ratio was based on the concept that, the design must comply with the rule:

Water harvested = Extra water required

Water harvested = Catchment area x Design Rainfall x Run–off coefficient x Efficient factor

$$= CA \times dR \times K \times EF \qquad (3.11)$$

Extra water required = Cropped field x (Crop water requirement – Design Rainfall)

$$= CF \times (ET_{crop} - dR)$$

$$CA \times dR \times K \times Ef = CF \times (ET_{crop} - dR)$$

If this formula is rearranged we finally obtain:

$$\frac{CA}{CF} = \frac{ET_{crop} - dR}{dR x K x Ef} \qquad (3.13)$$

3.2.3 Agronomic Practices

The maize was planted, two seeds per hole, at the spacing of 35cm between two holes and at 75cm between rows. This was assumed to allow evenly distribution of water between plants.

The crop evapotranspiration at late season stage was assumed to range between 5-6 mm/day (Doorenbros and Kassam, 1979).

Establishing the optimal depth of water and irrigation efficiency were relatively difficult. However,the depth of water was determined based on the amount of water required per each interval of irrigation divided by the effective wetted area.

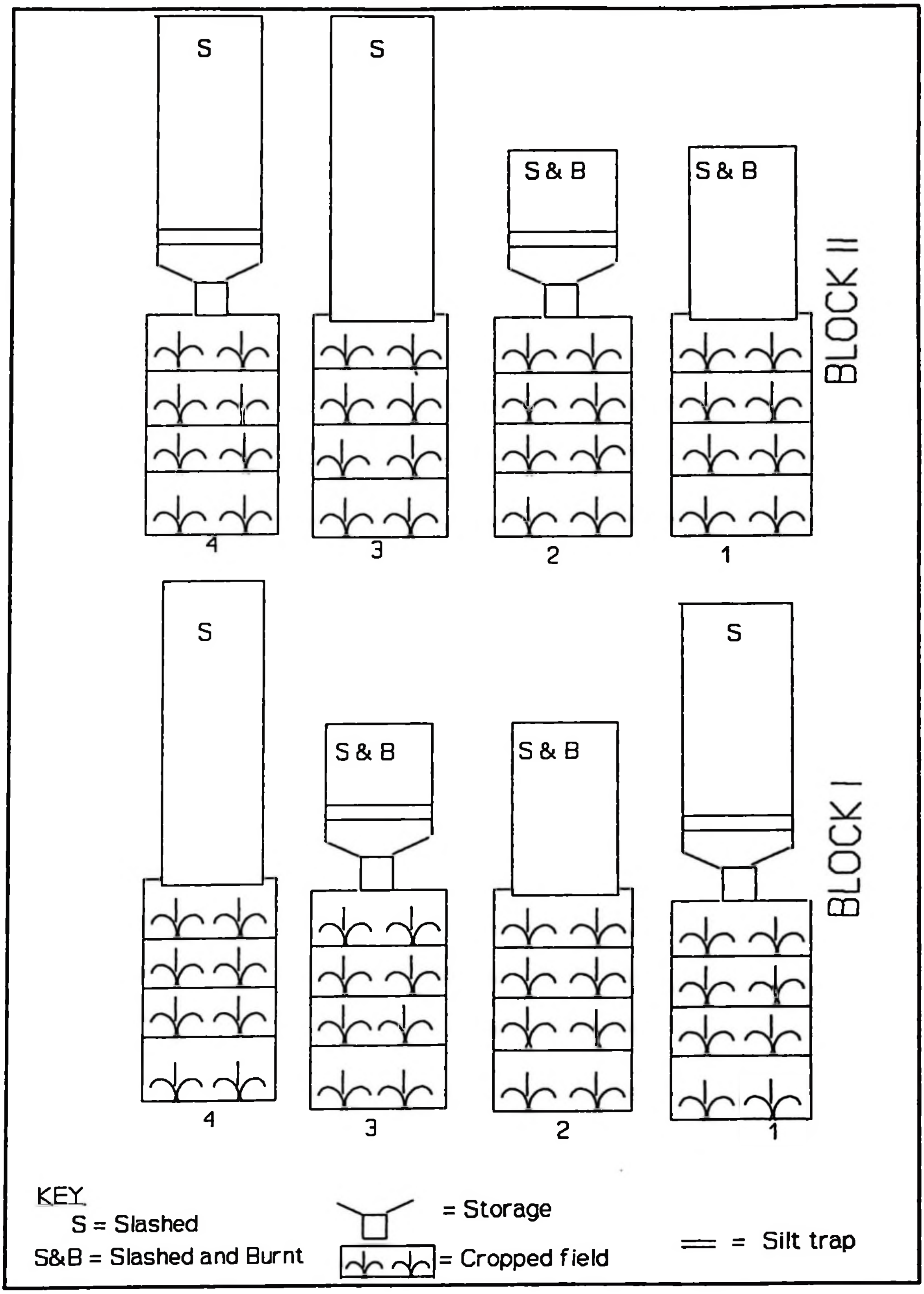

Figure 3.2: Layout of the experiment

3.2.4 Instrumentation and measurements

3.2.4.1 Weather data

The rainfall, maximum and minimum temperatures, evaporation, and wind data were obtained at Hombolo meteorological station (Fig.3.2).

3.2.4.2 Measurement of run-off

The run-off measurement data were recorded from the run-off collection system (Fig.3.3). The collection system consisted of a divider drum with 15 outlet pipes of diameter 1.91 cm. The central pipe was connected to the collector drum by a hose pipe. The pipes of the divider drum were adjusted such that, the overflow volume draining into the collector drum was 1/15 of the total overflow. Calibration of the run-off collection system was done in order to obtain the actual average ratio of the overflow that drained into the collector drum. This ratio and the apron surface area were used in the calculations of the total run-off volume from the catchment area. Run-off was measured directly from 100m^{2}and 200m^2 catchments. After each rainfall event, the total run-off volume entering the divider and collector drums was determined from depth of run-off, apron surface area, and over flow ratio of both divider and collector drums. This volume calculated from the three parameters minus run-off volume collected from apron surface area (apron surface area x Rainfall event), gave the total volume of run-off produced within the catchment area. This run-off volume was then converted from volume in litres to mm of rainfall based on the following relationships:

$$RO=\frac{Q}{CA} \tag{3.13}$$

$$=\frac{Q1x1000(cm^3/l)\,x10(mm/cm)}{CA(m^2)\,x100(cm/m)\,x100(cm/m)}$$

$$=\frac{Q}{CA}\,(mm)$$

Where:

Q = Run off volume in litres

RO = Run off in mm

CA = Catchment area in m^2

The collected run-off water was applied to the cropped fields at 7 days interval during the water requirement deficit, unless rainfall event occurred in between dry spells.

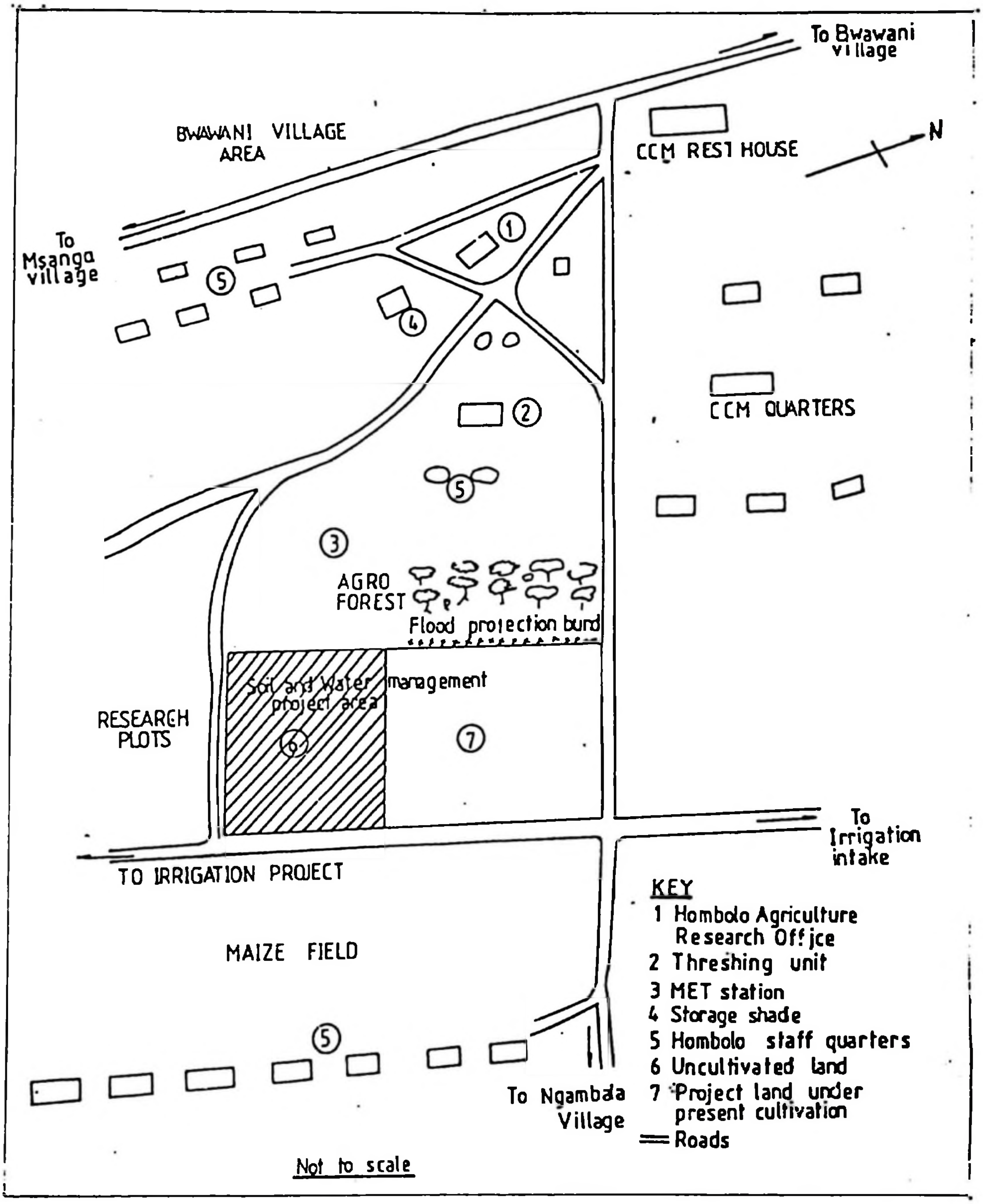

Figure 3.3: Location of experimental site in Hombolo Bwawani village

Source: Hatibu et al.(1993)

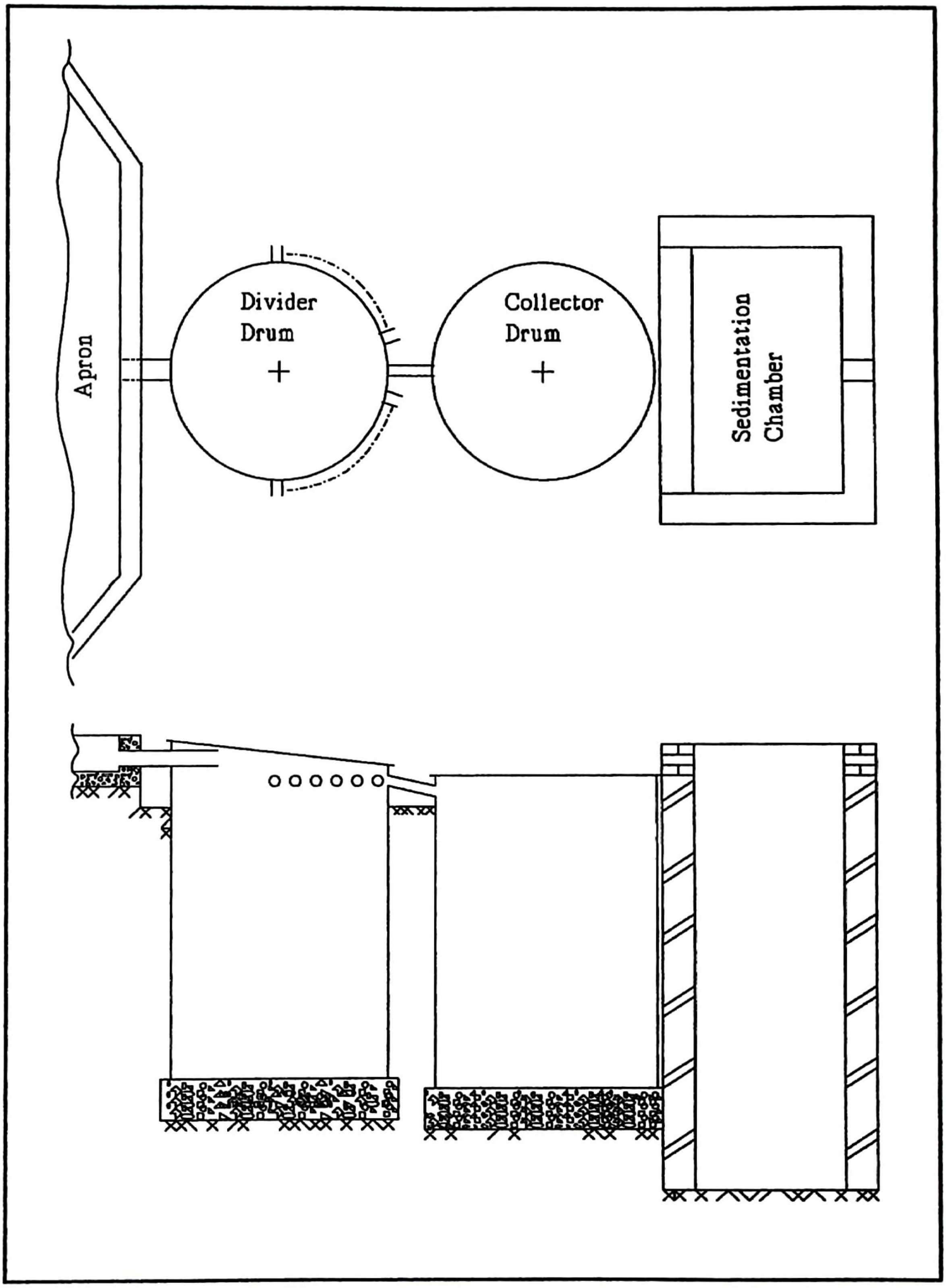

Figure 3.4: Run–off measuring system

3.2.4.3 Soil moisture content

Soil moisture content was measured using a CPN neutron probe (model 503 DR Hydroprobe) by taking counts at the depths of 10, 30, 50, 80, cm, after every 7 days if there is no rain, and after every rainfall event. Counts were then converted to moisture content, and depth of water in the profile was considered to be between 0–100cm.

3.2.4.4 Soil bulky density

The bulky density was determined using the method by Klute (1986). Bulky density cores of volume 98.2cm^3 (5cm diameter, 5cm length) were used to collect samples. Samples were taken at 10cm, 15cm, and 20cm depth. They were then oven dried at 104℃ for 24 hours.

3.2.4.5 Soil infiltration rate

The steady state infiltration rate was measured by double ring infiltrometer (Klute, 1986), which consists of an inner ring (27.8 cm diameter), surrounded by an outer ring (54.5 cm diameter).

3.3 Soil and crop management

3.3.1 Sowing and germination

The cropped fields were flat cultivated by a hand hoe to a depth of 15 cm. The field were sown on 05/01/95 with maize (Zea mays CV. Staha). A second sowing was carried out on 15/01/95 and approximately 90% germination was achieved.

3.3.2 Weeding and fertilizer application

Weeding and inter–rows cultivation was done twice by hand hoe to maintain plots clean of weeds. Then farm yard manure was applied in the cropped field at a rate of 10 t/ha. Thinning was carried out twice during the growing season.

3.3.3 Irrigation of the crops

Irrigation application started in the mid season stage(77 days after planting), at an interval of 7 days. At every interval, about 492 litres of water were applied per plot per irrigation .
The water in the large tanks were depleted during the grain filling stage (5/4/95), while the small tanks were depleted at the beginning this stage (30/3/95).

It is worth noting that, before the beginning of irrigation schedule, there were dry spell periods which occurred between rainfall events. There was therefore, a need to apply irrigation during this variable periods, to offset the soil moisture deficit prevailed. Consequently, the contribution of these inconsistent irrigation applications in terms of crop growth response to water, was difficult to evaluate in the final process of establishing crop growth response to irrigation.

3.3.4 Harvesting

The maize yield was harvested on 23/5/95 and weighed in Kgm. The final harvest from the plots with storage and plots without storage were weighed separately in order to be able to determine the yield variation between the two treatments.

3.4 Economic evaluation of RWH system

Gross margin analysis was used to evaluate the RWH system under this study. Two types of plots were considered under this system. One type of plots had RWH storage tank while the other type of plots had no RWH storage tank. The two types of plots were examined in terms of:

(a) Gross income determined from the total yield multiplied by price of the product at the current market price.

(b) Variable costs of farm inputs in detailed breakdown of farm operations.

(c) Gross margin for each type of plots, with and without RWH storage tank (Table 4.9).

(d) The cost of stored water (cost of tank and associated land management) were determined. These are regarded as fixed costs since irrigation tank is a durable asset providing benefits for several years.

(e) The fixed costs distributed over the life span of the storage tank which was assumed to be 10 years.

(f) Returns on Labour.

The computation formula for gross margins were as follows:

(a) Gross returns(Income) = Production output x Price

(b) Gross margin = Gross return (Income)–Total Variable Costs

(c) Labour returns = Gross margin / Total labour.

Total available labour was computed as:

Total number of workdays per month x total number of employees

3.5 Model structure and operation

The simulation model of RWH system used in this study, is an empirical model adopted from India and modified, with an intention of applying it, to evaluate the advantages accrued to this system. The objective of this system was to attain the optimum crop yield in semi-arid areas of Tanzania. The model was based on biophysical component and economic component respectively. The former component consisted of run-off, soil water balance, evapotranspiration, and yield response to water, while the latter component was composed of inputs and output prices. The two components were incorporated to form the biophysical model which was applied to evaluate the economic feasibility of RWH system.

The model is anticipated to act as a tool for technology transfer from both researcher to the farmer and from location to location. This aspect is reflected by the fact that, the model was formerly used in India's semi-arid tropics (SAT),and is now currently being tested in semi - arid area of Tanzania.

The modification effected in this study is reflected in the composition of both models. While Pandey model included the aspects covered in this study, it additionally includes root growth crop coefficient, and drainage submodels, which were omitted in this study. The crop coefficients used in this study were obtained from literature as constant parameters, whenever it was required to do so.

As regards to the evapotranspiration submodel, although both models focused on evaporation and transpiration aspects as independent parameters, but in this study, evapotranspiration was estimated on monthly basis. The modification is also reflected in the economic analysis, where Pandey model used NPV and IRR techniques, the economic analysis in this study was based on the gross margin technique. The other difference between the two models lies in the computer language used. While the Pandey simulation model was written in the Fortran, the simulation model in this study was written in Turbo Pascal.

Generally, modelling is a research tool which can be applied in the investigation complex of production systems such as soil- plant atmosphere continuum. In this context, the model in this study investigated the linkage between climatic variables, biophysical and economic processes. These phenomena are linked to the RWH system so as to improve the reliability of yield in semi-arid areas of Tanzania.

The model presented here uses input data concerning daily periods. As boundary conditions at the soil surface, one needs data on rainfall, potential soil evaporation and potential transpiration.

It identifies, field capacity (FC), permanent wilting point (PWP), available soil water to plant (AW), soil moisture at saturation point (Ssp), and readily available soil water (RAW).

The model also calculates surface run-off, determines the actual evapotranspiration, amount of water required to irrigate, and determines gross margin (net return) of RWH system.

3.5.1 Run-off submodel

The estimation of run-off was performed using a modified US soil conservation service equation (Pathak et al., 1984) cited by Pandey (1991), and the run-off was calculated by taking input of daily rainfall as follows:

$$Ro=\frac{(Ra-0.2s)^2}{Ra+0.8s} \qquad (3.14)$$

Where:

Ro= Run-off (mm)

Ra= Rainfall (mm)

S= Soil moisture retention parameter (water storage,mm)

In this technique, however, the soil moisture retention parameter,S,was determined as a function of soil moisture index (SM). This is because, soil moisture retention parameter, which determines the run-off curve number, is a continuous function of current soil moisture content.

The relationship between moisture content and soil moisture retention parameter is expressed as:

$$SM = V - S \tag{3.15}$$

Where:

V = Maximum value of moisture storage in the soil.

S = Soil moisture retention parameter.

Using equation (3.15) soil moisture retention parameter for any day can be estimated and the value of SM can be updated using soil moisture balance.

In view of this, the procedure used to estimate run–off started by calculating S for initial value of SM, then predicted run–off, and updated the soil moisture content.

The updated soil moisture content was used to estimate S for the next day. The maximum value of moisture storage in the soil was taken to be SM at saturation.

Thus, S for an initial value of SM was calculated as:

$$S = V - SM \tag{3.16}$$

3.5.2 Soil water balance submodel

The model used in this study to estimate the soil moisture balance was similar to the one proposed by Pandey (1991) and Simalenga (1989). The model have the following major components.

$$S_t = S_{t-1} + Ra_{t-1} + I_{t-1} - ETa_{t-1} - D_{t-1} - Ro_{t-1} \qquad (3.17)$$

Where:

St = Soil moisture content on day t

S = Soil moisture content

I = Irrigation

ETa = Actual evapotranspiration

D = Drainage

Ro = Runoff

All the terms are expressed in mm and subscripts t and t–1 represents the t^{th} and $(t-1)^{th}$ days respectively.

The individual component of the equation (3.17) was not computed individually, instead, the potential root zone of maize was divided into four layers, moving from top to the bottom. These layers are 10, 30, 50, 80,cm, respectively. The division of soil profile was based on the assumption that the moisture content on the top 80 cm of soil profile is adequate for the purpose of predicting water balance in this study.

The model inputs include rainfall, irrigation, potential evapotranspiration, Run-off, field capacity, Permanent wilting point, available soil moisture, moisture content at saturation and total available soil moisture.

Field capacity and permanent wilting point were determined from soil water retention characteristics (Table 3.2), while available soil moisture and moisture content at saturation were computed using the following expressions.

$$Sa = Fc - PwP \tag{3.18}$$

Where:

Fc = Field capacity
PwP = Permanent wilting point
Sa = Available soil moisture

Table 3.2 Soil water retention characteristics at Hombolo

pF	4.2	3.6	3	2.4	2.3	2	1	0
(%)v/v	17.4	19.7	21.5	25.3	25.9	26.6	28.2	31.8

3.5.3 Evapotranspiration submodel

Soil moisture is lost from the soil through various ways, but the largest and most difficult to measure or estimate is evapotranspiration. This study adopted the model used by Pandey

(1991) which was developed by Slabbers (1980). The principal parameter considered first was the critical moisture content at which actual transpiration falls short of the potential value. The critical moisture content was predicted using the following relationship:

$$a = 0.94 - \left(\frac{2.6}{PT}\right) \qquad (3.19)$$

Where :

a = Critical soil moisture as a proportion of total available moisture content.

PT = Potential transpiration (mm).

It is worth noting that, the submodel is applicable only for positive value of a. If it is negative value on any day, the value is set to zero. The potential transpiration denoted (PT) was calculated using basal crop coefficient. Pandey (1991) indicated that the relationship between conventional crop coefficient (kc) and the basal crop coefficient (K_{cb}) to be of the following form.

$$Kc = K_{cb} + Ks \qquad \textbf{(3.20)}$$

Where:

Ks = adjustment factor for soil evaporation

Since the sum of K_{cb} and Ks is always equal to unity, then the value for Ks is obtained as the difference between unity and basal crop coefficient. Given that evaporation from the reference surface is denoted by (Ep), and Potential evaporation as (PE), the potential transpiration was then computed from the following equations:

$$PE = Ks * EP \tag{3.21}$$

$$PT = K_{cb} * EP \tag{3.22}$$

The symbols are as explained above.

The evaporation from the reference surface was computed using the evaporation data recorded from nearby meteorological station at the experimental site.

The relationship in equations (3.21) and (3.22) was adopted to compute the potential evaporation. The pan coefficient used to obtain evaporation was 0.8, selected on the basis of the available data at the experimental site presented in Table 3.1. Potential transpiration was calculated using basal crop coefficient of 1.2 basing on the same suggestion as above. Therefore, the potential evapotranspiration (PTE) for maize was modelled using the relationship in equations (3.21) and (3.22). The PTE was computed on monthly basis and the results are presented in the Table 3.3 below.

Table 3.3 Monthly Potential evapotranspiration

PTE	Growing season 1994/95							
	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
(K_{cb} * EP)=PT	12.8	9.6	7.2	6.6	6.6	6.6	5.6	54.04
(Kc * EP)= PE	7.5	6.4	4.8	4.4	4.4	4.4	3.8	35.68

With respect to actual transpiration, it was predicted on the basis of Potential transpiration computed above, and the soil moisture content in the root zone, using the following relationship:

$$T = PT\text{, } if\ SM \geq a\ (ASM) \qquad (3.23)$$

$$T = \frac{SM \times PT}{a \times ASM}\text{, } when\ SM < a \times ASM \qquad (3.24)$$

Where:

T = Actual Transpiration

SM = Current soil moisture content in the root zone

ASM = Maximum available soil moisture content.

3.5.4 Yield response to water submodel

Several models have been developed to simulate yield response to water, these include additive models and multiplicative models. The model adopted in this study is the one which relate yield to evapotranspiration. In this model, yield deficit is linearly related to the seasonal evapotranspiration deficit. The model is of the following form:

$$1 - \frac{Y_a}{Y_m} = K_y(1 - \frac{ET_a}{PTE}) \qquad (3.25)$$

Where:

Ya = Actual Yield

Ym = Maximum Potential yield

ET_a = Actual Evapotranspiration

PTE = Potential Evapotranspiration

Ky = Yield response factor.

The response of yield to water supply was quantified through the yield response factor (Ky) which relates relative yield decrease (1–Ya/Ym) to relative evapotranspiration deficit (1–ETa/ETm). Potential evapotranspiration and actual evapotranspiration were estimated on monthly basis using equations (3.21),(3.22) and (3.23), (3.24) respectively. Thus, the product of yield response factor and relative evapotranspiration were used to determine yield decrease in percentage.

The input of the submodel are yield response factor (Ky) and potential evapotranspiration, while the output includes actual evapotranspiration and resultant yield. Determination of stress at various growth phases in this study were conducted on monthly basis for the whole growing season as shown in the Table 3.3.

3.5.5 Economic submodel

A number of techniques are available to perform the economic analysis of a crop production system, ranging from simple partial budget techniques to a more comprehensive discounted cash flow investment appraisal techniques.

In view of this, this study adopted gross margin technique to evaluate the economic feasibility of RWH system under consideration. The adoption of the gross margin technique was necessitated by the fact that, one growing season was taken into consideration. Thus, variable costs, fixed costs statement for each farm operation activities was prepared in details. The activities for which costs were recorded covered: land clearing, catchment development, materials mobilisation, tank construction, plots cultivation, planting, fertiliser application, pest control, water application, harvesting and processing.

Gross margin analysis for each type of plots with and without RWH storage tank, was computed using the following formulae:

Gross output = production x current market prices = gross returns

Gross margin = Gross returns – Total Variable costs.

Fixed cost was calculated from the cost of stored water (tanks and catchment development). However, the fixed cost was distributed over 10 years life span of storage tank.

Total available labour was calculated by multiplying total number of workdays per month by total number of employees.

3.6 Simulation model

3.6.1 Model inputs

3.6.1.1 Climatic variables data

Since the main aim of RWH system is to improve the reliability of yield in semi-arid areas, therefore, in order to assess the long term effects of RWH system, long sequences of weather data are needed. In view of this, the climatic data for 1992/94 – 1994/95 seasons were used to run the model.

The daily inputs of this model include; daily rainfall (mm), maximum and minimum temperature (℃), pan evaporation (mm), and dates of irrigation.

3.6.2 Model outputs

3.6.2.1 Run-off

The run-off data (mm) is generated for every input rainfall event that brings the top 80 cm soil layer to saturation, while the rainfall event that is in excess of that required to bring the top 80 cm soil layer to saturation is also considered as a run-off.

3.6.2.2 Soil moisture

The soil moisture status of a soil during a rainfall event is one of the major controls on run-off from the catchment area of RWH system. This can be explained by the soil condition before the rainfall event. The fact that the soil moisture model quantifies both the amount of soil moisture storage available in the cropped field and the rate of its availability, this qualifies soil moisture content (mm) for all soil layers as an output for soil water balance model for each simulated day. This requires soil moisture content to be updated daily. The components of the water balance equation (3.17) were programmed in a computer Turbo Pascal language. A programmed solution proceed from a day when the moisture status in known at day "t-1"to the next day"t". The equation is solved with that day's rainfall, evapotranspiration and run-off. A new moisture state found at the end of day (t) is used to begin the next days calculation of the moisture state.
In this way, the soil moisture content can be found for any day of the year with sequential iterations of equations (3.17).

The assumptions and equations modelling other components such as run-off, evapotranspiration were described in the previous subsections. Therefore, a generalized flow chart of all aspects of bioeconomic model is shown in the Figure 3.5. The model based on the above mentioned aspects have the following inputs data:

- Records of daily weather data (maximum &minimum temperatures, rainfall, and potential evaporation).
- Identification of soil parameters (Fc, PWP, ASM, SMsp)
- Determination of actual evapotranspiration (ETa)
- Calculation of amount of water to irrigate.
- Calculation of water application depth
- Determination of actual yield output
- Calculation of Variable costs
- Calculation of gross margin (net returns).

The procedure for designing modified bioeconomic simulation model is presented in appendix B.

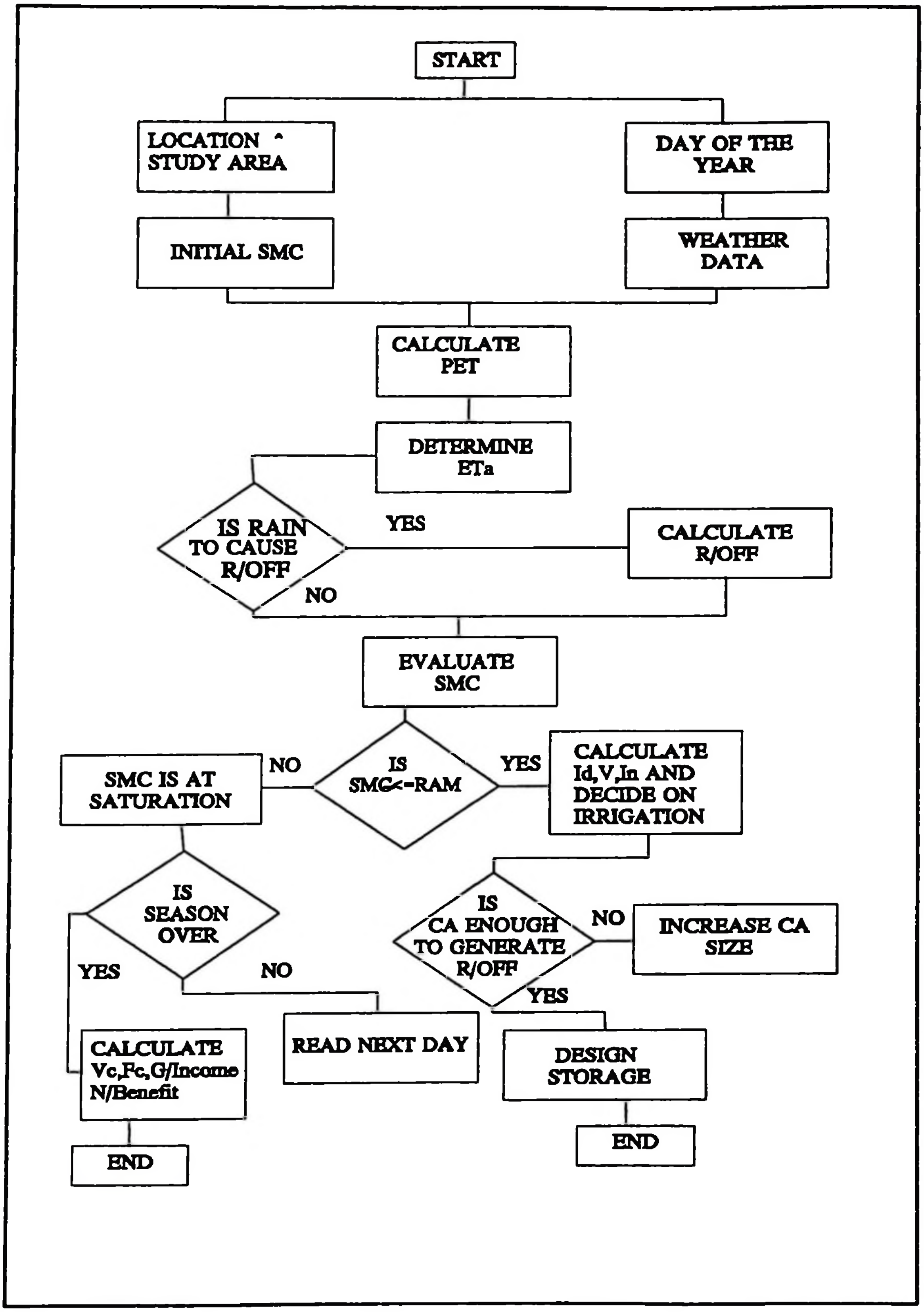

Figure 3.5: Flow chart of simulation model

3.6.3 Designing of RWH system model

In designing the RWH system the parameters that were taken into consideration included rainfall, water storage tank, and Crop water requirement, water application scheduling, and catchment size. Besides, factors such as soil type, and climatic variables were also considered because they affect RWH system.

The storage is a function of crop water requirement deficit, and cropped field size. Therefore, this study designed water storage based on the following formula:

$$\text{Harvested Water} = \text{Cropped Field} \times (ET_{crop} - P_{eff})$$

$$\text{Amount required} = CF \times (ET_{crop} - P_{eff})$$

$$= \text{Water depth} \times \text{cropped Field}$$

$$= Id \times CF \qquad (3.24)$$

where:

Id = water depth

CF = Cropped Field

ET_{crop} = Crop Water requirement

P_{eff} = Effective Rainfall

4. RESULTS AND DISCUSSION

4.1 Model Evaluation

4.1.1 Prediction and Validation of the model

4.1.1.1 Prediction of run-off Values

The run-off prediction model described in chapter three has been used to predict the run-off values. Run-off values were predicted using a modified USA soil conservation service equation (3.14). The procedure used to predict run-off started by calculating soil moisture retention parameter (S) value for initial value of soil moisture Index (SM), then predicted run-off values . The soil moisture content was updated daily. The updated soil moisture was used to estimate S for the next day, using the equation (3.16). The run-off model was run using rainfall and updated soil moisture retention parameter data. The run-off values generated per 100m^2 (2:1) catchment from 5/1/1995 (taken as Julian day one) to 23/4/1995 (taken as Julian day 119) are presented in Table 4.1.

4.1.1.2 Validation of run-off model

Validation test is the act of ascertaining statements that seem to be true of a model. Since models are developed for some particular purpose, validation can sensibly be done only in relation to that purpose. A model considered to be valid for one purpose may not be so for some other purpose. Validation test, therefore, is generally conducted by comparing the values of the variables predicted by the model with the corresponding variables in real world. The comparison may be done by employing statistical tools. In this context, correlation analysis and scatter diagrams were used in the validation of the models in the present study.

The run-off predictive model discussed in chapter three has been validated by MSTATC programme, using data collected from the experimental site (Hombolo). The prediction model used for predicting run-off values was run using rainfall, initial soil moisture retention parameter value, and daily weather data for the season 1994/95. The comparison of measured and simulated run-off values are presented in the Figure 4.1 and Figure 4.2 respectively.

A simple correlation analysis technique and scatter diagrams were used to analyse the data. The results showed that,
the simulated values were fairly close to the measured values, thus indicating the run-off generating potential. This is also reflected by the mean and variance of the simulated and measured values which were found to be 7.74 to 7.77 and 105.55 and 109.10 respectively. The close correlation was also confirmed by the correlation coefficient (r) which was found to be 0.974. The mean, variance, and correlation coefficients for both measured and

simulated run-off values are presented in the Table 4.2.

The scatter diagrams also indicated strength association between simulated and measured values as presented in the Figure 4.1 and Figure 4.2 respectively. The degree of correlation was assessed by producing a graph in which points on the diagram form a straight line of positive slope.

Good correlation between the two run-off values was realised in the graph line as presented in the Figure 4.1.

In Figure 4.2, points appear to be scattered smoothly along a 45^0 line which passes through the origin. However, points in Figure 4.2 seem to surround a straight line at lower angle. Similarly, points in the same figure are congested at higher angle. These situations suggest the underprediction in the case of lower angle, while congestion at higher angle suggests fair prediction.

The seemingly underprediction at lower angle may be attributed to the rainfall that had not reached threshold value to cause run-off, and the watershed retention parameter had also not attained maximum moisture storage in the soil to influence run-off yield.

In the case of congestion at higher angle, the points suggest that rainfall had attained threshold values, and watershed soil retention parameter had stabilised in terms of soil moisture storage to allow run-off yield accordingly.

Based on the correlation analysis and scatter diagrams, run–off is critically dependent on the depth and pattern of rainfall. The pattern of rainfall influences run–off through its effect on the soil retention parameter, for the higher the soil moisture storage in the soil, the higher the run–off potential and vice versa.

Based on this discussion, the model is therefore considered to be validated because it seems to simulate the pattern well, and the model predictions are satisfactory.

Table 4.1 Comparison of measured and simulated run–off values for 1994/95 season.

Date	Rainfall (mm)	Measured run–off (mm)	Simulated runoff (mm)
5.1.95	11.6	2.96	3.08
6.1.95	3.9	1.72	0.83
16.1.95	2.8	0.0	0.12
20.1.95	12.2	15.73	17.58
23.1.95	25.0	23.79	25.62
26.1.95	6.6	1.91	0.99
30.1.95	47.8	30.37	29.30
8.2.95	43.7	29.46	28.30
11.2.95	5.3	3.13	2.33
18.2.95	13.9	10.99	10.55
22.2.95	4.8	3.98	1.82
25.2.95	53.8	35.76	33.55
26.2.95	42.6	31.16	32.44
28.2.95	10.4	10.28	8.70
3.3.95	54.7	32.21	31.41
4.3.95	21.7	15.37	15.59
7.3.95	7.3	9.92	11.15
8.3.95	23.8	19.18	18.56
11.3.95	30.6	23.69	20.45
13.3.95	44.9	32.96	29.85
15.3.95	4.0	1.87	0.47
17.3.95	6.7	4.75	2.19
9.4.95	10.1	7.22	9.01
23.4.95	31.4	13.27	13.81

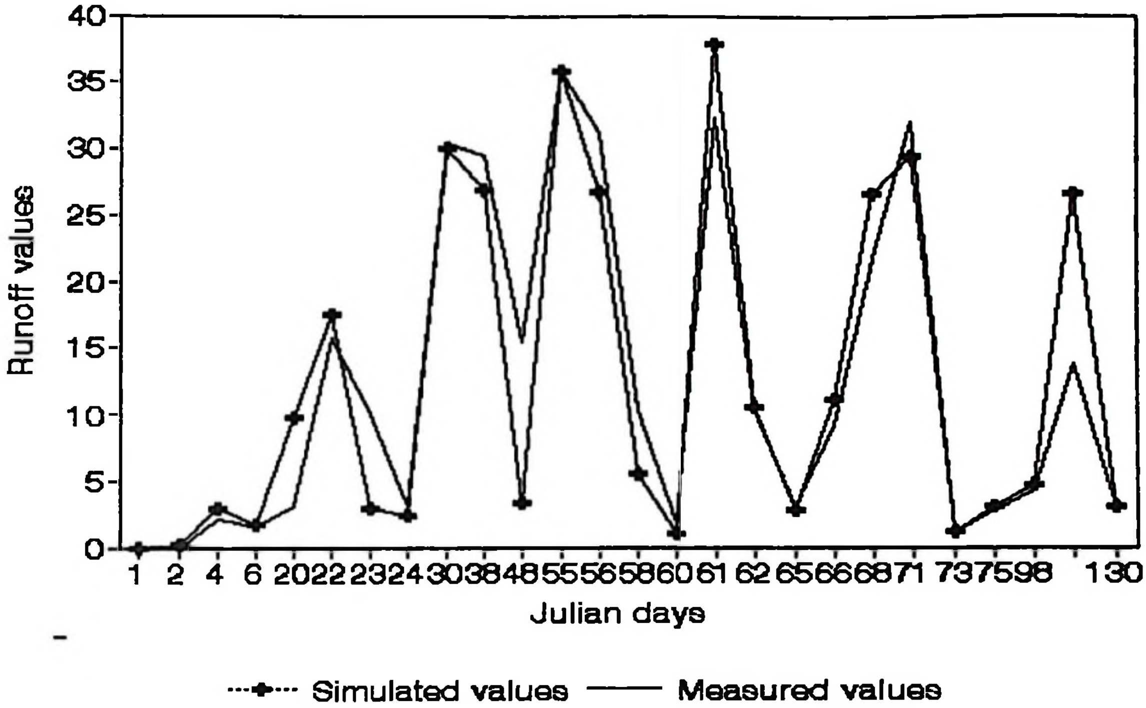

Figure 4.1: Comparison of measured and simulated run–off values under RWH system for 1994/95 season.

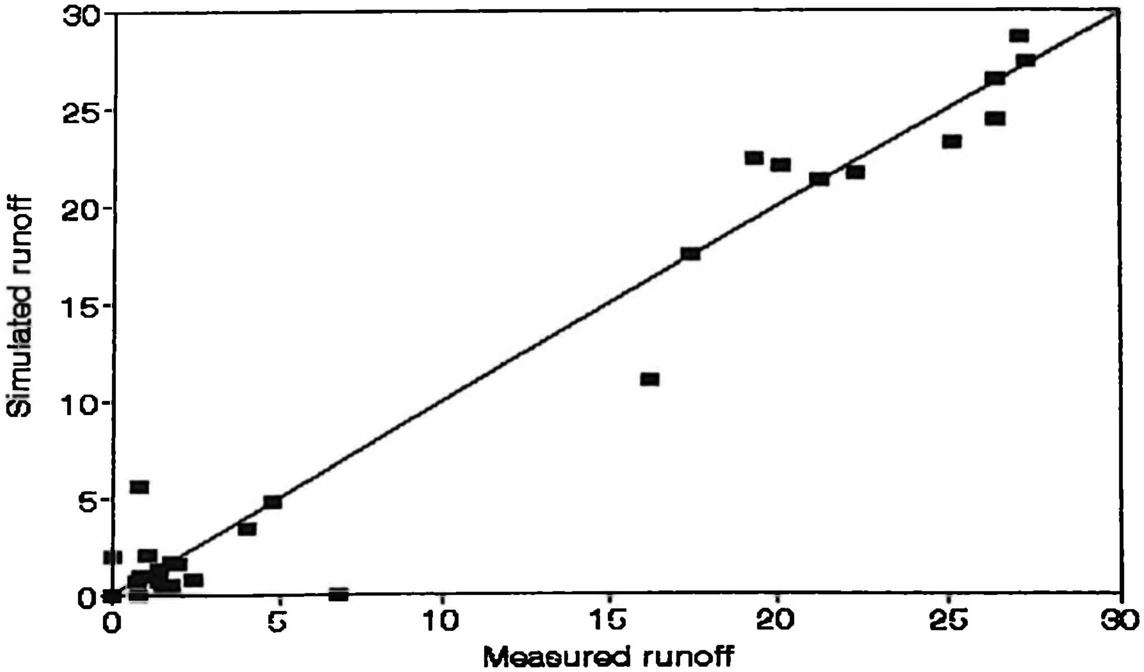

Figure 4.2: Comparison of measured and simulated run–off values under RWH system for 1994/95 season.

Table 4.2 correlation analysis of measured and simulated run–off values under RWH system for 1994/95

Variable Number	Number of Observations	Mean	Variance	Correlation Coefficient
1	23	7.77	105.55	0.974
2	23	7.74	109.10	0.974

Where:

1 = Measured run-off

2 = Simulated run-off

4.1.1.3 Prediction of soil moisture content values

The prediction model (3.17) was used to predict soil moisture content values. Under this mode of operation, the model was provided with inputs which included daily events such as measured daily soil moisture content, rainfall, irrigation, evapotranspiration, and weather data. A programmed solution proceeded from day one (5/1/1995) when the soil moisture status was known, and all other information required for simulating soil water balance as described in chapter three of the present study. In this way, the soil moisture content for any day could be found with sequential iterations of the equation. The simulated and measured soil moisture content values are presented in Table 4.3.

4.1.1.4 Validation of the soil moisture content model

The soil moisture content equation (3.17) was used to simulate daily soil moisture content values. The simulated values were compared with those obtained by Neutron probe measurement during the study period of January to May, 1995 and found good agreement between the simulated and measured values as can be seen in the Figure 4.3 and Figure 4.4 respectively. The scatter diagrams were used to validate this model. It is, however, clear from the Figure 4.3 that, the model tend to overpredict the soil moisture content. Based on the correlation analysis technique which was also used to validate the soil moisture content prediction model, the strong correlation between the two soil moisture content values was underscored. This can be confirmed by the correlation coefficients (r) which range between 0.65 and 0.858. The results are represented in the Table 4.4.

Inspite of the good agreement, one limitation which was encountered in modelling soil water balance was the drainage. The problem can be observed in the simulated and measured soil moisture content in Figure 4.3. The points formed in the graph along the straight line which passes through the origin seem to suggest overprediction. This could have occurred both after rainfall and irrigation. The explanation for this behaviour is attributed to the omission of drainage component in the model. The drainage was assumed to be instantaneous. Drainage can be modelled satisfactorily only by considering both the saturated and unsaturated flow and the gradient in water potential between the root zone and below it, which was beyond scope of this study.

Table 4.3. Comparison of measured and simulated soil moisture content values for 1994/95 season

Date	Measured smc	Simulated smc
2.1.95	22.06	18.00
6.1.95	24.08	23.30
14.1.95	23.38	23.20
20.1.95	24.10	26.60
23.1.95	27.56	27.86
26.1.95	27.26	20.26
31.1.95	29.94	30.72
6.2.95	31.20	29.50
8.2.95	29.82	31.62
13.2.95	29.48	28.38
18.2.95	29.50	30.62
22.2.95	25.68	26.12
25.2.95	28.04	27.22
26.2.95	30.98	32.78
3.3.95	28.20	29.07
4.3.95	32.02	33.79
8.3.95	30.88	30.88
11.3.95	30.30	29.70
13.3.95	31.10	30.69
15.3.95	30.06	31.56
17.3.95	29.54	30.45
24.3.95	28.68	27.92
31.3.95	27.18	26.38
7.4.95	26.34	26.14
10.4.95	26.02	25.76
19.4.95	25.92	25.01
24.4.95	25.88	28.46

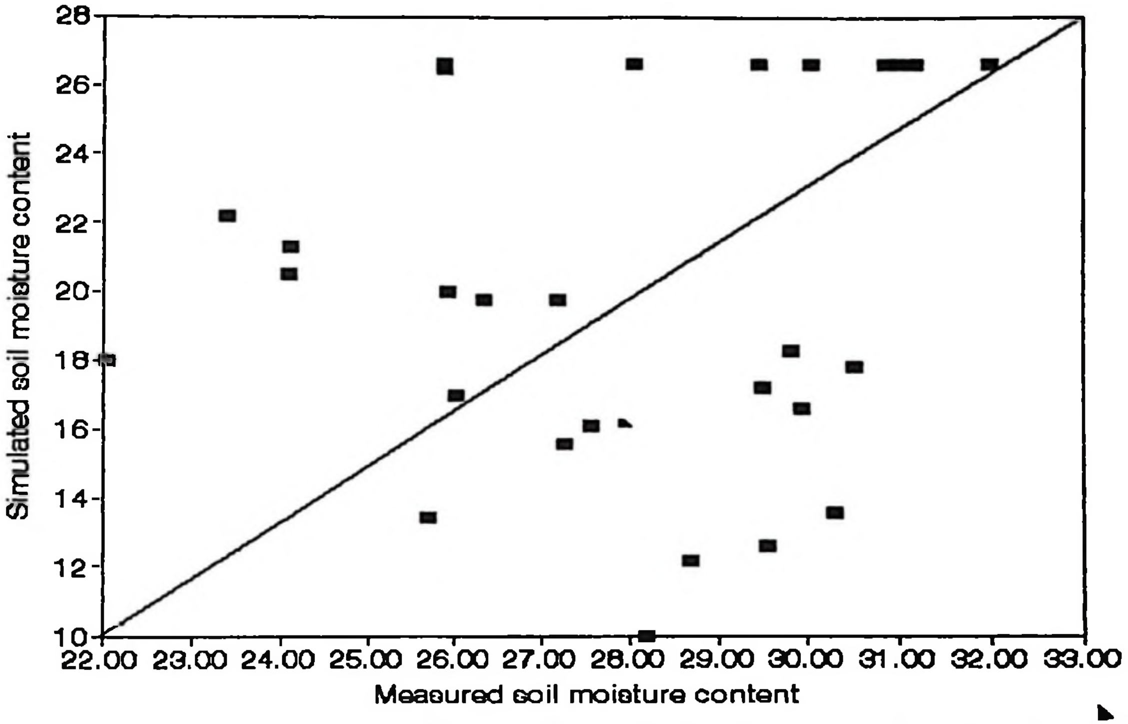

Figure 4.3: Comparison of measured and simulated soil moisture content values under RWH system for 1994/95 season.

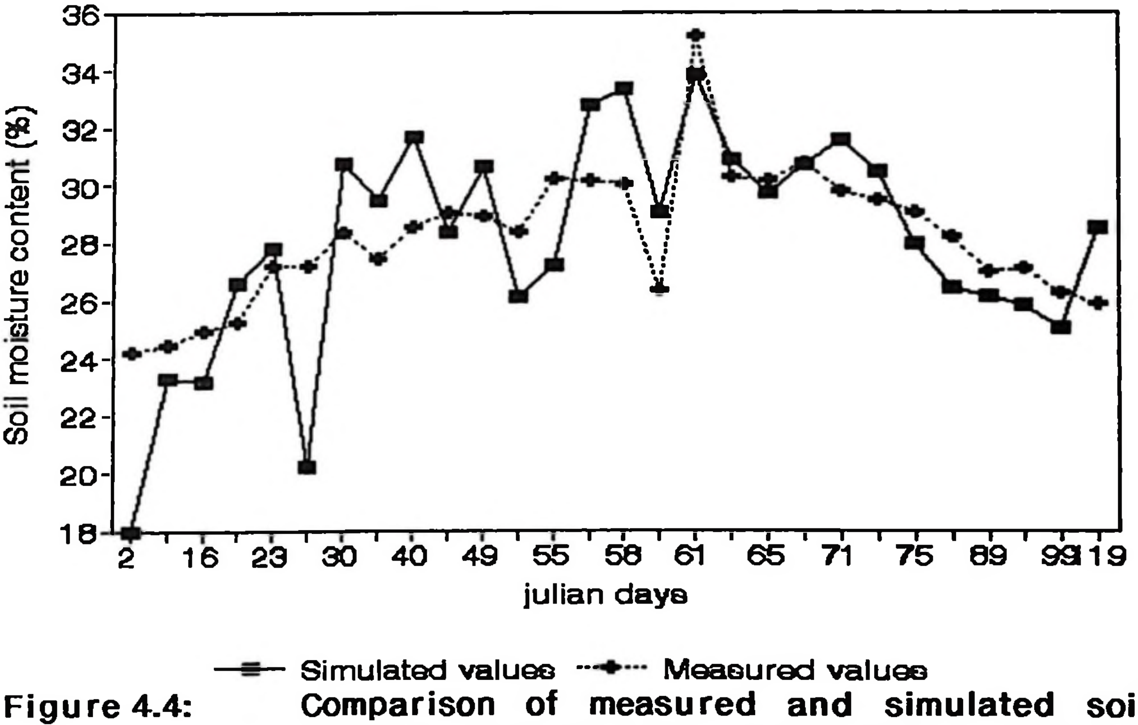

Figure 4.4: Comparison of measured and simulated soil moisture content values under RWH system for 1994/95 season.

Table 4.4. Correlation analysis of measured and simulated values of soil moisture content under RWH system for 1994/95 season.

Type of crop	Depth of measurement	Number of measurement	Regression coefficient	Correlation coefficient	Regression equation
Maize	10	28	0.580	0.650	$Y=13.82+0.567X$
	30	28	1.211	0.858	$Y=-5.93+1.211X$
	50	28	1.203	0.747	$Y=-5.87+1.203X$
	80	28	6.068	0.594	$Y=12.08+0.607X$

4.1.1.5 Prediction of crop yield response to water

For estimating yield response to moisture deficit at various growth phases, estimates of actual and potential evapotranspiration for each growth phase (irrigation interval) and the resultant yield are required. In keeping with the discussion in chapter three, the prediction model adopted in this study was the one which relate yield to relative evapotranspiration (3.25). For the determination of actual transpiration, the data for the potential transpiration calculated on monthly basis was used instead of data on maximum water use at each growth phase. This is because the time series data on yield response for each growth phase, which could have been used to determine the response of plant to soil moisture deficit in each growth phase was not available. Other parameters which were used in the determination of actual transpiration, after which the relative transpiration was determined, include the critical moisture content (proportion of total available soil moisture content), which was predicted using the equation (3.19), and total available soil moisture content, calculated from the equation (3.18).

The simulation water balance model was used to predict the actual transpiration values. However, the simulated actual transpiration values may not be reliable, because the range for potential transpiration data, used in the simulation process was very low as it was for one growing season only. The actual transpiration values are presented in the appendix A2.

The relative transpiration and the constant yield response factor equation (3.25) were later used in the prediction of crop yield.

The prediction of crop yield was effected using the crop yield model (3.25), which was provided with the inputs such as the total relative transpiration and the appropriate yield response factor for the total growing period. The yield response factor was selected based on the weather data available at the experimental site. The actual output yield from the plots bearing RWH storage facility and those which do not, were then incorporated with the other two above mentioned parameters to predict the simulated yield. The simulated data was compared with the actual yield output values. The output results are represented the Figure 4.5 and Figure 4.6 respectively.

4.1.1.6 Validation of crop yield response model

The correlation coefficient analysis, scatter diagrams, and the Duncan's multiple range test (DMRT) techniques were used to validate the crop yield model. Based on the correlation coefficient analysis, good agreement was realised between the simulated and actual yield outputs, indicating satisfactory model performance. This is verified by the correlation coefficient of 0.996. Statistical distribution between actual and simulated yield outputs are shown in the Table 4.5. The generated data were also used to compare actual and predicted yield outputs in terms of scatter diagrams. Figure 4.5 and Figure 4.6 show the comparison between the actual and simulated yield outputs.

Table 4.5. Statistical distribution between measured and simulated yield values.

Variable Number	Number of measurement	Mean	Correlation coefficient
1	5	2.58	0.996
2	5	2.22	0.996

Where:

1 = Measured yield

2 = Simulated yield

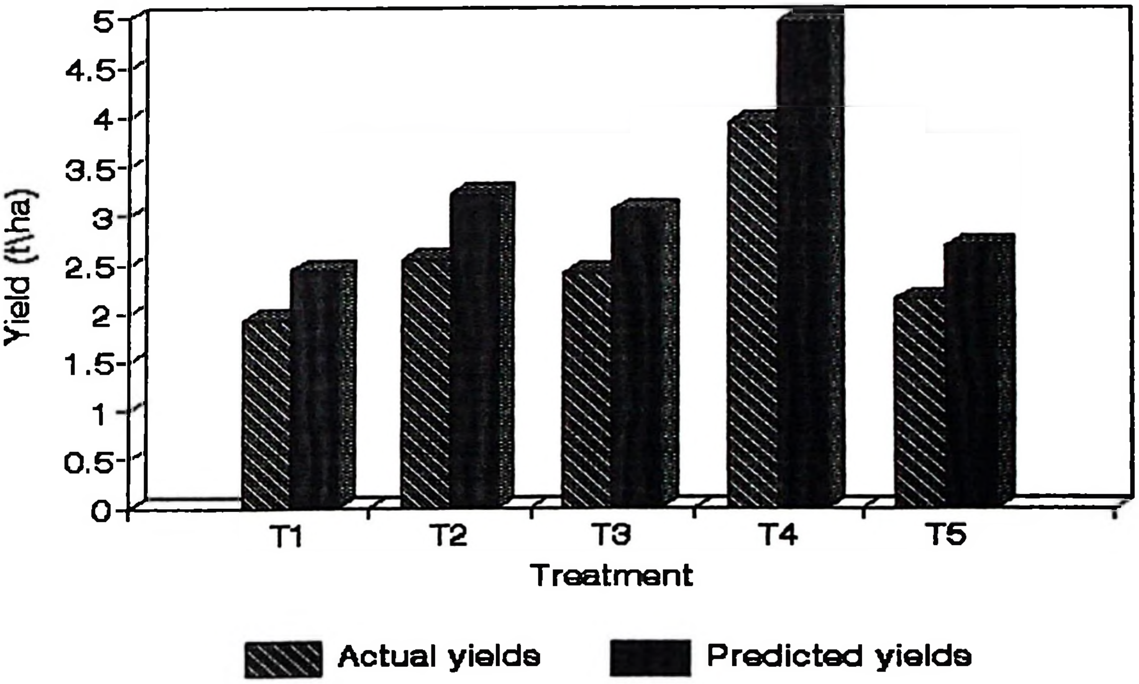

Figure 4.5: Comparison of actual and simulated yield output under RWH system for 1994/95 season.

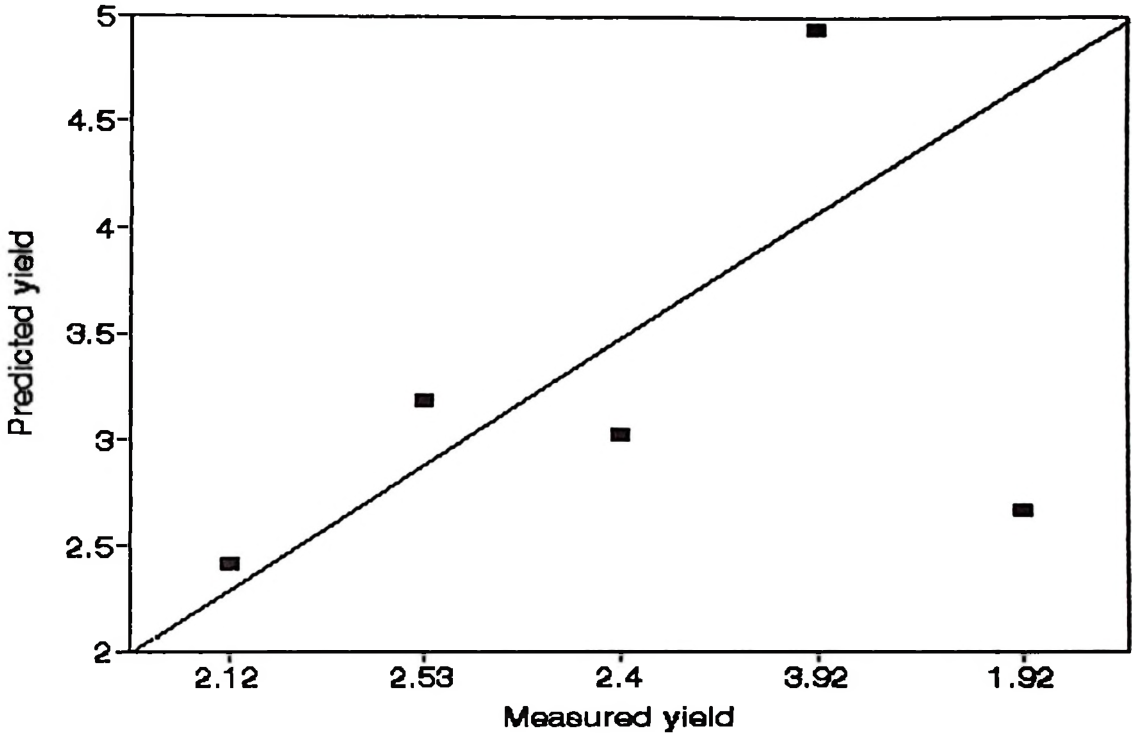

Figure 4.6: Comparison actual and simulated yield output under RWH system for 1994/95 season.

As regards the performance of the model, points in Figure 4.6 appear to be scattered above the 45° line passing through origin. This suggests overprediction of the model. The reason behind the overprediction might be due to the application of constant parameters. Besides, using data calculated on seasonal basis which does not show multiplicative response effect of water use at each growth stage, might also have contributed to the overprediction. The values of correlation coefficient suggest the omission of threshold values in the respective growth stages. However, should these threshold values be included in the model, it might perform much better than it does now.

Bearing in mind that, the main focus of this study was to establish the economic feasibility of RWH system under this study, it was important to establish the impact of use of RWH storage on yield in relation to the non-use of RWH storage.

The difference in yield output between the two types of plots with and without RWH storage, was tested in order to establish the impact questioned above. The analysis of variance was used to test the significant difference between the two type of plots and within each type of plots (Table 4.7). The results indicate significant difference in yield output between the two type of plots, while results within each type of plots indicate non-significant difference in yield output. This is supported by the computed and tabulated F values. The computed F values between the two type of plots at 5% level of significance was found to be 9.019, while the Tabulated F values at the same level of significance was found to be 3.63. Whereas the computed F value within each type of plots at 5% level of significance was found to be 0.0165, the Tabulated F value was 3.48 respectively.

The implication of the result is that, since the computed F value is larger than the tabulated F value between the two type of plots, this indicates highly significant difference between the yield outputs of the two type of plots. In the case of within each type of plots, the computed F value is less than the tabulated F value, implying that the difference in yield outputs is not significant.

The coefficient of variation is 14.35 % which justifies the precision of the experiment.

Means separation for maize crop yield was also conducted, using Duncan's multiple range test (DMRT). The results also indicate variation in yield between treatments with and without RWH storage as shown in the Table 4.6.

Based on the DMRT at 5 % level of significance, the means for treatments, T1, T3, T5, were found to be significantly different from the treatment means of T2 and T4 respectively. This is supported by the results in the Table 4.6, which indicate that, the largest treatment means values are greater than the computed difference between the largest mean and the largest tabular value of T test (3.268 – 1.060 = 2.268). In the same context, since the treatment means values of the T1, T3, T5 are less than the computed difference, this implies that, these treatment means yield are significantly different from the largest treatment means yield, which in this case are the treatment means yield of T2 and T4 respectively.

These significant difference tests confirmed the yield difference in treatments T4 and T2 on one hand, and treatment T3 and T5 on the other hand. These treatments belong to different type of plots (with and without RWH storage). The difference is attributable to the RWH Treatment. This is reflected by the relative yields, produced from differently treated plots (with and without RWH storage). The plots with RWH storage facility produced relatively high yield, while the plots without storage facility produced comparatively low yield.

Whereas the yield produced under treatment T4 was 3.92 t/ha (CA:CF ratio of 4:1 with storage), the yield produced under treatment T5 was 1.92 t/ha (CA: CF ratio of 4:1 without storage).

In the same trend, the yield produced under treatment T2 was 2.53 t/ha (CA:CF ratio of 2:1 with storage), while the yield produced under treatment T3 was 2.4 t/ha (CA:CF ratio of 2:1 without storage) respectively.

The total yield produced from treatment control T1 was 2.12 t/ha, this seem to be higher than yield from T5 despite that the latter had direct access to run-off harvested within catchment (RWH without storage). The reason behind this may be attributed to the fact that, the control plot in one block was located relatively in depression site, where sub-surface run-off, which was beyond the scope of this study, could have contributed to producing high yield than expected. The explanation behind this could be that , the capillary movement of water to and from sub-surface might have naturally replenished the soil moisture deficit that would have constrained the crop growth. Consequently, T1 produced relatively high crop yield.

For the other treatments (T2,T3,T4,T5) which were located slightly upslope, the explanation behind the difference in yield produced from each individual treatment, could be attributed to moisture status experienced by plants during growth cycle. RWH storage was used to offset the soil moisture deficit, caused by the rainfall shortage particularly during the critical growth stages of the plants. This explains why the plots with RWH storage produced relatively high yield than plots without RWH storage. In this context therefore, soil moisture variation remains the major determining factor for variation in yield produced from the described treatments above.

Table 4.6. Means separation for maize crop yield by Duncan's multiple range test at 5% level of significance.

Treatment		Original order	Mean Yield	Ranked order	Mean Yield
T1*	Mean	1	1.060B	4	3.268A
T2	Mean	2	2.630AB	2	2.630AB
T3**	Mean	3	2.091AB	3	2.091AB
T4	Mean	4	3.263A	5	1.916AB
T5**	Mean	5	1.916AB	1	1.060B

Where: * = Without RWH

** = RWH without storage

Means followed by the same letter(s) are not significantly different at 5% probability by Duncan's multiple range test.

Table 4.7. Analysis of variance for RWH effect on yield output.

Source of variation	SS	df	MS	Computed F	Tabular F
Between	1.240	4	0.310	9.019**	3.63
Within	0.172	5	0.034	0.0165ns	3.48
Total	1.412	9			

CV = 14.35%

Where:

** = Highly significant

ns = Non-significant

4.2 Economic analysis

4.2.1 Prediction of gross margin at plot level

The economic analysis was performed using the gross margin technique. The gross margin at plot level was determined using the inputs that included, variable costs, fixed costs for each farm operation activities prepared in detailed. The gross margin for each type of plots with and without RWH storage was calculated using the gross margin model as described in chapter three. Total available labour was also calculated. A summary of gross margin calculation for each type of plots with and without RWH storage is presented in the Table 4.9.

4.2.2 Validation of gross margin model

The model was tested using t–test at 5% level of significance. The results indicated that, the gross margin of plots with RWH storage was significantly different from the gross margin of plots without RWH storage. The results was based on the following parameters namely variance, standard deviation, and the mean as presented in the Table 4.8.

The gross margin analysis attempted to highlight the economic aspects of RWH storage in relation to situation without RWH storage. The results implied that RWH with storage is the most attractive of the two types of plots, given the high coefficients of gross margin reflected by the RWH with storage situation.

The results evaluation, therefore, suggest that RWH with storage is economically feasible for growing maize in semi–arid areas such as Hombolo.

Table 4.8 Significance tests of economic model results

	Plots with RWH storage	Plots without RWH storage
Mean	248.8	181.5
Variance	15077.1	6761.8
Standard deviation	82.2	122.2

Table 4.9 Gross margin calculation for maize crop grown with and without RWH system

Maize grown under RWH system		
Yield (t/ha)		5.8985
Producer price (Tshs./t)		72,000.00
Gross return (Yield x Price)		424,656.00
FIXED COST Inputs:	Mandays	Cost
Land clearing	40	40,000.00
Measuring of catchment	10	10,000.00
Cost of pegs	4	4,000.00
Bunds building	45	45,000.00
Tank construction:		
Tank excavation	40	80,000.00
Brick layering:		
Skilled labour	25	180,000.00
Unskilled labour	25	80,000.00
Watering & compaction of tank surface	10	12,000.00
Silt trap construction	20	90,000.00
TOTAL LABOUR	219	
LABOUR UTILIZATION COST		541,000.00
Material costs:		
Cements (75 bags)		300,000.00
Aggregates & sand (7 tonnes)		25,000.00
Bricks (1875)		312,500.00
Transport		100,000.00
TOTAL FIXED INPUT COST		1,278,500.00
Fixed input costs distribited over life span of tank (10 years)		127,850.00
VARIABLE COSTS:		
Plots cultivation	40	40,000.00
Planting	26	26,000.00

Weeding	20	20,000.00
Thinning	20	20,000.00
Manure application	4	4,000.00
Chemical application	4	4,000.00
Water application	40	40,000.00
Harvesting	25	25,000.00
Threshing	15	15,000.00
Dehusking	20	20,000.00
TOTAL LABOUR	214	
LABOUR UTILIZATION COST		214,000.00
Material cost:		
Pesticide (10 litre)		8,000.00
Seed		15,000.00
Farm manure (10 tones)		15,000.00
GRAND TOTAL LABOUR	433	
TOTAL VARIABLE COST		252,000.00
GROSS MARGIN (GM)		172,656.00
RETURNS ON LABOUR (GM/TOT LABOUR)		399.00
Maize grown without RWH system:		
Yield (t/ha)		4,007.00
Producer price (Tshs./t)		72,000.00
Gross return		288,504.00
TOTAL LABOUR	214	
LABOUR UTILIZATION COST		214,000.00
TOTAL VARIABLE COST		252,000.00
GROSS MARGIN		36,504.00
RETURNS ON LABOUR		171.00

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This study was aimed at evaluating the economic feasibility of RWH storage system under consideration. This involved assessing the applicability of the structured modified bioeconomic model developed in Indian condition. The essence of this study therefore, was to evaluate the performance of this model in local condition of Tanzania in a modified mode of operation.

In an attempt to achieve this objective, measured and simulated yield data were correlated in this exercise, to examine the applicability of this model in areas situated in harsh climatic condition with emphasis on unreliable and erratic rainfall areas such as Hombolo in Dodoma.

In view of the above findings the following conclusions can be made:

(i) Results generally have shown good agreement between simulated and measured data values of soil moisture content, run–off yield, and maize yield respectively.

(ii) The bioeconomic model can be used to simulate the daily soilmoisture content variation using climatological data and simple soil characteristics. Apparently, farm sites differ in terms of soils, moisture content, topography, these usually are reflected by variations in land capability, hence no universal soil moisture criteria can cater for different soil types and climate advantages. Therefore each soil type can be treated separately and the model is to give guidance only. Therefore, to use the model to simulate soil moisture content at different location with different soil type and climate, different parameters will have to be calibrated and used in the model for the new location. The major parameters that will have to be considered include, watershed soil water retention parameter, soil moisture content, and run-off yield. This will, therefore require actual field tests to be conducted and results be used to calibrate the model before put in use.

(iii) Gross margin results (net benefits) and returns on labour spent, indicate relatively high positive coefficients derived from plots with RWH storage compared to the plots without RWH storage.

(iv) Based on high gross margin coefficients and returns on labour for one growing season, conclusion can be made that RWH system is profitable and has potential for improving agricultural production in semi-arid areas like Hombolo in Dodoma.

(v) Soil- crop- water relationships were simulated using the model, and simulated values were correlated with measured data available from the field experiment. Out of this comparison, it was possible to conclude that, the catchment size ratio of 4:1 of RWH storage system was economic size for maize crop growing at Hombolo.

The conclusions are drawn from data sets obtained from the controlled field experiments designed with actual farm conditions in mind . The field experiments however, may not be fully representative of the on-farm conditions because of differences in farm size, household labour allocation, availability and opportunity costs. Nevertheless, they give a base line indications of the economic feasibility of RWH based crop production system.

The model however, showed weakness in terms of measuring evapotranspiration, and drainage. Using constant parameters from literature and assuming that drainage is instantaneous, might have led to overprediction, also the determination of potential evapotranspiration (PET) on monthly basis rather than on growth phases might have contributed to overprediction of yield response to water as well.

As regards to the gross margin calculation, computation based on one growing season could not have given better reflection of price variations that characterises Tanzania market, hence over estimation of net returns.

5.2 Recommendations

Based on the above findings the following recommendations can be made:

(i) The procedure used in this study for estimating soil moisture content, run-off, yield response, can be extended and used to simulate the three parameters mentioned above. However, since this is an empirical model, comparison with field observations that reflect authentic farm characteristics should be made once another location is chosen.

(ii) It is also recommended that, further studies should include root growth, soil drainage submodels so as to be precise in determining soil moisture status as well as readily available water to crops.

(iii) Economic analysis carried out in this study was based on the gross margin technique, which determines short-term net benefits. Since the storage tank is a long-term asset which generates a stream of benefits for several years in future, it is therefore recommended that further studies based on net present value (NPV) and internal rate of return (IRR) be carried out. Both criteria entails long term data series. The derived results will strengthen the findings of this study.

The RWH technology applied in this study should therefore be extended to on-farm conditions and by results of farmer participatory research . The inclusion of the RWH tested here along with other biological measures, land use systems and whole farming system is recommended.

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APPENDICES

Appendix A: Bioeconomic model

This programme determines daily soil water balance ,daily crop water requirement, day to apply supplementary irrigation. It calculates size of storage, and determines return from supplementary.

```
PROGRAM BIO_ECONOMIC_MODEL(INPUT,OUTPUT);
 USES CRT;
  CONST
  MaxD = 131;
  Area = 50;
   FC = 26.6;
    D = 1;
  TYPE
  GEN=ARRAY[1..MaxD] of real;
  VAR
  Ra,S,IRR,PET,SMC,RUNF,ETa,V,Id:GEN;
  Result:text;
  Value_in:text;
     N,Day:INTEGER;
   MinAw,RAM:Real;
  PROCEDURE  pause;
```

```
   VAR
   Proceed:char;
   BEGIN
   Writeln;
   Writeln;
   Writeln('         THIS IS RWH BIO ECONOMIC MODEL');
   Writeln('         ——————————————————————————————');
   writeln;
   writeln;
   writeln('         PRESS ENTER KEY TO CONTINUE');
   Readln;
   END;

PROCEDURE Calc_RAM(VAR RAM,MinAw:Real);
 VAR Day:integer;
  BEGIN
    For day:=1 TO MaxD DO
   MinAW:=FC/3;
   RAM:=0.6*D*(FC-MinAw);
  END;

 PROCEDURE Calc_ETa(VAR ETa,PET:GEN;var RAM,MinAw:Real);
      VAR
      Day:integer;
     BEGIN
      For Day:=1 to MaxD Do
```

```
   ETa[Day]:=PET[day]*MinAw/RAM;
  end;

PROCEDURE Calc_RUNF(VAR RUNF,Ra,S:GEN);
     VAR
     Day:integer;
 BEGIN
   For Day:=1 to MaxD do IF Ra[Day]>RAM THEN
   RUNF[Day]:=sqr((Ra[Day])-(0.2*S[Day]))/
  ((Ra[Day]) + (0.8*S[Day])) ELSE RUNF[DAY]:=0
 END;

PROCEDURE Calc_SMC(VAR SMC,Ra,IRR,ETa:GEN);
  VAR
  Day:integer;
 BEGIN
  For day:=1 to MaxD DO  IF Ra[Day]<RAM THEN
  SMC[Day]:= Ra[Day] + IRR[Day] - ETa[Day] ELSE SMC[Day]:=FC;
  For day:=1 to MaxD DO
  IF SMC[Day]<=0 THEN SMC[Day]:=0;
  For day:=1 to MaxD DO
  IF Ra[Day]<=RAM THEN RUNF[Day]:=0;
 END;

PROCEDURE Calc_V(VAR V,Ra,ETa,RUNF,SMC:GEN);
  VAR
```

```
    Day:integer;
  BEGIN
    For day:=1 to MaxD DO  IF SMC[Day]<RAM THEN
    V[Day]:=ETa[Day]-Ra[Day]+RUNF[Day]+SMC[Day]-SMC[Day-1];
   For day:=1 to MaxD DO IF V[Day]<0 THEN V[Day]:=0;
  END;


 PROCEDURE Calc_Id(VAR Id,V:GEN);
    VAR
    Day:integer;
  BEGIN
    For day:=1 to MaxD DO
    Id[Day]:= V[Day]/Area;
   For day:=1 to MaxD DO
  END;
PROCEDURE READ_Data(VAR Ra,S,PET,IRR:GEN);
     VAR
     Day:Integer;
     Value_in:text;
   BEGIN
     ASSIGN(Value_in,'A:\Value.Pas');
     RESET(Value_in);
     Readln(Value_in);
     n:=0;
     WHILE NOT EOF (Value_in) DO
      BEGIN
```

```
    n:=n+1;
    day:=n;
    Readln(Value_in,Day,Ra[day],s[day],pet[day],irr[day]);
   END;
  END;
PROCEDURE WRITE_Result(VAR Ra,RUNF,ETa,SMC,V,Id:GEN);
 VAR
 Day:integer;
 Results:text;
 BEGIN
Window(6,10,75,40);
ASSIGN(result,'A:\Output.pas');
REWRITE(result);
writeln(result,'          SUMMARY OF THE OUTPUT');
writeln(result,'============================================
==============================');
writeln(result,'day','Ra(mm)':8,'Vol':5,'Id':8,'RUNF(mm)':10,'ETa(
mm)':8,'SMC(mm)':8 );
writeln(result,'============================================
==============================');
For Day:=1 to MaxD Do
Writeln(result,Day,Ra[Day]:8:2,V[day]:8:2,Id[Day]:8:2,RUNF[Day]
:8:2,ETa[Day]:8:2,SMC[Day]:8:2);
writeln(result);
writeln(result,'============================================
==============================');
```

```
writeln(result);
 END;
 PROCEDURE alert;
 BEGIN
 CLRSCR;
 Writeln;writeln;
 Writeln('1.':10,'PROGRAM EXECUTION HAS BEGUN ');
 Writeln;
 Writeln('3.':10,'THE RESULTS ARE IN FILE OUTPUT');
 Writeln;
 END;
 BEGIN
 clrscr;
 read_data(Ra,S,PET,IRR);
 calc_RAM(RAM,MinAw);
 calc_ETa(ETa,PET,RAM,MinAw);
 calc_RUNF(RUNF,Ra,S);
 calc_SMC(SMC,Ra,IRR,ETa);
 calc_V(V,Ra,ETa,RUNF,SMC);
 calc_Id(Id,V);
 write_result(Ra,RUNF,ETa,SMC,V,Id);
 Alert;
 PAUSE
 END.
```

Appendix A1: Model inputs values.

Day	Ra	PET	IRR	S
1	1.9	0	2.1	0
2	2.8	23.3	1.2	0
3	0	0	1.4	0
4	7	0	1.6	0
5	0.9	0	1.6	0
6	3.9	22.5	2.2	0
7	0	0	2.6	0
8	0	0	1.8	0
9	0	0	2.8	0
10	0	0	3	0
11	0	0	3.6	0
12	0	0	3	0
13	0	0	3.2	0
14	0	23.2	3.2	0
15	0	0	3.4	0
16	2.8	0	1.9	0
17	0	0	3.6	0
18	0	0	3	0
19	1.1	0	2.6	0
20	11.2	21.3	3.1	0
21	0	0	2.6	0
22	17.4	0	2.6	0
23	7.4	19.1	1.6	0
24	5.4	0	1	0
25	0	0	2	0
26	6.6	20.1	1.2	0
27	0.1	0	2.6	0
28	0	0	2.6	0
29	0	0	2.2	0
30	47.8	20.1	5.5	0
31	0	0	4.2	0
32	0	0	4.8	0
33	0	0	4.2	0
34	0	0	4.2	0
35	0	0	6.1	0
36	0	0	5.1	0
37	0	0	8.8	0
38	43.7	19.3	1.3	0
39	0.2	0	2.8	0
40	1.9	0	3.1	0
41	4.4	0	1.9	0
42	3	0	1.3	0
43	0	19.2	3.3	0
44	0.6	0	2.6	0
45	0	0	3.2	0

46	0	0	3.5	0
47	0	0	1.5	0
48	13.9	19.5	3.3	0
49	1.2	0	2.6	0
50	0	0	3.9	0
51	1.1	0	3.4	0
52	4.8	19.6	1.6	0
53	0	0	3.2	0
54	0	0	6.8	0
55	53.8	19.6	4.9	0
56	42.6	17.9	1.4	0
57	0.2	0	2.9	0
58	10.2	18	2.9	0
59	0	0	5.5	0
60	3.5	0	10.3	0
61	54.7	18	3.9	0
62	21.7	14.7	3.4	0
63	0.2	0	3.7	0
64	0	0	6.7	0
65	7.3	0	4.4	0
66	23.8	17.3	3.2	0
67	0	0	5.8	0
68	30.6	0	5.1	0
69	0	17.8	4.1	0
70	0	0	9.1	0
71	44.9	17	3.2	0
72	0	0	4.1	0
73	4	18.1	4.1	0
74	0	0	7.1	0
75	6.7	19.1	5.5	0
76	0	0	5.1	0
77	0	0	4.6	0
78	0	0	5.5	0
79	0	0	4.6	0
80	0	0	5.1	0
81	0	0	4.1	60
82	0	19.1	5.5	0
83	0	0	6.4	0
84	0	0	4.1	0
85	0	0	4.6	0
86	0	0	5.5	0
87	0	0	4.1	0
88	0	0	6.0	0
89	0	20.6	2.6	60
90	0.3	0	3.8	0
91	0	0	4.8	0
92	0	0	2.9	0
93	0	0	5.4	0
94	0	0	2.6	0
95	0	0	3.8	0
96	0	21.7	4.5	0

97	0	0	4.6	0
98	9.7	0	3.3	0
99	1.2	22.3	3	0
100	0.2	0	4.2	0
101	0	0	3.8	0
102	0	0	3.2	0
103	0	0	2.9	0
104	0	0	2.9	0
105	0	0	3.2	0
107	0	0	3.8	0
108	0	0	3.7	0
109	0.8	22.1	2.7	0
110	0.7	0	3.2	0
111	0	0	2.6	0
112	0	0	5.1	0
113	31.4	0	3.2	0
114	0.5	22.2	3.5	0
115	0	0	3.5	0
116	0	0	2.9	0
117	0	0	3.2	0
118	0	0	2.5	0
119	1.4	0	2.9	0
120	0	0	2.9	0
121	0	0	2.9	0
122	0	0	2.6	0
123	0	0	2.3	0
124	0	0	1.9	0
125	0	0	3.5	0
126	0	0	2.9	0
127	0	0	3.5	0
128	0	0	3.8	0
129	0	0	2.7	0
130	8	0	1.9	0

Appendix A2: Summary of the model output

day	Ra(mm)	Vol	Id	RUNF(mm)	ETa(mm)	SMC(mm)
1	1.90	0.00	0.00	0.00	1.7500	18.00
2	2.80	0.00	0.00	0.00	1.0000	1.80
3	0.00	0.00	0.00	0.00	1.1667	0.00
4	7.00	0.00	0.00	1.67	1.3333	5.67
5	0.90	0.00	0.00	0.00	1.3333	0.00
6	3.90	0.00	0.00	2.07	1.8333	23.30
7	0.00	0.10	0.00	0.00	2.1667	0.00
8	0.00	1.50	0.03	0.00	1.5000	0.00
9	0.00	2.33	0.05	0.00	2.3333	0.00
10	0.00	2.50	0.05	0.00	2.5000	0.00
11	0.00	3.00	0.06	0.00	3.0000	0.00
12	0.00	2.50	0.05	0.00	2.5000	0.00
13	0.00	2.67	0.05	0.00	2.6667	0.00
14	0.00	2.67	0.05	0.00	2.6667	23.20
15	0.00	2.83	0.06	0.00	2.8333	0.00
16	2.80	0.00	0.00	0.00	1.5833	1.22
17	0.00	1.78	0.04	0.00	3.0000	0.00
18	0.00	2.50	0.05	0.00	2.5000	0.00
19	1.10	1.07	0.02	0.00	2.1667	0.00
20	11.20	0.00	0.00	8.71	2.5833	26.60
21	0.00	0.00	0.00	0.00	2.1667	0.00
22	17.40	0.00	0.00	17.40	2.1667	26.60
23	7.40	0.00	0.00	5.67	1.3333	6.07
24	5.40	0.00	0.00	0.73	0.8333	4.57
25	0.00	0.00	0.00	0.00	1.6667	0.00
26	6.60	0.00	0.00	4.94	1.0000	20.26
27	0.10	0.00	0.00	0.00	2.1667	0.00
28	0.00	2.17	0.04	0.00	2.1667	0.00
29	0.00	1.83	0.04	0.00	1.8333	0.00
30	47.80	0.00	0.00	30.72	4.5833	30.72
31	0.00	0.00	0.00	0.00	3.5000	0.00
32	0.00	4.00	0.08	0.00	4.0000	0.00
33	0.00	3.50	0.07	0.00	3.5000	0.00
34	0.00	3.50	0.07	0.00	3.5000	0.00
35	0.00	5.08	0.10	0.00	5.0833	0.00
36	0.00	4.25	0.08	0.00	4.2500	0.00
37	0.00	7.33	0.15	0.00	7.3333	0.00
38	43.70	0.00	0.00	31.84	1.0833	31.62
39	0.20	0.00	0.00	0.00	2.3333	0.00
40	1.90	0.68	0.01	0.00	2.5833	0.00
41	4.40	0.00	0.00	0.00	1.5833	2.82
42	3.00	0.00	0.00	0.00	1.0833	1.92
43	0.00	0.83	0.02	0.00	2.7500	28.38
44	0.60	1.57	0.03	0.00	2.1667	0.00
45	0.00	2.67	0.05	0.00	2.6667	0.00
46	0.00	2.92	0.06	0.00	2.9167	0.00
47	0.00	1.25	0.02	0.00	1.2500	0.00

48	13.90	0.00	0.00	3.39	2.7500	30.62
49	1.20	0.00	0.00	0.00	2.1667	0.00
50	0.00	3.25	0.07	0.00	3.2500	0.00
51	1.10	1.73	0.03	0.00	2.8333	0.00
52	4.80	0.00	0.00	0.52	1.3333	26.12
53	0.00	0.00	0.00	0.00	2.6667	0.00
54	0.00	5.67	0.11	0.00	5.6667	0.00
55	53.80	0.00	0.00	35.81	4.0833	27.22
56	42.60	0.00	0.00	26.75	1.1667	32.78
57	0.20	0.00	0.00	0.00	2.4167	0.00
58	10.20	0.00	0.00	4.78	2.4167	33.78
59	0.00	0.00	0.00	0.00	4.5833	0.00
60	3.50	5.08	0.10	2.00	8.5833	0.00
61	54.70	0.00	0.00	37.79	3.2500	29.07
62	21.70	0.00	0.00	10.52	2.8333	33.79
63	0.20	0.00	0.00	0.00	3.0833	0.00
64	0.00	5.58	0.11	0.00	5.5833	0.00
65	7.30	0.00	0.00	4.80	3.6667	3.63
66	23.80	0.00	0.00	10.99	2.6667	30.88
67	0.00	0.00	0.00	0.00	4.8333	0.00
68	30.60	0.00	0.00	21.60	4.2500	29.70
69	0.00	0.00	0.00	0.00	3.4167	0.00
70	0.00	7.58	0.15	0.00	7.5833	0.00
71	44.90	0.00	0.00	29.44	2.6667	30.69
72	0.00	0.00	0.00	0.00	3.4167	0.00
73	4.00	0.00	0.00	0.00	3.4167	31.58
74	0.00	5.33	0.11	0.00	5.9167	0.00
75	6.70	0.00	0.00	2.80	4.5833	30.12
76	0.00	2.13	0.04	0.00	4.2500	0.00
77	0.00	3.83	0.08	0.00	3.8333	0.00
78	0.00	4.58	0.09	0.00	4.5833	0.00
79	0.00	3.83	0.08	0.00	3.8333	0.00
80	0.00	4.25	0.08	0.00	4.2500	0.00
81	0.00	0.00	0.00	0.00	3.4167	27.92
82	0.00	0.00	0.00	0.00	4.5833	0.00
83	0.00	5.33	0.11	0.00	5.3333	0.00
84	0.00	3.42	0.07	0.00	3.4167	0.00
85	0.00	3.83	0.08	0.00	3.8333	0.00
86	0.00	4.58	0.09	0.00	4.5833	0.00
87	0.00	3.42	0.07	0.00	3.4167	0.00
88	0.00	5.00	0.10	0.00	5.0000	0.00
89	0.00	0.00	0.00	0.00	2.1667	26.38
90	0.30	0.00	0.00	0.00	3.1667	0.00
91	0.00	4.00	0.08	0.00	4.0000	0.00
92	0.00	2.42	0.05	0.00	2.4167	0.00
93	0.00	4.50	0.09	0.00	4.5000	0.00
94	0.00	2.17	0.04	0.00	2.1667	0.00
95	0.00	3.17	0.06	0.00	3.1667	0.00
96	0.00	3.75	0.07	0.00	3.7500	26.12
97	0.00	3.83	0.08	0.00	3.8333	0.00
98	9.70	0.00	0.00	4.78	2.7500	25.76

99	1.20	0.00	0.00	0.00	2.5000	0.00
100	0.20	3.30	0.07	0.00	3.5000	0.00
101	0.00	3.17	0.06	0.00	3.1667	0.00
102	0.00	2.67	0.05	0.00	2.6667	0.00
103	0.00	2.42	0.05	0.00	2.4167	0.00
104	0.00	2.42	0.05	0.00	2.4167	0.00
105	0.00	2.67	0.05	0.00	2.6667	0.00
106	0.00	0.00	0.00	0.00	0.0000	0.00
107	0.00	3.17	0.06	0.00	3.1667	0.00
108	0.00	3.08	0.06	0.00	3.0833	25.01
109	0.80	1.45	0.03	0.00	2.2500	0.00
110	0.70	1.97	0.04	0.00	2.6667	0.00
111	0.00	2.17	0.04	0.00	2.1667	0.00
112	0.00	4.25	0.08	0.00	4.2500	0.00
113	31.40	0.00	0.00	22.35	2.6667	28.46
114	0.50	0.00	0.00	0.00	2.9167	0.00
115	0.00	2.92	0.06	0.00	2.9167	0.00
116	0.00	2.42	0.05	0.00	2.4167	0.00
117	0.00	2.67	0.05	0.00	2.6667	0.00
118	0.00	2.08	0.04	0.00	2.0833	0.00
119	1.40	1.02	0.02	0.00	2.4167	0.00
120	0.00	2.42	0.05	0.00	2.4167	0.00
121	0.00	2.42	0.05	0.00	2.4167	0.00
122	0.00	2.17	0.04	0.00	2.1667	0.00
123	0.00	1.92	0.04	0.00	1.9167	0.00
124	0.00	1.58	0.03	0.00	1.5833	0.00
125	0.00	2.92	0.06	0.00	2.9167	0.00
126	0.00	2.42	0.05	0.00	2.4167	0.00
127	0.00	2.92	0.06	0.00	2.9167	0.00
128	0.00	3.17	0.06	0.00	3.1667	0.00
129	0.00	2.25	0.04	0.00	2.2500	0.00
130	8.00	0.00	0.00	4.80	1.5833	6.42

Appendix B: Design Procedure of modified bioeconomic model of RWH system

- Read daily climatic data from data file
- Read the initial available soil moisture content
- Determination of Fc, PWP, ASM, SMsp. These were determined from the equations from general information, as well as other researchers and from soil data collected at the experimental site.
- Determination of ASM given as:

$$ASM = D_{rz} \frac{(Fc - Pwp)}{100} \qquad (9)$$

- Determination of critical soil moisture as a proportion of total available moisture content expressed by the equation:

  a = 0.94 − (2.6/PT) **(10)**
- Determination of readily available soil moisture content (RASMc)
- RASM = P.Drz.ASM
- Read ETcrop , P_{eff}, Ro , SMc,i.
- Determination of effective rainfall for the growing season as:

$$P_{Eff,Gs} = P_{tot,Gs} \times \frac{ETm}{P_{tot,Gs}} + AIn,Gs \qquad (11)$$

If SMc,i < a implies need for water application (irrigation).

- Compute net irrigation application (In)

$$I_n = ETcrop - P_{Eff} - Ro + (Fc - \theta c) \quad (12)$$

- Compute water application depth (Id)

$$Id = \frac{I_n}{Ea} \quad (13)$$

- Compute volume of water of application

$$V = Id \times CF \quad (14)$$

$$V = Id \times CF = [\frac{ETcrop - PEff - Ro + (Fc - \theta c)}{Ea}] CF \quad (15)$$

- Determination of catchment size

$$\frac{CA}{CF} = \frac{ETcrop - P_{Eff}}{P_{Eff} \times k \times Ef} \quad (16)$$

- Calculation of run-off(Ro)

$$Ro = \frac{(Ra - 0.2\,s)^2}{Ra + 0.8\,s} \quad (17)$$

- Compute actual evapotranspiration

$$T = PT \text{ , if } SM \geq a\ (ASM) \tag{18}$$

$$T = \frac{SM \times PT}{a \times ASM} \text{ , When } SM < a \times ASM \tag{19}$$

$$PT = Kc\, b \times Ep \tag{20}$$

- Compute yield reduction in percentage

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y \left(1 - \frac{ET_a}{PTE}\right) \tag{21}$$

- Compute net return

Gross margin = Gross Income – Variable cost

$$Net\ Return = Py\, Y - \phi\,(W)\, CF - \psi\,(TW) \tag{22}$$