WATER-BALANCE AND RICE YIELDS IN A TROPICAL ENVIRONMENT: - A CASE STUDY OF MWEA IRRIGATION SETTLEMENT, KIRINYAGA DISTRICT, KENYA

by

ISAAC J. NDOLO

A thesis submitted in part fulfilment for the degree of Master of Science (M.Sc.) in Geography (Climatology) in the University of Nairobi.

UNIVERSITY OF NAIROBI

November 1985

DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

Signature ....

ISAAC J. NDOLO

This thesis has been submitted for examination with my approval as University Supervisor.

Signature ....

PROF. R.S. ODINGO

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Prof. R.S. Odingo (of Department of Geography, University of Nairobi) for his invaluable guidance, continuous evaluation of this thesis, the important and very relevant suggestions, help and tolerance he exercised during the entire period of the preparation and writing of the thesis.

The author is also very grateful to Dr. I.J. Stewart (of World Hunger Alleviation through Response Farming, W.H.A;R.F., Davis, California) and Mr. J.O. Mugah of Kenya Agricultural Research Institute (K.A.R.I.), who both provided guidance and methodology on analysis of data for this work. Many thanks also go to the Kenya National Irrigation Board (N.I.B.) field officers at Mwea Irrigation Settlement who provided most of the raw data on which this work is based. They also allowed the author to consult their other records.

Appreciation must also be recorded to Mr. D. Mungai of the Department of Geography, University of Nairobi who spared time to discuss the framework of this thesis and provided invaluable comments on the work.

Special thanks go to Prof. J.E. Lewis of McGill University, Department of Geography, Canada for reading the manuscript and for offering very useful suggestions.

The author feels indebted to his wife Agnes Wambui, son Mukuvi and daughter Kamene for their tolerance when this work was being done.

Last but not least, the author thanks Mrs. Mumo for her patience and care in typing this thesis.

ABSTRACT

This study is primarily concerned with the investigation of water requirements of Sindano rice under irrigation conditions in Mwea Irrigation Settlement Scheme in the Kirinyaga District of the Central Province of Kenya. The study is based on the assumption that under tropical conditions, water requirements of plants are decisive on yields provided the soils are suitable. In the Mwea Irrigation Settlement Scheme, rice agriculture depends on rainfall, but rice yields are maintained by supplementary irrigation. The study therefore started with the further assumption that the nature and efficiency of this supplementary irrigation would be decisive in determining the level and quantity of rice yields in the study area.

The water requirement for Sindano rice, (ETrice), was estimated by Pan Evaporation method on ten-day basis during the crop season for 7 seasons determined by the availability of data.

It was found that Sindano rice crop requires about 691mm of water, the mean for the 7 seasons whose standard deviation was 56.5mm.

The seasonal Sindano rice water requirement in Mwea, obtained in this study compares well with the results obtained by Leonard (1948), working with other rice varieties in Japan, obtained 685mm. However, the Mwea values obtained were considerably lower than those obtained by Lourence and Pruitt (1971) working in California and using data based on ten-year mean. Their ETrice figure was 890mm.

The cumulative soil-water balance method developed by the International Rice Research Institute (I.R.R.I) as demonstrated by Oldeman and Frere (1982) was used to calculate the rice seasonal water balances of Mwea paddy fields for ten-day periods. It was found that in most of the ten-day periods, the Sindano rice water requirement was met by rainfall and supplementary irrigation and the surplus water was stored in the bunded paddy fields. In some of the ten-day periods, there were overflows due to "over-irrigation".

Of the seven seasons considered in the study, the 1971 season was found to be the only one which had suitable water management for rice agriculture as indicated by Doorenbos and Kassam (1979). The amount of water in the paddy fields for each of the ten-day periods during this season matched the water requirements of Sindano rice calculated on the basis of potential evapotranspiration (Pan Evaporation method).

The seasonal irrigation efficiencies in the area were calculated by use of a formula modified from Hagan et al. (1967) and Schmueli (1979) and applied by van Gessel (1982). The highest seasonal irrigation efficiency for the seven seasons was found to be 83% in the 1971 season and the lowest was 46% in the 1982 season. The other five seasons had irrigation efficiencies well above 60% which is the postulated lower bound for furrow irrigation (Sarraf, 1971). The seasonal effective rainfall amounts during the rice growing seasons were obtained by use of simple water balance calculations developed by Kashasha (1982) for dry-land crops but modified by the author for paddy rice.

The highest percentage of seasonal effective rainfall obtained was 92% for both 1970 and 1971 seasons. The lowest was 44% in the 1974 season. Seasonal effective rainfall in the area was found to be primarily influenced by the temporal distribution of the seasonal rains considered on ten-day period basis and also by the soil moisture conditions, stage of growth of the rice crop, and the previous irrigation depth.

The simple linear regression model and analysis of variance were used to establish the significance of water management to rice water requirements and also grain yield in Mwea Irrigation Settlement. The

significance was tested by F-test statistic at 90% confidence limit ($\alpha = 0.10$). The water requirement by Sindano rice in ten-day periods was found to be linearly and significantly related to rainfall plus irrigation with a coefficient of determination, $r^2 = 0.87$, for the seven seasons (84 ten-day periods).

No significant relationships were found between Sindano rice grain yield and seasonal water deficit. Similarly, the respective periods of first 100, 30-40 and 50-90 days after transplanting water deficits were not significantly associated with rice grain yield. In the same way, seasonal overflow and seasonal deep percolation were not found to be significantly related to rice grain yield for six of the seasons studied, excluding the 1981 season. This season had the lowest yield due to a strike by the tenant farmers in the area which led to an incomplete harvest, and unsatisfactory records for purposes of calculating the significance of water management to yields.

On the basis of the results obtained in the study, it was concluded that water variables in Mwea Irrigation Settlement explain only a small percentage of the variability of seasonal rice grain yield. Seasonal rice grain yields are not significantly related to water management. Due to this, it was concluded that other environmental factors including socio-economic considerations may have to be examined for a fuller explanation of the season to season fluctuations of the rice grain yield in Mwea Irrigation Settlement.

TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES AND THEIR CAPTIONS

Page

LIST OF TABLES AND THEIR CAPTIONS

CHAPTER 1: INTRODUCTION

1.1. Statement of the research problem

This study intends to estimate the water use by the rice crop and the supply of water by rainfall and supplementary irrigation during the rice growing season in Mwea Irrigation Settlement. It is also the intention of the study to investigate the influence of water availability during the crop season on rice yields.

Crop-water studies in East Africa have concentrated mainly on "rainfed" crops especially maize while water use by "wetland" crops such as paddy rice has not been properly elucidated hence the need for this study. Most agronomic studies on paddy rice stress the aspects of soil management, temperature and field crop maintenance leaving the aspect of water assumed to be non-limiting to the crop production.

The importance of availability of water for plant crop growth cannot be under-estimated in agronomic studies. This study investigates the rice-water relationship by estimating the rice potential evapotranspiration, (ETrice), and then comparing the values with the supply of water by rainfall and supplementary irrigation on a ten-day basis for the entire rice season in Mwea Irrigation Settlement.

The cumulative soil-water balance model is used to assess the seasonal water conditions in Mwea paddy fields and consequently, estimates of the seasonal irrigation efficiency are simulated. This helps to determine the optimum irrigation scheduling procedures suitable for rice agriculture in the area.

This study, in addition, investigates whether the seasonal variations in water availability are responsible for fluctuations in rice grain yields in Mwea Irrigation Settlement.

1.2. Literature Review

1.2.1. Theoretical Basis

Man throughout history has been able to deal with his environment successfully by developing plants and improving crop varieties adapted to his needs. He has developed suitable practices to use water, fertilizer and pesticides for increased agricultural production. Despite these achievements, he has not been able to master climate and has remained under the threat of drought resulting in crop failure.

In the tropics where the major climatic conditions are not precisely predictable, crop failures due to low and erratic rainfall during the crop growing seasons have been frequent. Crop-climate studies in the tropics are essential to improve our

The cumulative soil-water balance model is used to assess the seasonal water conditions in Mwea paddy fields and consequently, estimates of the seasonal irrigation efficiency are simulated. This helps to determine the optimum irrigation scheduling procedures suitable for rice agriculture in the area.

This study, in addition, investigates whether the seasonal variations in water availability are responsible for fluctuations in rice grain yields in Mwea Irrigation Settlement.

1.2. Literature Review

1.2.1. Theoretical Basis

Man throughout history has been able to deal with his environment successfully by developing plants and improving crop varieties adapted to his needs. He has developed suitable practices to use water, fertilizer and pesticides for increased agricultural production. Despite these achievements, he has not been able to master climate and has remained under the threat of drought resulting in crop failure.

In the tropics where the major climatic conditions are not precisely predictable, crop failures due to low and erratic rainfall during the crop growing seasons have been frequent. Crop-climate studies in the tropics are essential to improve our understanding of the problem of crop failures through scientifically informed interventions. Such studies have been intensified in the last thirty years since the classical contributions of Thornthwaite (1948) and other workers who were inspired by Thornthwaite's work. Numerous results and suggestions from agro-climatological studies have helped scientists to better understand crop environment interactions. Porter (1981) noted that the growth of crops in a particular environment depends on their ability to integrate the environmental factors, both abiotic and biotic with the influence by man being the most important.

Of the various climatic factors at work in the plant environment in the tropics, rainfall is the major one which limits the agricultural potential of land. The three specific characteristics of rainfall which play this significant role are, its amount, frequency and intensity during the crop growing season (Dastane, 1974).

The above characteristics of rainfall are very unpredictable in the tropics and have made the tropical environment a risky place for agricultural pursuit if considered in terms of assured crop harvests. In their discussion of crop water requirements in tropical areas, Sarker and Biswas (1978) have stressed that the importance of rainfall even more than other climatic elements for successful agriculture. In their view, the relationship is best illustrated in water balance simulations for specific areas.

Earlier investigations of rainfall in East Africa by Griffiths (1958) were based on the assumptions that its annual distribution is normal for most parts of the region. Nevertheless, basing their work on these assumptions, climatologists proceeded to calculate probabilities of receiving certain selected amounts of rainfall suited to specific crops as was done for maize by Braun (1977) in Machakos and Kitui Districts, Kenya. This has proved to be incorrect as will be discussed in later sections of this study.

However, recent analyses of rainfall for crop agriculture dispute the use of the mean annual or even the mean monthly rainfall amounts in calculation of probabilities mainly because it has been shown that variations in shorter periods such as five or ten days are not indicated while they may have decisive effects on crop growth and eventually the crop yield.

Analysis of rainfall data for crop agriculture should be based on the actual amount of rainfall received within shorter periods of the crop season (da Mota, 1978 and Mungai, 1985). The analysis of rainfall alone is not sufficient to define and identify suitable growing seasons for specified crops. Equally important are other considerations such as the soil moisture status before and after rainfall because it determines the water availability for crops. Stewart and Wang'ati (1978) noted that the water needs of crops in some parts of East Africa are inversely correlated with rainfall such that when the water needs of crops are high, rainfall is low and yet the crops still manage to grow. This observation calls for further investigation of the significance of soil moisture conditions and how the rainfall received within a certain period contributes to the soil moisture storage.

Not all rainfall received is available to crops as is now scientifically well established. Of the rainfall received, some will be lost as run-off and evaporation while part of that which goes into the soil, some is lost as deep percolation beyond the root zone of crops. Dastane (1974) indicated the pathway of rain water and showed that only a proportion of the rainfall received is available to crops which he defined as "effective rainfall". The amount of effective rainfall depends on the soil moisture conditions and the soil water retention capability. Thus in planning for agriculture, the aspect of water loss is equally as important as the amount available for the plant use.

The evaporation potential of the atmosphere is another important aspect to he considered when estimating the water availability to crops during their growing season. Jackson (1977) indicated that the evaporative demand of the atmosphere depends on the nature of the evaporating surface and the availability of water. The surface modifies the climatic elements by creating differences in net radiation received which is the driving force for evaporation.

Doorenbos and Pruitt (1975) noted that evaporation integrates numerous climatic elements which include solar radiation, temperature, wind run and the atmospheric vapour pressure gradient. Commenting on the same issue, Hargreaves (1975) asserted that since evaporation is termed as an integrator of energy, it can be used to determine water requirements by crops as their potential transpiration is positively correlated with potential evaporation. To demonstrate this principle, Mugah and Stewart (1982) estimated water requirement by maize using evaporation data from Kenya Agricultural Research Institute, Muguga.

Other losses of water from the soil surface and within the soil are clearly understood when water balance simulations are done. Slatyer (1968) assessed the water balance model as a difficult one to apply since it requires elaborate and specialised data on soil water conditions such as field capacity and wilting point then rainfall, evapotranspiration and irrigation (if any).

The water balance model according to Chang (1968) requires relationships which predict the available water capacity of the soil in the crop root zone, the increment of soil water storage after rainfall or irrigation, drainage below the root zone and evapotranspiration from the cropped surface. Franquin (1978) noted that despite the complexity of the water balance model, it can be constructed based entirely on the ratio of rainfall to potential evapotranspiration while Agnew (1982) described the water balance model as the plant-soil-water system in a two-dimensional series of hydrological inputs and outputs.

From the above observations, it is evident that there is no one agreed water balance model but the concept can be defined according to specific research requirements based on the intended purpose of its application. Rijks (1975) added that the availability of reliable data for specified water balance simulations is essential since water requirements of crops vary with their stages of growth and development during their growing season.

1.2.2. Crop-related Studies - Rice

Most agroclimatologists who have worked on the climatological requirements of the rice crop have emphasised the fact that the crop shows a wide adaptability to different soils and climatic conditions. Roy and Seetharaman (1977) noted that despite this wide adaptability of the crop to climate, rice crop has its specific climatic setting for optimum yields. They emphasised the fact that the requirements in general are damp warm climates, where temperatures and humidity are high, prolonged sunshine and assured supply of water.

Doorenbos and Kassam (1979) outlined the standard environmental requirements by paddy rice crop as dry sunny weather, deep well-aerated soil and 300-700mm of water during the crop growing season. Ghildyal and Jana (1967) said that variations in the environmental conditions especially temperatures and water supply influence rice yields significantly.

Roy and Seetharaman (1977) also carried out a research in India as an attempt to understand the effect of climatic variables on rice crop at different phases of its growth and development. Their results showed that rice reacts differently to various climatic parameters at the various phases. From their multiple regression model, they found that the ripening phase of rice is the most susceptible to excessive rainfall while a deviation of ± 1°C from the mean minimum daily temperature (18°C) during this phase has a reducing effect on the rice yields.

Previous studies done on water use by rice in different parts of the world vary in emphasis and conclusions. Leonard (1948) found that the seasonal water requirement of rice in Japan varies from 685 to 1300mm. In Thailand, Kung (1965) reported that the crop requires 1240mm of water throughout the entire season. In Laos, Kotter (1968) found that the seasonal rice water requirement is 1390mm. Lourence and Pruitt (1971) simulated the ten-year mean seasonal water use by rice in California and obtained 890mm as the seasonal rice water requirement. The variability of water requirement by the crop in different parts of the world is associated with different rice varieties, soil moisture retentions, climatic environments and water management in the rice fields.

Other researchers have investigated the effects of water deficiencies during the rice growing seasons. Enyi (1963) found out that the critical period for paddy-field waterlogging in Nigeria is 4 weeks before and 4 weeks after transplanting. According to Salter and Goode (1967), rice crop needs more water at heading and flowering. They warned that a deficiency at these periods can reduce the crop yield significantly. Matsushima (1966) reported that the critical period for water deficit or excess in rice fields of Malaysia is 20 days before, to 10 days after heading.

Studies on water use by paddy rice in East Africa have probably been overlooked since in the areas where the crop is grown, irrigation water is readily available. Due to this, agronomists tend to assume that water is not a limiting factor for rice agriculture. Despite this, it should be realised that; although water is readily available, there are some aspects of water management in the paddy fields such as scheduling of irrigation to avoid overflooding and leaching of nutrients which are very important. van Gessel (1982) examined the factors that determine the water requirements of rice in Mwea Irrigation Settlement and reported them as rainfall, irrigation scheduling and the soil characteristics. He did not emphasise the crop characteristics an an integral part in the determination of Mwea paddy fields' water requirements. Water use by rice and management of water in paddy fields requires investigation for specific sites where the crop is grown while results and recommendations from other areas are obviously not transferrable due to the differences in environmental settings.

1.3. Justification for Choice of Research Topic

Although extensive studies have been done on agronomy of rice in Asian countries and in the United States (California), in African countries, little has been done. This has posed a problem of choice for the suitable water management practices for the rice in the continent. In Kenya, some researchers have applied "blindly" rice-climate research findings from other countries which have different climatic regimes and soils.

This is one reason why it is necessary to mount a study to meet this very important need so as to provide rice agronomists in the country with specific results of research for local application in their work.

Mwea Irrigation Settlement is so far the most successful rice scheme in East Africa where water for irrigation is readily available and the method of water conveyance is relatively cheap. The season to season variations in yields in this scheme have not yet been explained. It is the purpose of the present study to investigate whether these variations in rice yields are due to water management during the crop season.

The water balance components considered in this study are useful as they provide an overview of the water conditions in Mwea paddy fields since they indicate soil moisture changes, evapotranspiration by the crop and drainage on a cumulative basis for entire seasons.

The demand for rice in Kenya has increased considerably in the past decade. This has forced the Government to import rice grain to meet the local demand of the cereal. The present study aims at contributing to a better understanding of rice-water relationships and consequently the possibility of increasing rice yields in all those areas where the crop is grown in the country by improving water management.

1.4. Objectives, Scope and Limitations of the Study

The purpose of this study is to use available meteorological data to estimate the water requirement of rice (ETrice) and to relate it to water supply in the paddy fields of Mwea. This leads to analysis of the seasonal cumulative soil-water balance of Mwea Irrigation Settlement. Further analysis to assess the significance of water supply to the requirements in the paddy fields during the rice season is carried out. This helps in finding out whether the season to season fluctuations in rice yields in the area are attributed to different seasonal levels of water supply.

The study is based on the proposition that the water available to the crop is derived from rainfall, irrigation and from water storage in the paddy soils. The principal aim of this research is to simulate cumulative soil-water balances for paddy fields in the area. The specific objectives of the study are as follows:

i) To estimate the water requirement of rice in Mwea during the growing season using available meteorological data and taking into consideration the growth phases of the rice crop in the area.

ii) To examine the seasonal effective rainfall in the area during the rice growing season as well as the seasonal irrigation efficiency.

iii) To assess the significance of water supply (by rainfall and irrigation) to rice yields in Mwea during the crop season.

This study is largely a quantitative analysis of water supply and requirements in Mwea Irrigation Settlement and makes use of the previously developed crop-climate models.

In modelling crop water requirements and the availability of water, the models used must account for seasonal interaction effects of at least temperature, soil moisture and an energy term (evaporation). The influence of these and other environmental factors on the production of seasonal yields change during the life cycle of the crop. The paddy fields of Mwea are flooded for most of the rice season making it difficult to perform actual analysis of the soil physical properties in the area. This study uses the soil water data obtained from the experimental results of Mwea Vertisols by van Gessel (1979).

The analytic models used in this study are not for detailed biological analyses, for instance, dry matter production but stress the impact of standard climatological variables on crop growth and eventually their influence on rice yields. The next section of this chapter indicates the formulated research hypotheses for this study.

1.5. Research Hypotheses

This study as any other scientific research has stipulated specific objectives and to achieve these objectives, null hypotheses are formulated. According to Gomez and Gomez (1976), agroclimatological studies need to have hypotheses which test the validity of the conceptualised framework from which further deductions can be made.

Chatterjee and Price (1977) outlined the methods required in testing the stated null hypotheses. In this study, the stated hypotheses relate seasonal water input in the paddy fields of Mwea to rice water requirements and grain yields.

The formulated null hypotheses for this study are as follows:

i) Ho: Seasonal fluctuations in rice yields of Mwea Irrigation Settlement are not significantly associated with variations in seasonal rainfall.

   Although in tropical regions, rainfall is the major climatic element which determines the agricultural potential, for irrigated crops excess rainfall during certain periods may reduce crop yields. Similarly, inadequate rainfall may have the same effect on crop yield.

ii) Ho: The relationship between rice water requirements (ETrice) and the seasonal applied water (rainfall and irrigation) in Mwea Irrigation Settlement is not significant.

It must be emphasised that the testing of the degree of association between seasonal applied water and the rice water requirements in Mwea does not necessarily establish the periods of rice water stress. This is due to the fact that the applied water is only considered separately from the storage of moisture in the soil.

iii) Ho: Seasonal irrigation and rainfall in Mwea do not account significantly for the variations in rice yields.

While it is noted that many factors contribute to crop yields (see Fig. 1), the above hypothesis is formulated to establish the degree of association between rice yields and seasonal applied water.

1.6. Operational Definitions and Concepts

This study has some operational terms which have been defined differently by various authors in related fields of research. The terms have been defined below as an indication of their meaning in this study.

Paddy: This is the rice crop grown under submerged conditions. The term in other cases has been used to mean unhusked rice grains (Kotter, 1968). Paddy in this study defines the rice crop grown under submerged conditions or the flooded rice. 'Paddy fields' are the flooded grounds where the paddy is grown.

Evaporation: Evaporation is the change of state of water from liquid or solid to vapour.. This occurs if there is an input of energy (solar radiation) at the moist surface. There has to be a negative vertical gradient of vapour pressure above the surface for this process to occur. The amount of evaporation from a surface depends on the available moisture within the soil and on the rate of diffusion of water vapour away from the surface. In this study, evaporation is used to mean the amount of water lost from open water body as measured by Class "A" Pan Evaporimeters.

Evapotranspiration: This is the total water loss by evaporation from the ground, wet surfaces of the vegetation and transpiration from the vegetal cover. Evapotranspiration is governed by factors, both of the surface and climate. Surface factors comprise of the availability of water, the type of soil and the nature of the plant covering. Climatic influences, on the other hand, are expressed in the heat or energy available to effect the necessary evaporation of moisture and the ability of the atmosphere to accept the moisture being evaporated.

If surface conditions are non-restrictive in the sense that water is plentiful and able to move readily through the soil so that plants can transpire freely, "potential evapotranspiration" will be achieved.

Thus potential evapotranspiration is the evaporation that would occur from a large (one or more hectares), wetted and vegetated land surface (Penman, 1963). Potential evapotranspiration differs from "actual evapotranspiration" which takes place under limited water supply.

In this study, potential evapotranspiration is used synonimously with crop evapotranspiration which otherwise, is the crop water requirement (ETrice). For paddy, evapotranspiration occurs at the potential rate since the soil is saturated for most part of its growing season (Robertson, 1975).

1.7. Conceptual Model

Crop-environment inter-relationships are very complex since the environment incorporates the biotic and abiotic factors which by themselves are inter-related. Similarly, the crop characteristics in terms of growth and development are also inter-dependent. Hence the complexity of the plant-environment system cannot be under-estimated.

In studying the crop-environment interactions, the need for a dynamic model is necessary and it should indicate the importance or contribution of each environmental factor to the growth and performance of the specific crop in the defined environment.

This study therefore, developed a conceptual crop production model presented in Figure 1. This model encompasses the crop and the environment factors and their interactions. The Figure indicates that crop characteristics are mainly influenced by the environmental setting. It demonstrates that climate, soil and field crop management are the most important environmental factors which determine crop production although this might not be true in general since in some regions, a possibility of other local production determining processes may exert a constraining role in plant production.

In the elucidation of crop-water relationships, which is the basis of this study, it is evident from the crop production model that agroclimatic studies are only a simplification of a complex system. The present study is based on the model presented in Figure 1 and will only concentrate on climatic variables (see Fig. 2) and some variables on rice growth and development in an attempt to estimate the rice water requirement in the study area. However,

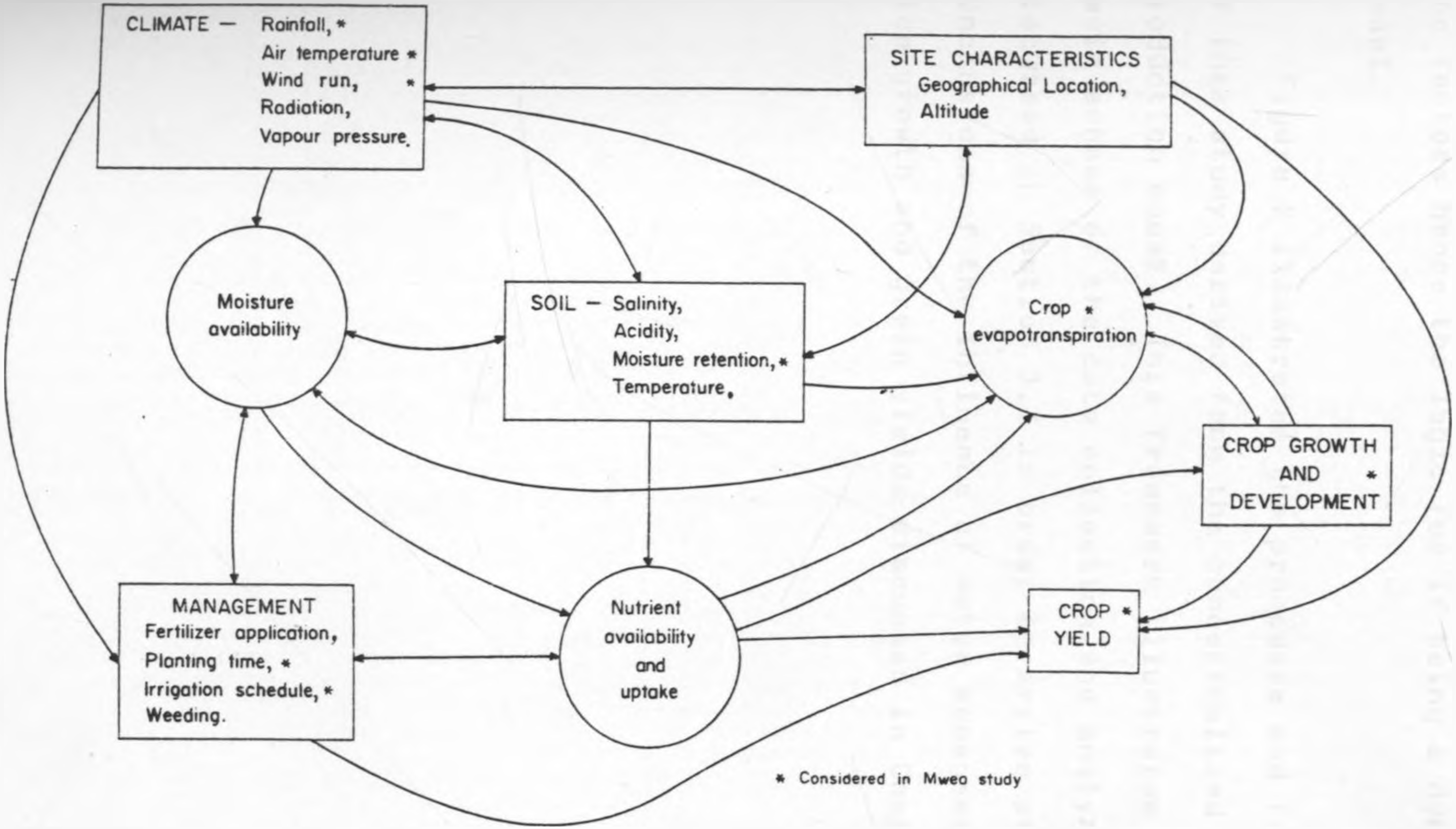


Fig. I CONCEPTUAL CROP PRODUCTION MODEL

it should be noted that a change in any of the variables in this model generates differences in all the factors hence the logic for it being a dynamic model.

Figure 2 illustrates the procedure and framework of this study derived from the conceptualized crop production model. This framework illustrates the basic scheme of the data collection and analysis as discussed in Section 3.3 in order to arrive at the conclusions of the influence of water management to rice growth and grain yields discussed in Chapter 4.

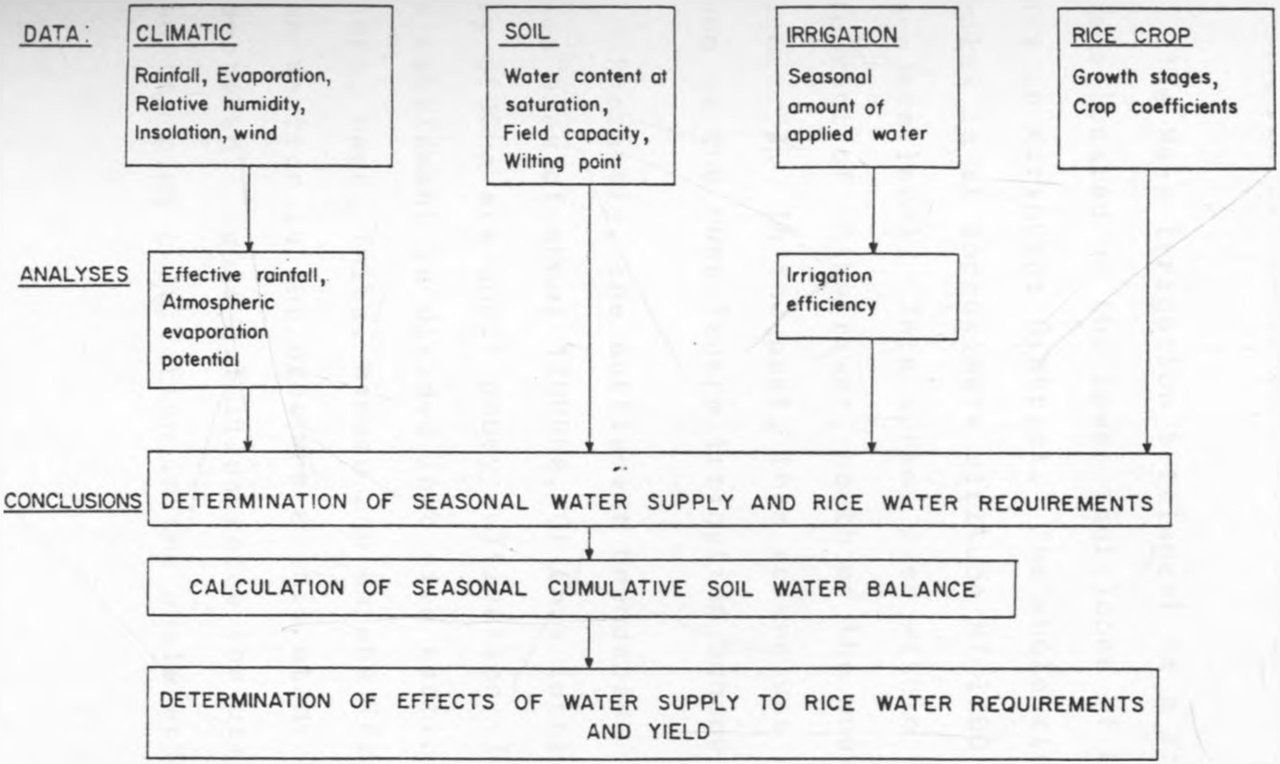


Fig. 2 STUDY-RELATED CONCEPTUAL MODEL

CHAPTER 2: BACKGROUND TO THE STUDY AREA

The Mwea Irrigation Settlement is a rice growing scheme located on the lower footslopes of Mount Kenya in Kirinyaga District. The whole rice growing complex is at approximate altitude of 1300 metres above sea-level. This scheme lies within the upper catchment of Thiba river, south of the mountain (Figure 3). In the past, this scheme was originally known as the Mwea-Tebere Irrigation Scheme.

Presently, the settlement boundaries enclose a gross area of about 12000ha. Of this total area, only 6100ha are under paddy cultivation (Table 2.1). The settlement is divided into five sections called Tebere, Mwea, Thiba, Wamumu and Karaba (Figure 4). Mwea section is the area where this study was undertaken. Table 2.1 illustrates the utilization of land for rice cultivation in the whole scheme.

CHAPTER 2: BACKGROUND TO THE STUDY AREA

The Mwea Irrigation Settlement is a rice growing scheme located on the lower footslopes of Mount Kenya in Kirinyaga District. The whole rice growing complex is at approximate altitude of 1300 metres above sea-level. This scheme lies within the upper catchment of Thiba river, south of the mountain (Figure 3). In the past, this scheme was originally known as the Mwea-Tebere Irrigation Scheme.

Presently, the settlement boundaries enclose a gross area of about 12000ha. Of this total area, only 6100ha are under paddy cultivation (Table 2.1). The settlement is divided into five sections called Tebere, Mwea, Thiba, Wamumu and Karaba (Figure 4). Mwea section is the area where this study was undertaken. Table 2.1 illustrates the utilization of land for rice cultivation in the whole scheme.

Fig 3 LOCATION OF MWEA IRRIGATION SETTLEMENT

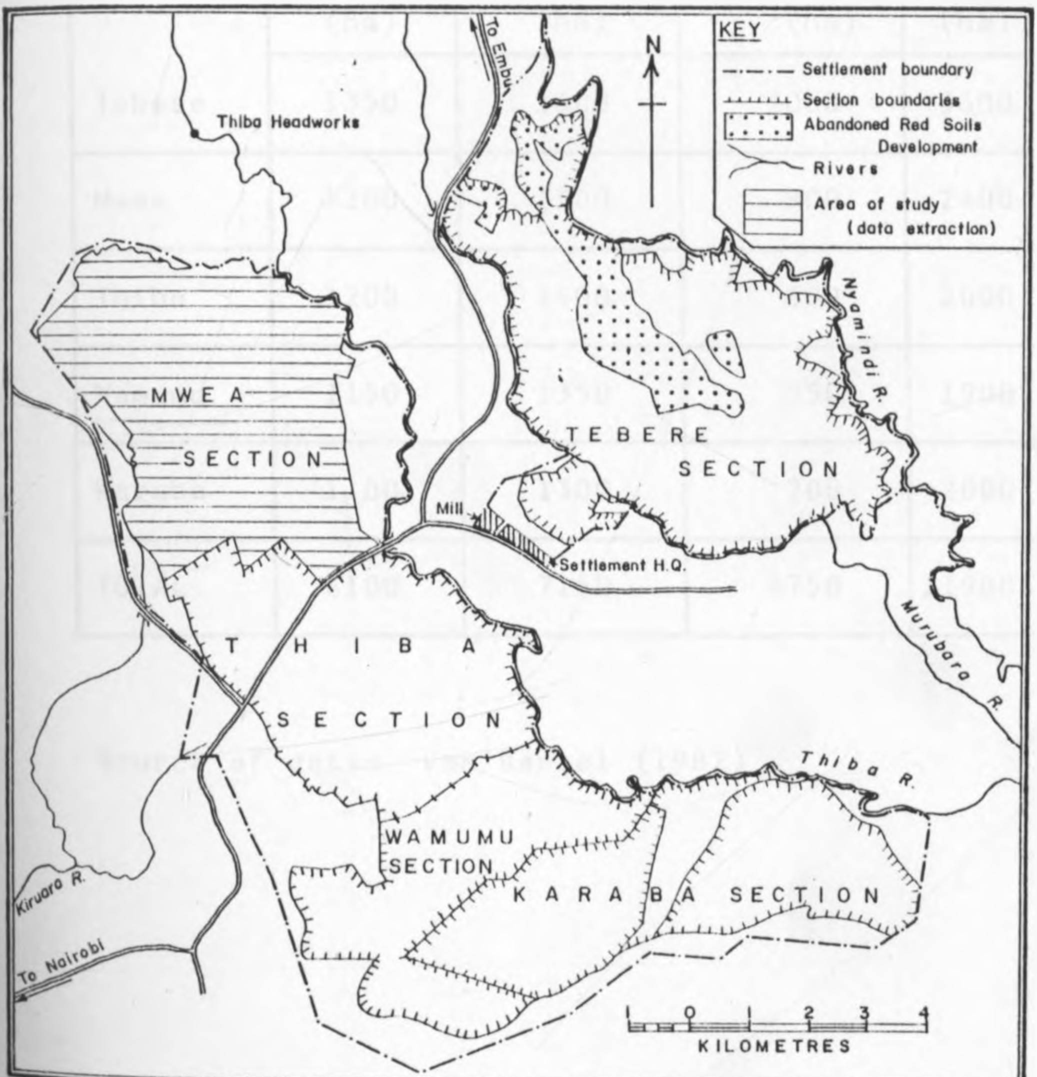


Fig 4 MAP OF MWEA IRRIGATION SETTLEMENT

Table 2.1: The net and gross areas of rice and non-rice lands in Mwea Irrigation Settlement

SECTION	RICE LAND		NON-RICE LAND	GROSS TOTAL
	Net area (ha)	Gross area (ha)	Gross area (ha)	Area (ha)
Tebere	1350	1600	2000	3600
Mwea	1300	1500	900	2400
Thiba	1200	1400	600	2000
Wamumu	1150	1350	550	1900
Karaba	1100	1300	700	2000
TOTAL	6100	7150	4750	11900

Source of data: van Gessel (1982)

The table shows that there are areas in the scheme where rice can be grown in each section but at the time of research these areas were not under rice cultivation. For the non-rice land, Tebere section has largest area (2000ha). This land is not suitable for growth of rice because of the presence of large areas with red soils which are known to be unsuitable for paddy rice agriculture because of their relatively high porosity leading to rapid water loss.

The Mwea Irrigation Settlement consists of a gently undulating landscape of unpronounced ridges of red soils which run from north-west to south-east. These ridges vary in width from 100 metres to 2 kilometres, and are on average about 10 to 25 metres high. The clay basins of the area lie between the ridges and they form the paddy land. These basins vary in length from 1 kilometre in the higher north-west part of Mwea Irrigation Settlement to over 10 kilometres in the lower south-eastern part of the scheme. Their width varies from 100 metres in the higher parts to almost 5 kilometres in the central parts.

In the last series of eruptions on Mount Kenya, the Thiba basalts filled up existing river valleys higher up the mountain spreading outwards at lower parts, Mwea being one, and were filled with sediments. The poor drainage over these areas led to the formation of dark coloured heavy clay soils, the Vertisols. Vertisols have a thick black surface layer, relatively low in organic matter and the top soil varies in depth from 40 to 50cm.

These soils are the basis of rice cultivation in the Mwea and according to Wang'ati (1972), are uniformly black, sub-angular blocky, cracking when dry and usually with a coarse granular surface. The soils swell substantially when wet and have low permeability rates. They have commonly been referred to as "Black-cotton soils"; but in Mwea-Tebere area, they were found to be particularly suitable for paddy rice.

According to Giglioli (1979), the typical valley bottom soils in the area consist of 60-80% clay, 10-25% silt and 5-10% sand. van Gessel (1982) did an analysis of the moisture characteristics of the Mwea Vertisols at different depths of the soil and his results, which are useful for water balance studies, are presented in Table 2.2.

Table 2.2: Moisture content by volume (%) in the various soil layers of Mwea Irrigation Settlement before and after flooding.

Soil layer depth (cm)	Before flooding (%)	After flooding (%)
0-30	65	74
30-60	61	63
60-90	60	60

Source of data: van Gessel (1982)

The Table illustrates that the moisture content in volume percentage increases considerably at the top layer (0-30 cm) while there is relatively small increase at the middle layer (0-60 cm) and no change at the lower layer. The top layer is of much concern in this study since it is the root zone of the rice crop and the water content in this layer is of prime importance in water balance calculations. The Table leads to further conclusion that water percolation rate to the lower soil layers in the Mwea Vertisols is low which is one of the requirements of paddy rice agriculture.

2.1. Climate and micro-climate of the study area

The climate of the study area is influenced by its location near the equator and also by its proximity to Mount Kenya. The mountain affects the area's regional circulation of winds hence modifying the rainfall distribution. Generally, the climate is tropical due to the influence of the Inter-tropical Convergence Zone (ITCZ), producing bimodal rainfall pattern.

Table 2.3 illustrates the monthly averages of meteorological data from Mwea Agrometeorological station for a period of twenty years (1963-1982). The mean annual temperature of the area is about 22°C, with mean monthly maximum in March, (over 23°C), and

Table 2.3: Monthly means of selected climatological data for Mwea from 1963 to 1982

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Mean Temperature (°C)	21.3	22.6	23.3	23.0	22.2	21.0	20.2	20.5	22.0	23.0	22.2	21.0	22.0
R.H. (%)	55	52	57	66	67	66	67	64	57	56	66	63	61.3
Sunshine (hrs/day)	9.1	9.0	8.0	7.3	6.8	5.3	3.7	3.9	6.5	6.5	7.0	8.7	6.8
Windspeed (km/h)	5.8	6.4	6.3	5.1	3.9	3.4	4.2	5.3	6.4	6.4	5.2	5.6	5.3
Class 'A' Pan Evaporation (mm/month)	197	213	225	178	147	126	121	148	187	212	158	177	2089
Rainfall (mm/month)	25	22	100	274	145	29	17	15	17	117	169	43	973

Source of data: Mwea Meteorological Station (No. 9037112) mean monthly minimums in July and August. (20°C). This shows the low range of monthly temperature fluctuations in the area.

The relative humidity in the area varies from 70% in the morning hours to 45% in the afternoons. The average daily sunshine hours is lowest in July, about 4 hours and highest in January, about 9 hours a day.

The average daily windspeeds range from 3.4 km/hr in June to 6.4 km/hr in February, September and October. The mean daily pan evaporation is highest in February and March (about 7mm/day), towards the end of the dry season and lowest during the period June through August, (about 4.8mm/day).

The twenty-year mean annual rainfall for Mwea is 973mm (see Figure 5). For most of the seasons considered in this study, the total annual rainfall is found to have been below the mean annual value for the twenty years. The rainfall pattern of the area is bimodal with the long rains coming in March to May, and the short rains in October to December.

Comparison of the twenty-year monthly averages of rainfall and pan evaporation is presented in Figure 6. It is seen from the Figure that pan evaporation in the area exceeds rainfall in all the months except during the long rain season months. The largest

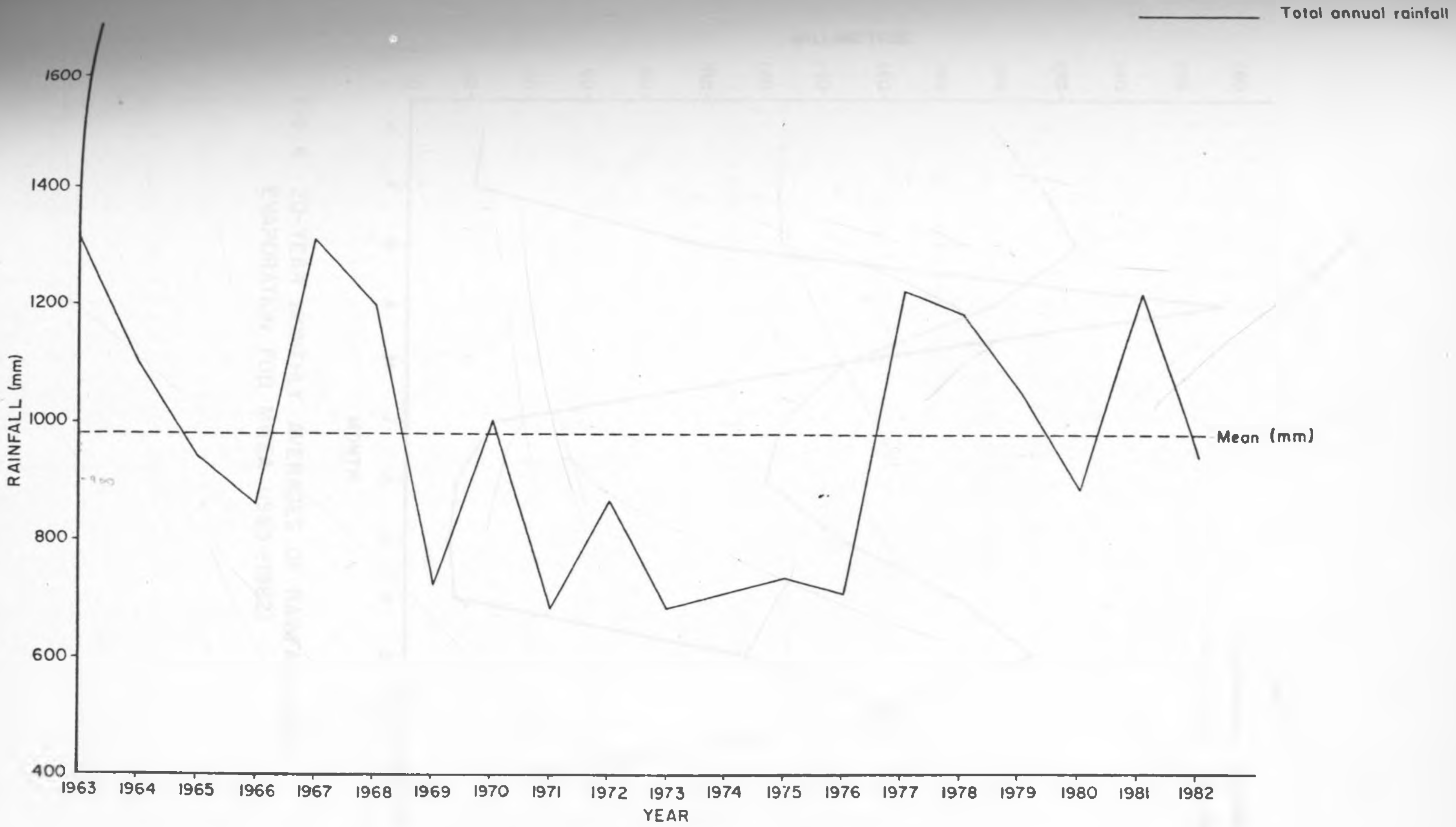


Fig. 5 ANNUAL RAINFALL TOTALS AT MWEA (1963—1982)

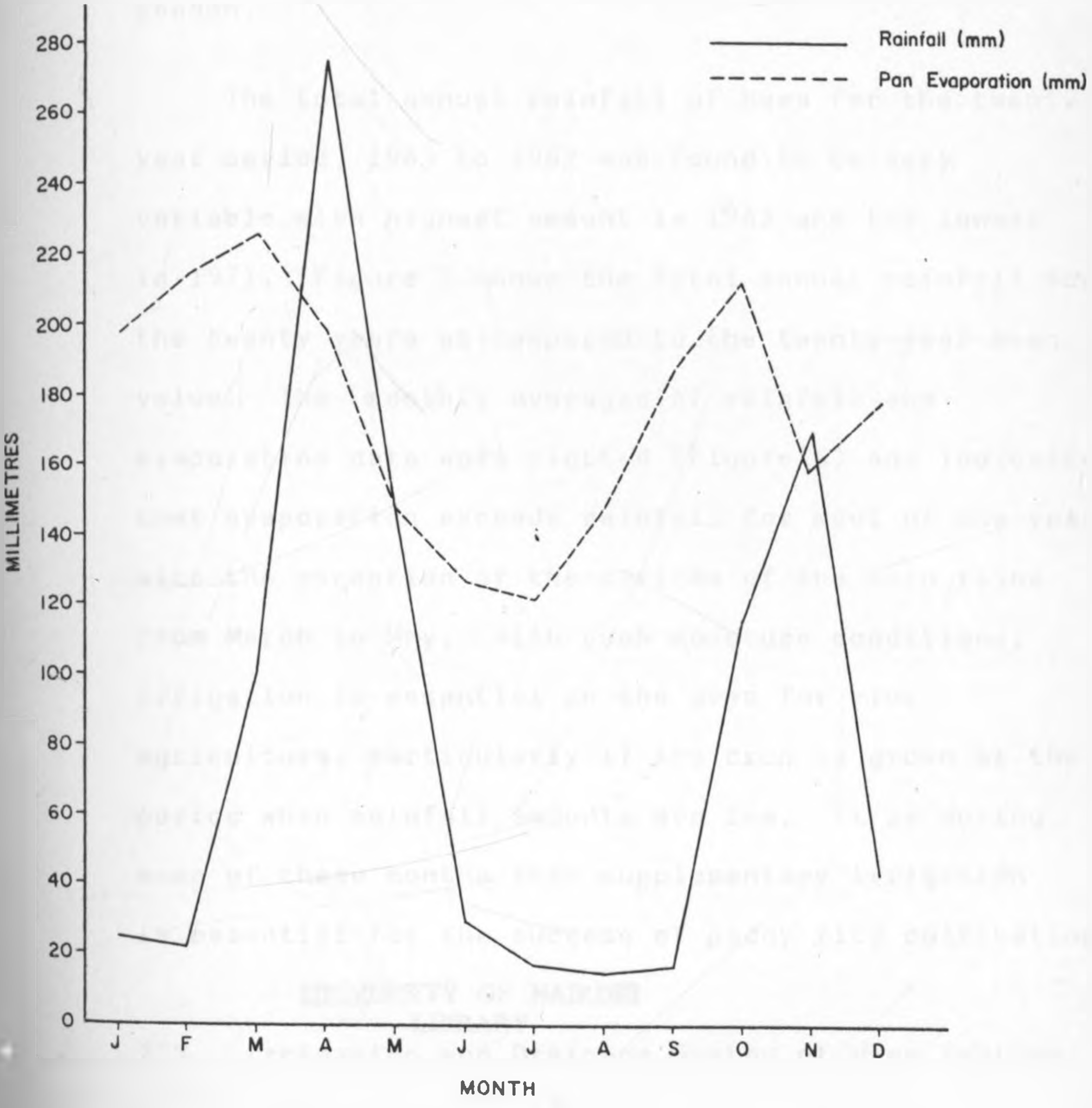


Fig. 6 20-YEAR MONTHLY AVERAGES OF RAINFALL AND EVAPORATION FOR MWEA (1963–1982) difference where pan evaporation exceeds rainfall is in August to September, a part of the rice growing season.

The total annual rainfall of Mwea for the twenty year period, 1963 to 1982 was found to be very variable with highest amount in 1963 and the lowest in 1971. Figure 5 shows the total annual rainfall for the twenty years as compared to the twenty-year mean value. The monthly averages of rainfall and evaporation data were plotted (Figure 6) and indicated that evaporation exceeds rainfall for most of the year with the exception of the periods of the main rains from March to May. With such moisture conditions, irrigation is essential in the area for rice agriculture, particularly if the crop is grown at the period when rainfall amounts are low. It is during some of these months that supplementary irrigation is essential for the success of paddy rice cultivation.

2.2. Irrigation and Drainage System of Mwea Section

Water for irrigation in the whole scheme is supplied from two rivers, namely, Thiba and Nyamindi which are tributaries of the Tana. The water is diverted from these rivers by gravity, thus no pumping of the water is done. The main supplier of water to the scheme is the Thiba river which supplies water to approximately 80% of the total area under paddy cultivation. The other 20% of the total area obtains water from Nyamindi river. The water is diverted from the rivers through the headworks of each river.

The water diverted from Thiba headworks is conveyed by main canals to Mwea, Thiba, Wamumu and Karaba sections of the settlement scheme. Since the scheme depends on water supply from the two rivers, two different canal systems have been constructed. A main canal for each system and its branch canals convey the water to the different field units within the sections. Figure 7 shows the irrigation and drainage system of the Mwea section from Thiba headworks. There is a continuous flow of water in these canals and control of the water is done by use of sluice gates at each turn-out after the required amount of water has been conveyed to the paddy fields.

2.3. Rice Agronomic Practices in the Study Area

In Mwea Irrigation Settlement, three varieties of rice are grown, namely, Sindano, Basmati and the recently introduced B.G. 90. Of the three, Sindano is the highest yielding variety and is the most popularly grown in the area. According to trials undertaken in Mwea for choice of the suitable growing season, putting into consideration the climatic requirements of rice, Veen (1973) noted that the influence of

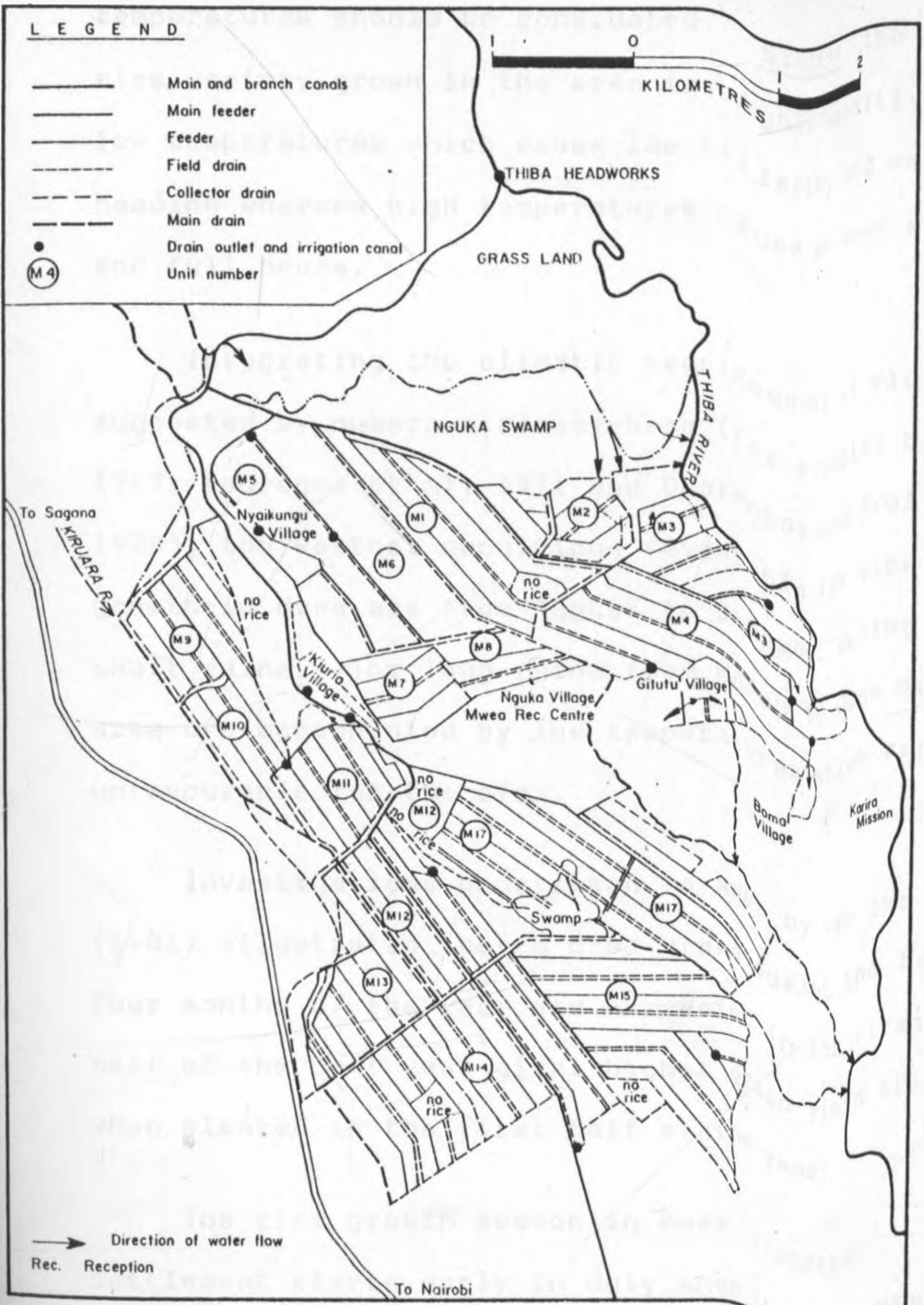


Fig. 7 IRRIGATION AND DRAINAGE NETWORK OF THE MWEA SECTION

temperatures should be considered. Sindano, the main rice variety grown in the area is highly sensitive to low temperatures which cause low tillering and empty heading whereas high temperatures cause an even stand and full heads.

Integrating the climatic requirements of rice as suggested by numerous researchers (for example, Halm, 1967; Lourence et al, 1971 and Doorenbos and Pruitt, 1979), the weather conditions favourable for rice growth in Mwea are from August to December during the short rains. The long rains from March to June in the area are accompanied by low temperatures which are unfavourable for the crop.

Investigations undertaken in Mwea by van der Wal (1981) illustrated that a crop grown during the last four months of the year and harvested in the first half of the next year gives higher grain yield than when planted in the first half of the year.

The rice growth season in Mwea Irrigation Settlement starts early in July when the seeds are planted in nurseries. Pre-planting flooding of the paddy fields is done from March to August (Figure 8). The level of water in the bunded paddy fields is kept at a maximum level of 10-15cm above the soil during the transplanting period.

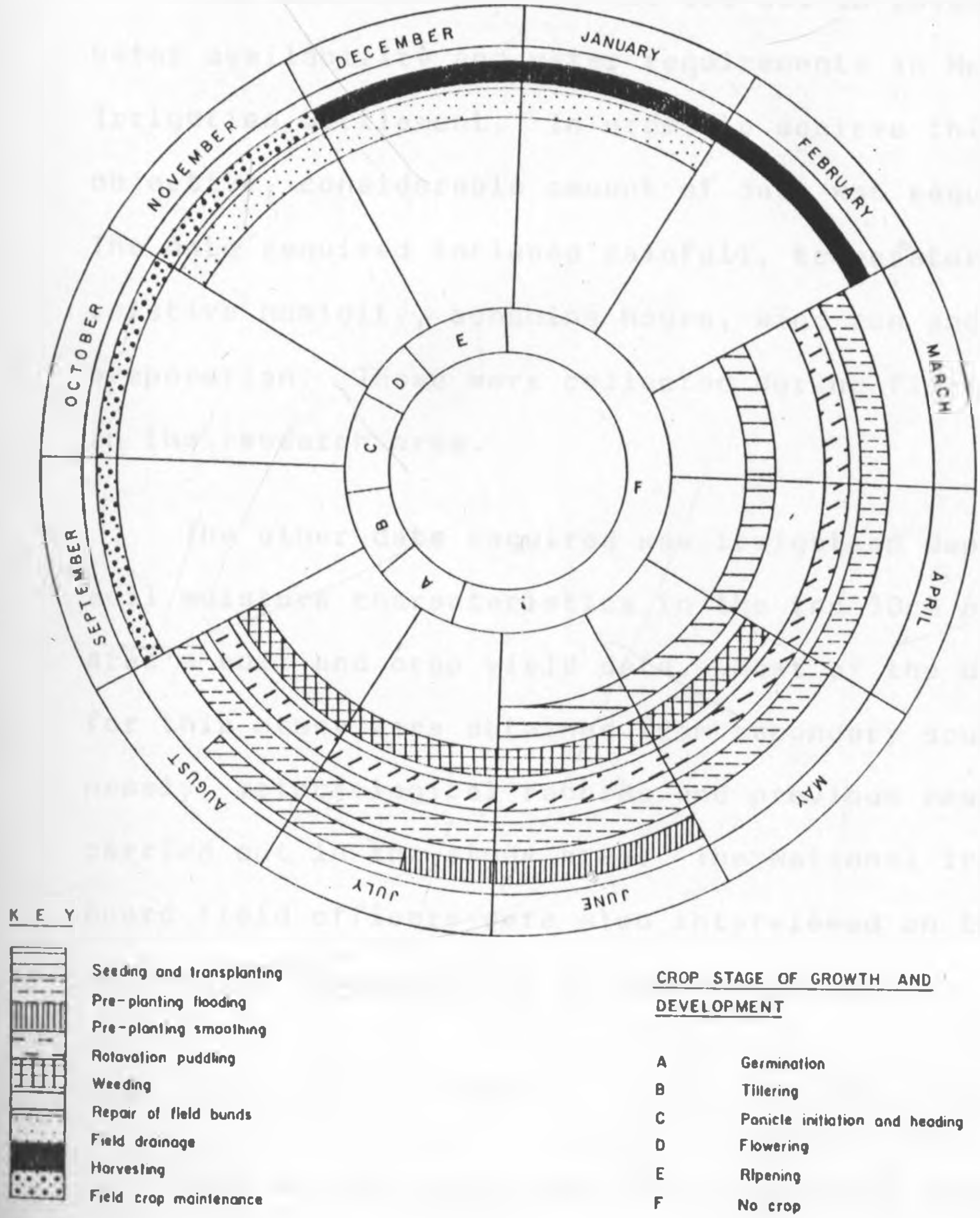


Fig. 8 FARMING OPERATIONS CHART FOR MWEA IRRIGATION SETTLEMENT

CHAPTER 3: RESEARCH METHODOLOGY

This research project was set out to assess the water availability and water requirements in Mwea Irrigation Settlement. In order to achieve this objective, considerable amount of data was required. The data required included rainfall, temperature, relative humidity, sunshine hours, wind run and evaporation. These were collected during field work in the research area.

The other data required was irrigation depths, soil moisture characteristics in the top 30cm of the area's soil and crop yield data. Most of the data for this study were obtained from secondary sources namely, meteorological records and previous researches carried out in the study area. The National Irrigation Board field officers were also interviewed on the agronomy of Sindano rice in the area.

3.1. Collection of data

This section deals with the individual data sets collected with a description of the purposes of such data sets in relation to the objectives of this study.

3.1.1. Rainfall

The rainfall data was collected on a daily basis for 20 years (1963-1982). This data was later organised on a ten-day basis from the dates of rice transplanting to the time of the crop's ripening. Not all the 20 seasons' rainfall data is used in the rice-climate relationship analysis although the entire series was used to characterise the rainfall conditions of the study area (see Chapter 2).

The use of ten-day periods (decades) in agrometeorological studies was advocated by Russell (1960) and has become a popular phenomenon in such studies (Doorenbos and Pruitt 1975). This study adopts the ten-day periods in grouping meteorological data during the rice growing season in Mwea. The following meteorological data is tabulated based on the decades of the growing season. Thus this data was collected after the rice transplanting dates were determined. The rainfall data is the total of each of the ten-day periods.

3.1.2. Relative humidity

The mean relative humidity data was collected on ten-day basis. The mean daily relative humidity was first obtained and for each ten-day period, the mean was calculated. The data is required as input to determine the pan evaporation coefficients as indicated in section 3.3.1.

3.1.3. Windrun

The windrun (km/day) data was collected also on a ten-day basis for the previously established periods of the rice growing seasons in the study area. This data is similarly used as input to determine the Class 'A' pan coefficient.

3.1.4. Pan Evaporation

The Pan evaporation (E_{pan}), in millimetres per day was collected from the Class 'A' Pan evaporimeter in Mwea Agrometeorological Station. The mean evaporation (mm/day) during each of the ten-day periods is used to estimate the rice water requirements on a ten-day basis (see Section 3.3.1).

3.1.5. Irrigation depths

The amount of irrigation water in depth equivalent mm day^{-1} was collected from the National Irrigation Board records and the values for each ten-day period are the totals of irrigation water (mm $10days^{-1}$).

3.1.6. Soil moisture

The soil moisture data required for Mwea Vertisols is the moisture capacity of the soil at saturation, field capacity and wilting point. This information is essential to determine water availability to the rice crop during its growing season. This data, for the top 30cm layer of the Mwea Vertisols, was obtained from van Gessel (1982) who had performed laboratory tests on the soil to determine the water properties of the area's soil.

3.1.7. Rice crop data

The rice crop data collected include the Sindano rice variety phenological stages as shown in Figure 9 and the grain yield. The grain yield data at 15% moisture content was available from the National Irrigation Board records for twenty seasons (1963-1982) and is in tons per hectare.

3.2. Summary of Collected Data

This section shows some of the data which was collected by field observation and some of the data extracted from previous researches from the study area for the seven seasons considered in this study.

3.2.1. Rice data

The data on dates of transplanting of Sindano variety is shown in Table 3.1. below.

Table 3.1: Transplanting dates of Sindano Rice in Mwea Section for Selected Seven Seasons

Season	Transplanting date
1970	4/9
1971	1/9
1972	31/8
1973	28/8
1974	31/8
1981	10/8
1982	11/8

The dates of transplanting rice seedlings in Mwea Irrigation Settlement are determined by the National Irrigation Board's Section Heads depending on the readiness of the paddy fields.

The stages of growth and development of Sindano rice variety in Mwea were obtained and are shown in Table 3.2.

Table 3.2. Stages of growth and development of <u>Sindano</u> rice in Mwea

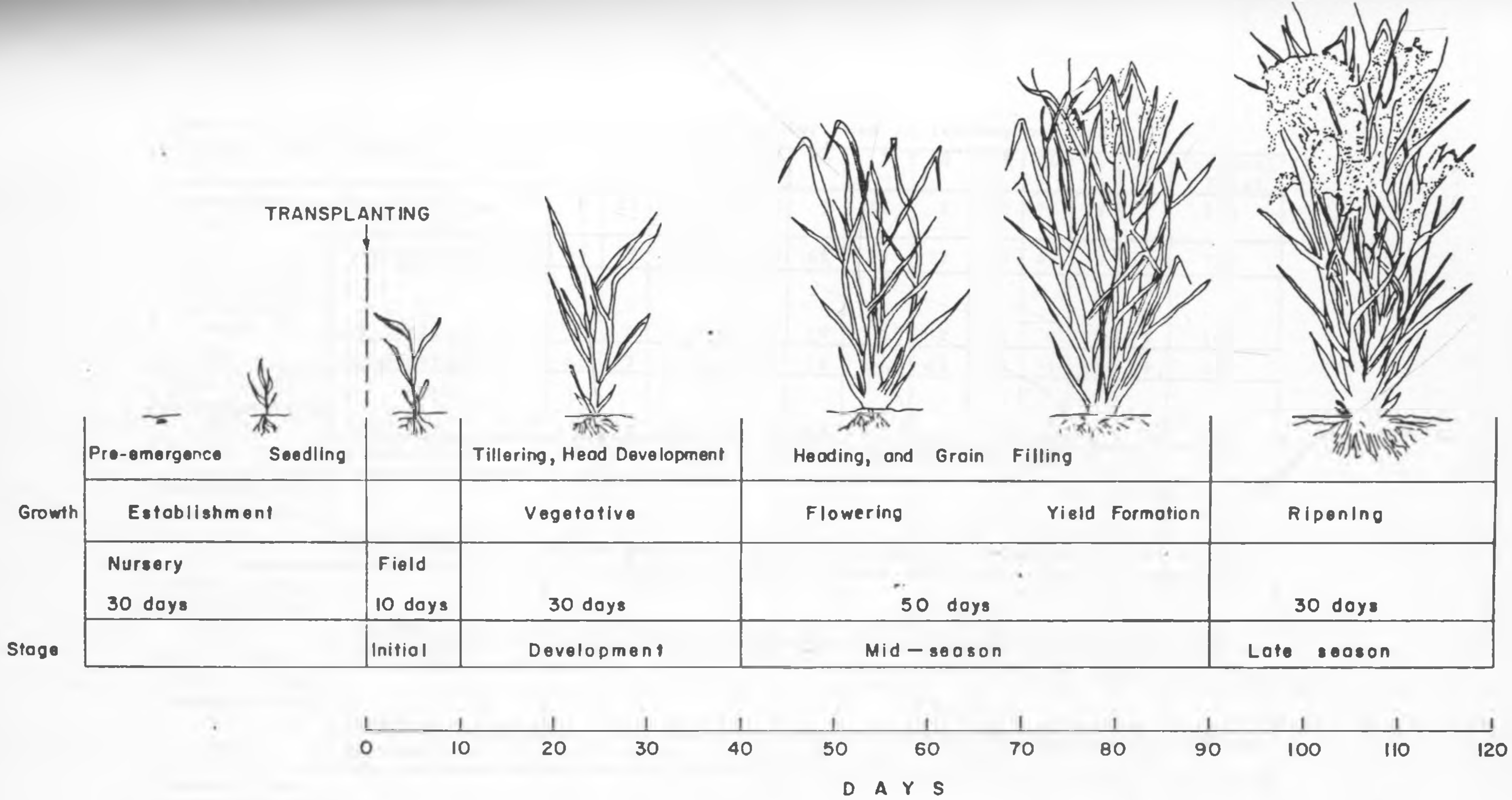
<u>Stage</u>	<u>Growth</u>	<u>Period (days)</u>
Initial	Establishment	10
Development	Tillering and head development	30
Mid-season	Heading, flowering and grain filling	50
Late season	Ripening	30
Total season days		120

The information presented in Table 3.2.shows that <u>Sindano</u> rice variety in Mwea matures in a period of 120 days after transplanting and this information has been presented, indicating the critical periods in <u>Sindano</u> rice growth, in a diagram (Figure 9).

The root system of <u>Sindano</u> rice variety increases gradually from transplanting reaching a maximum at the time of heading and decreasing after flowering while at maturity, most of the roots are dead. At the time of head initiation, root growth is horizontal producing a dense sub-surface mat. The maximum root depth of rice in Mwea is about 25cm.

3.2.2. Rainfall and evaporation

Rainfall and evaporation data were collected from



	Pre-emergence Seedling		Tillering, Head Development	Heading, and Grain Filling	
Growth	Establishment		Vegetative	Flowering Yield Formation	Ripening
	Nursery 30 days	Field 10 days	30 days	50 days	30 days
Stage		Initial	Development	Mid — season	Late season

Figure 9 GROWTH PERIODS OF <u>SINDANO</u> RICE VARIETY IN MWEA

Table 3.3: Seasonal rainfall and evaporation data for Mwea in ten-day periods

Season: 1970	Decade	1	2	3	4	5	6	7	8	9	10	11	12	Seasonal Total
Transplanting Date	Rainfall (mm)	0	13	1	1	0	1	14	1	20	78	28	1	158
4/8	Evaporation (mm)	56	42	35	62	60	64	83	72	79	45	56	66	720
Season: 1971 Transplanting Date	Rainfall	1	0	0	1	1	29	0	9	71	0	29	23	164
1/9	Evaporation	61	73	74	78	81	76	84	65	49	74	63	59	837
Season: 1972 Transplanting Date	Rainfall	8	12	13	6	36	158	92	50	24	20	17	0	436
31/8	Evaporation	73	62	88	75	64	57	55	49	53	46	53	56	731
Season: 1973 Transplanting Date	Rainfall	0	4	27	0	56	10	54	144	4	30	9	0	338
28/8	Evaporation	65	65	77	62	79	67	74	60	58	55	55	61	778
Season: 1974 Transplanting Date	Rainfall	9	3	0	0	1	14	82	54	13	2	20	0	198
31/8	Evaporation	48	53	45	71	78	58	45	45	55	58	61	64	681
Season: 1981 Transplanting Date	Rainfall	2	0	0	17	2	28	0	117	14	40	39	25	284
10/8	Evaporation	56	64	69	75	58	82	80	54	65	45	46	60	754
Season: 1982 Transplanting Date	Rainfall	0	1	0	1	30	136	168	45	19	39	27	24	491
11/8	Evaporation	44	49	65	67	63	85	45	54	54	41	32	56	655

Source of data: Mwea Agro-meteorological station (90.37112) the Mwea Agrometeorological Station (90.37112) in the irrigation scheme. The data were collected on ten-day basis from the date of transplanting to harvesting, a period of 120 days. Table 3.3 shows the total rainfall received in each ten-day period while the evaporation values are the totals of each decade. The evaporation values were recorded from Class 'A' Pan evaporimeter. This pan is covered with a wire mesh screen, painted black inside and situated in a green grass surrounding.

3.2.3. Soil moisture data

The soil moisture data to the depth of 30cm were obtained from the findings of van Gessel (1982). These data were determined from soil samples from Mwea subjected to laboratory tests. The average values of the top 30cm soil are shown in Table 3.4.

Table 3.4: Soil moisture content at the depth of 30cm in the Mwea Vertisols

Level	Amount in mm.
Saturation (S_o)	175
Field capacity (S_f)	125
Wilting point (S_w)	60

Source of data: van Gessel (1982)

3.3. Physical and statistical models used in analysis of data

There are several models which could be used for the analysis of agro-climatological data. As already indicated, the choice of models to be applied in a study will depend, mainly, on the availability of input data, and their applicability in the research area. However, the choice of models to be used should be related to the purpose(s) of the specific study.

This study uses both agro-climatological and statistical models for analysis of collected data in order to:

(a) estimate the water requirement by rice (ETrice), at the successive stages of rice growth and development.

(b) estimate the seasonal effective rainfall in Mwea paddy fields during the rice growth period.

(c) simulate seasonal water balances in the study area where various climatic variables such as solar radiation, relative humidity, windrun and rainfall are integrated to estimate water availability and the need for supplementary irrigation.

(d) estimate the seasonal irrigation efficiency in the study area.

(e) assess the impact of seasonal water application in Mwea paddy fields on rice grain yields.

A sequence of the application of the models has already been indicated in Figure 2.

3.3.1. Evaluation of the crop water requirement of rice (ETrice)

Direct measurement of rice evapotranspiration in Mwea are not available. Therefore, in order to estimate the rice water requirement, empirical methods have to be used. Use of empirical methods to estimate crop evapotranspiration are popular in many agroclimatological studies where data is not available. Doorenbos and Pruitt (1975) recommend four empirical formulae for estimating crop evapotranspiration using meteorological data; namely, the Penman method, Equilibrium model, Pan Evaporation, and Blaney-Criddle method. Each of these methods gives reasonable approximation of crop evapotranspiration for a specified period provided the meteorological data is accurate.

The choice of any of the above methods depends mostly on the availability of its input meteorological data. Knowledge of the crop growth stages and the period of growth from planting or transplanting to harvesting is a pre-requisite also.

Of the above methods, the Penman and Pan Evaporation methods are the most widely used. Studies have shown that these two methods estimate crop evapotranspiration close to lysimetric measurements. Pruitt (1960) suggested that Pan Evaporation observations are among the more reliable ways of predicting evapotranspiration by a crop provided that the pans for measurements are well maintained to ensure reliable measurements.

Due to the availability of the input data required, this study uses the Pan Evaporation method to estimate rice evapotranspiration in Mwea. This method, according to a study by Mugah and Stewart (1982) for estimating evapotranspiration by Katumani Composite B maize in Muguga, gave the nearest approximation to the lysimeter measurements compared to the estimates by Penman method and Equilibrium model.

The Pan Evaporation method according to Doorenbos and Pruitt (1975) is formulated as follows:

$$ET_{crop} = Kc[E_{pan} \times Kp] \;\ldots\ldots\ldots\ldots \;(1)$$

Where

ET_{crop} = evapotranspiration by the crop in mm.

E_{pan} = pan evaporation measurement in mm.

Kc = crop coefficient

Kp = pan coefficient

The Epan values used in this study are from the Class 'A' pan evaporimeter in Mwea. The crop coefficient is determined for specific crops as the ratio of maximum crop evapotranspiration to potential evaporation, (ETm/Eo), and depends on the stage of growth and development of the crop under investigation.

The pan coefficient is a factor determined by the prevailing relative humidity and windrun, two metres above the ground. The mean values of relative humidity and 24-hour windrun are used to determine the pan coefficient as indicated by Doorenbos and Pruitt (1975), see Table 3.5.

In the estimation of crop evapotranspiration, the U.S.A. Pan evaporimeter is classified by the World Meteorological Organization as the standard Pan. The Kenya Class 'A' pan measurements therefore have to be converted to equivalent U.S.A. Class 'A' pan measurements. According to Kaila (1983), the Kenya Class 'A' Pan values have to be factored by 1.05, for Mwea pan to obtain the equivalent U.S.A. Class 'A' pan (see Table 3.6).

Table 3.5: Pan Coefficient (Kp) for Mwea Class 'A' Pan at different levels of mean relative humidity and 24-hour windrun.

	MEAN RELATIVE HUMIDITY (%)		
	Low 40	Medium 40-70	High 70
Windrun (km/day)			
Light $<$175	0.65	0.75	0.85
Moderate 175-425	0.60	0.70	0.75
Strong 425-700	0.55	0.60	0.65
Very strong $>$ 700	0.45	0.55	0.60

Source of data: Doorenbos and Pruitt (1975).

The estimation of rice evapotranspiration in Mwea uses the formula below:

$$ET_{rice} = K_c[1.05 \times E_{pan} \times K_p] \quad \ldots\ldots..(2)$$

Where

ET_{rice} = rice evapotranspiration in millimetres and the other variables are as in (1).

The rice crop coefficient Kc, which is the ratio of maximum rice evapotranspiration to potential evaporation was not determined directly due to lack of maximum rice evapotranspiration data in Mwea. The selection of rice crop coefficients at the various stages of growth is based on previous researches on rice by Doorenbos and Kassam (1979) and van Gessel (1982) and a crop coefficient curve is drawn (Figure 10). The pan coefficients (Kp), are obtained from Table 3.5.

An example of calculations of rice evapotranspiration by Pan evaporation method on a ten-day basis for a single season is shown in Table 3.6 whose entries will be explained row by row. Row one shows the ten-day groups for the entire rice growing season. The second row shows the ten-day averages (in mm/day) of class 'A' Pan evaporation values from Mwea Class 'A' Pan.

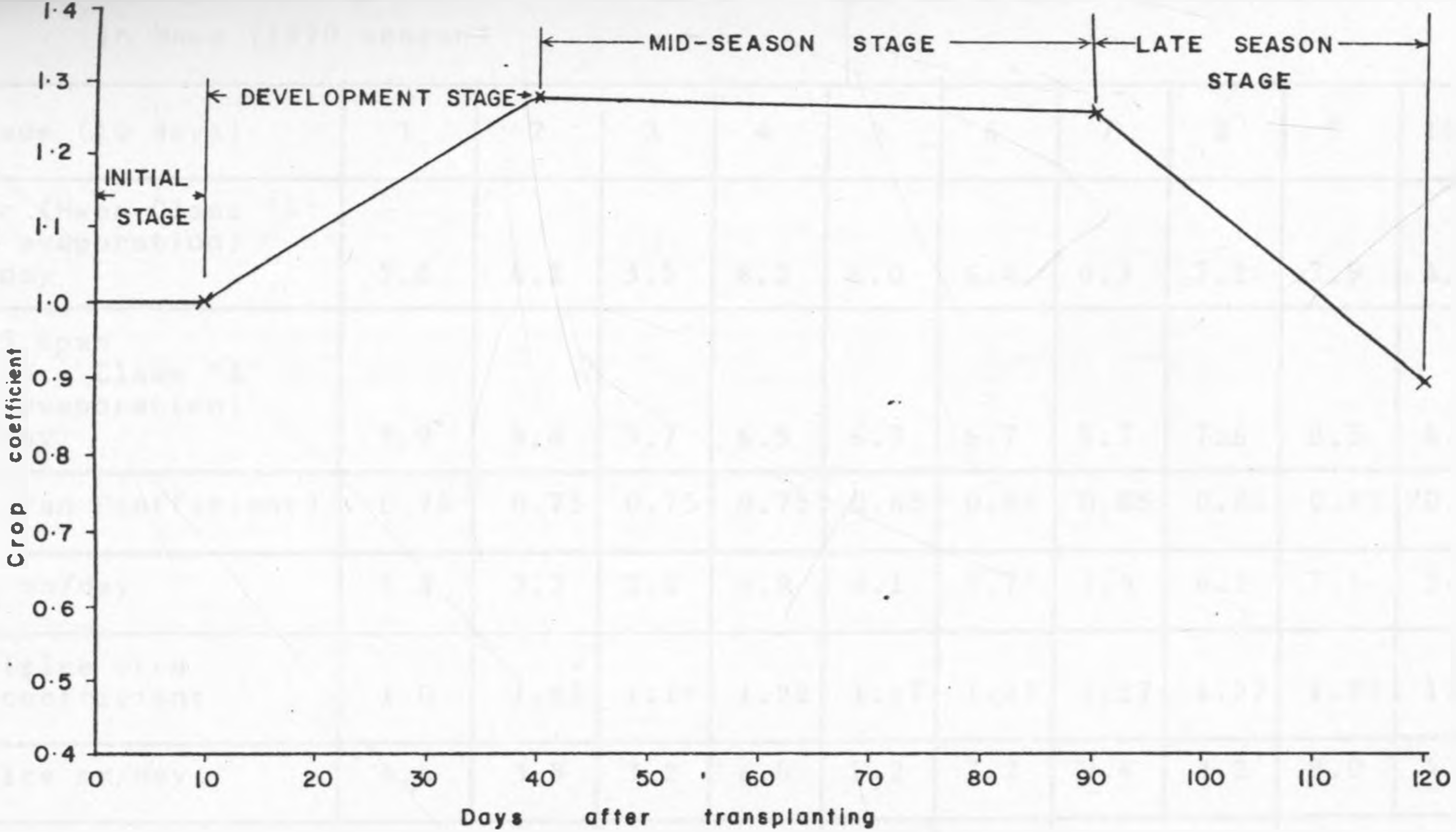


Fig. 10 PLOTTED CROP COEFFICIENT CURVE FOR SINDANO RICE IN MWEA

Table 3.6: A sample calculation of ETrice in ten-day periods by Pan Evaporation method in Mwea (1970 season)

(1) Decade (10 days)	1	2	3	4	5	6	7	8	9	10	11	12
(2) Epan (Mwea Class 'A' Pan evaporation) mm/day	5.6	4.2	3.5	6.2	6.0	6.4	8.3	7.2	7.9	4.5	5.6	6.6
(3) 1.05 Epan (U.S.A. Class 'A' Pan evaporation) mm/day	5.9	4.4	3.7	6.5	6.3	6.7	8.7	7.6	8.3	4.7	5.9	6.9
(4) Kp (Pan Coefficient)	0.75	0.75	0.75	0.75	0.65	0.85	0.85	0.85	0.85	0.75	0.85	0.85
(5) ET_o mm/day	4.4	3.3	2.8	4.9	4.1	5.7	7.4	6.5	7.1	3.5	4.7	5.7
(6) Kc (rice crop coefficient	1.0	1.05	1.13	1.22	1.27	1.27	1.27	1.27	1.27	1.20	1.06	0.95
(7) ETrice mm/day	4.4	3.5	3.2	6.0	5.2	7.2	9.4	8.2	9.0	4.2	5.0	5.4
(8) Cumulative ETrice mm	44	79	111	171	223	295	389	471	561	603	653	707

In the third row are the U.S.A. Class 'A' Pan values obtained by conversion of the entries of the second row by multiplying them by 1.05. The fourth row has the entries of pan coefficients (see Table 3.5) obtained depending on the mean relative humidity and mean windrun.

The fifth row presents the entries of reference crop evapotranspiration, ETo, which in this case, is the evapotranspiration from green grass presumed to be completely shading the ground and not deficient of water. The values are obtained by multiplying the corresponding entries of the third and fourth rows. In the sixth row are entries of the rice crop coefficient derived from Figure 10.

The seventh row has the entries of rice evapotranspiration (ETrice) obtained by multiplication of corresponding entries of the fifth and sixth rows. The eighth row shows the total cumulative rice evapotranspiration (ETrice). Thus this row generates the total seasonal rice evapotranspiration at the last decade.

3.3.2. Evaluation of effective rainfall

In most areas where irrigation is practised, rainfall is more than sufficient at certain times and even when it is sufficient to meet the crop water requirements, certain amounts of rain water may be lost as run-off or deep percolation. Thus a method of determining the proportion of the total rainfall, within a specified period, available to a crop for evapotranspiration is necessary.

The first thing to investigate when considering rainfall for agricultural purposes is the total amount of rainfall received within the growing season and to assess whether it is adequate to meet the crop water requirements. Secondly, how the rainfall is distributed during the season. This disqualifies the use of mean values of seasonal rainfall as has been shown by Fenner (1982).

A suitable approach is estimating the available rainwater to crops is the method of effective rainfall. Effective rainfall is the portion of total annual or seasonal rainfall which is useful directly or indirectly for crop production at the site where it falls. Effective rainfall according to Dastane (1974) is the water intercepted by vegetation, that which is lost by evaporation from the soil surface and that which is lost by evapotranspiration during crop growth. Consequently, ineffective rainfall is that portion which is lost by surface run-off and deep percolation below the root zone of the crop.

Water management experts have devised many techniques for estimating effective rainfall depending on the soil, climatic characteristics and principal crops of the areas where these techniques were developed. However, the various methods of estimating effective rainfall use the daily readings of recorded rainfall as the basis of estimation.

Among the numerous methods of estimating effective rainfall are the Renfro method, United States Department of Agriculture's Soil Conservation Service, (U.S.D.A, S.C.S) method and the U.S. Bureau of Reclamation method as shown by Dastane (1974).

A suitable method of estimating effective rainfall should be based on water-balance calculations for determining the portion of the total rainfall which is available for crop evapotranspiration. Similarly, the consideration of storage in the root zone is essential. Kashasha (1982) developed a water-balance approach to estimate effective rainfall for dry land crops. His method is mathematically presented as follows:

Water management experts have devised many techniques for estimating effective rainfall depending on the soil, climatic characteristics and principal crops of the areas where these techniques were developed. However, the various methods of estimating effective rainfall use the daily readings of recorded rainfall as the basis of estimation.

Among the numerous methods of estimating effective rainfall are the Renfro method, United States Department of Agriculture's Soil Conservation Service, (U.S.D.A, S.C.S) method and the U.S. Bureau of Reclamation method as shown by Dastane (1974).

A suitable method of estimating effective rainfall should be based on water-balance calculations for determining the portion of the total rainfall which is available for crop evapotranspiration. Similarly, the consideration of storage in the root zone is essential. Kashasha (1982) developed a water-balance approach to estimate effective rainfall for dry land crops. His method is mathematically presented as follows:

$$Re = R - ETcrop + dS - RO \quad \ldots\ldots\ldots\ldots (3)$$

Where

Re = effective rainfall

R = total rainfall

ETcrop = crop evapotranspiration

dS = soil moisture recharge

and RO = run-off

All the values are in millimetres.

The equation above, (3), is only applicable for crops grown without supplementary irrigation. For irrigated crops, (3) has to be modified to cater for irrigation water.

This equation is modified in this study to estimate effective rainfall in Mwea paddy fields as follows:

$$Re_i = IRR_i - ETrice_i + R_i + dS_i - OF_i \quad \ldots\ldots (4)$$

Where

Re, ETrice, R and dS are as in equation (3)

OF = overflow from the bunded paddy fields.

IRR = irrigation water

i = specific 10-day period.

Under irrigated conditions, effectiveness of rainfall can only be estimated after establishment of the extent to which irrigation has met the crop water requirement. The contribution to soil moisture as

Table 3.7: A sample calculation of effective rainfall for Mwea for the 1970 season

10-day period	1	2	3	4	5	6	7	8	9	10	11	12	Season Total
ETrice (mm)	44	35	32	60	52	72	94	82	90	42	50	54	707
Irrigation (IRR) (mm)	78	50	52	140	70	63	70	84	41	20	0	0	668
IRR-ETrice (mm)	+34	+15	+20	+80	+18	+9	+24	+2	-49	-22	-50	-54	
Rainfall (R) (mm)	0	13	1	1	0	1	14	1	20	78	28	1	158
dS (mm)	+34	+28	+21	+81	+11	0	0	0	0	+29	0	0	
Overflow (mm) (OF)	0	0	0	0	7	10	38	3	0	27	0	0	85
Effective rainfall (Re) (mm)	0	13	1	1	0	0	0	0	20	51	28	1	115

Maximum water in the paddy field = 375mm

Total amount of rainfall = 158mm
Total effective rainfall = 115mm

Seasonal effective rainfall $= (\frac{115}{158} \times 100)$ percentage = 73%

Source of data: Calculated from field data well as storage above the surface if the field is bunded are also considered.

Estimation of effective rainfall in Mwea is done by use of equation (4). The soil moisture content data at the upper 30cm layer are shown in Table 3.4. Prior to transplanting, the paddy fields are flooded with about 25mm of water. Thus the total amount of water before transplanting is 200mm.

The paddy fields are bunded to a height of 200mm above the soil surface. Table 3.7 shows a sample calculation of seasonal effective rainfall of Mwea by ten-day periods as generated by equation (4).

3.3.3. Evaluation of the cumulative soil-water balance

Water-balance calculations are widely used in agro-climatology as they form the basis for assessing how water requirements of a specific crop are met and also assessing the irrigation requirement, both its quantity and interval. Jackson (1977) outlines the importance of water-balance studies.

The water-balance models used in agroclimatological studies vary according to specific purposes of the study and the conditions in which the model will be used. The two distinct water-balance models are:

(a) those used in calculating the water balances of dry-land crops, and

(b) those used in calculating water balances for irrigated or flooded crops.

This study uses the water balance model which applies to case (b) above as it deals with irrigated rice crop. A suitable model for flooded rice fields was developed by the International Rice Research Institute (IRRI) in 1981 as reported and demonstrated by Oldeman and Frere (1982). The model is mathematically formulated as follows:

$$S_i = S_{i-1} + R_i - ET_{(crop)i} - SP_i - OF_i - GW_i \ldots\ldots (5)$$

Where

S_i and S_{i-1} = soil water content during period i and the previous period (i-1) respectively.

R_i = total rainfall during period i.

$ET_{(crop)}$ = crop evapotranspiration in period i.

SP_i = seepage and percolation in period i.

OF_i = overflow or runoff in period i.

GW_i = ground water contribution in period i.

This model does not consider irrigation in the water-balance calculation and for the case of Mwea, the model is modified to cater for irrigation water.

The modified model for Mwea is shown below:

$$S_i = S_{i-1} + (IRR_i + R_i) - ET_{(rice)i} - SP_i - OF_i \quad ....(6)$$

Where all the symbols are as in (5) except IRR which is the irrigation water. The i in equation (6) specifies a decade (10-days) during the rice growing season. The values are in millimetres.

Each of the variables in equation (6) is discussed in the following part of this section.

(a) Irrigation and rainfall (IRR+R)

This is the amount of applied water in the paddy fields and is the addition of rainfall and irrigation for each ten-day period.

(b) Rice evapotranspiration (ETrice)

The data on rice evapotranspiration is obtained by calculations from equation (2) as shown by the example in Table 3.6.

(c) Seepage and percolation rates (SP)

This is the amount of water which drains below the 30cm soil depth. Seepage and percolation rates are difficult components to measure and in most water balance calculations, they are estimated. Laboratory results from Mwea Vertisols by van Gessel (1982) showed that the Mwea Vertisols have a percolation rate of 0.5 to 1mm per day below 30cm.

Seepage in this study is dismissed on the grounds that the amount of water which seeps from a paddy field is compensated by that which seeps into the paddy field.

Moorman and Breemen (1978) observed that percolation losses in paddy fields occur when the soil moisture content is above field capacity and the magnitude increases with increased soil moisture content.

Use of formulae adopted from Oldeman and Frere (1982) enables estimation of percolation losses in ten-day periods for Mwea Vertisols. Following are the formulae adopted from Oldeman and Frere (1982) depending on the soil water content at each ten-day period. These formulae are considered as applicable to all Vertisols and as such are used in this study.

(i) If $S_i < S_f$, $SP_i = 0$ ....(7)

(ii) If $S_f \leq S_i < S_o$, $SP_i = 0.5SPA(S_i - S_f)/S_o - S_f$ ...(8)

(iii) If $S_i \geq S_o$, $SP_i = 0.5SPA + 1.5SPA(S_i - S_o)/H$ ...(9)

Where:

S_i = soil water content in the rootzone at decade i.

S_o = soil water at saturation and flooding.

S_f = soil water at field capacity to a depth of 30cm.

SPA = average percolation rate in a specified period for specific soil.

H = height of the bunds above the soil surface.

All the variables are in millimetres.

An example of calculating percolation loss in a decade (10-days) for Mwea Irrigation Settlement is shown below.

The soil water content at the upper 30cm layer of the Vertisols of Mwea are shown in Table 3.4.

Hence the available water (S_a) in the 30cm top soil is 65mm and the difference between saturation and field capacity (S_o-S_f) is 50mm.

The height of bunds in Mwea Irrigation Settlement is about 200mm above the surface.

If the soil water in a certain decade is 100mm, then S_i = 100mm which is less than S_f ($100 < 125$) and as such SP_i = 0 [from equation(7)].

If the soil water is 150mm, $S_i = 150$ hence $S_f < S_i < S_o$ ($125 < 150 < 175$) hence using equation (8).

$SP_i = 0.5 \times 10\ [25/50] = 5 \times 0.5 = 2.5$mm.

If the soil water is 236mm, $S_i = 236$, hence $S_i > S_o$ ($236 > 175$) thus from equation (9).

$SP_i = 0.5 \times 10 + 1.5 \times 10\ (61/200)$

$= 5 + 15(0.305)$

$= 9.6$mm.

(d) Overflow (OF)

This is the amount of water in excess of the soil water content at saturation (175mm) and the mean height of the bunds in the paddy fields (200mm). The height of the bunds in Mwea section of the Settlement is not uniform but 200 millimetres above the soil surface was found to be the most common. Any amount of water in excess of 375mm is considered as overflow, after having determined the percolation losses.

(e) Soil water content(s)

The amount of soil water in the top 30cm by beginning of transplanting of rice in the paddy fields has to be determined before the cumulative soil water balance calculation commences. The soil water content at the beginning of the season is at saturation 175mm and this value is assumed to be the same for every beginning of the season. The rest of the values of the soil water content for each decade can then be determined using equation (6).

The seasonal water balance calculations in Mwea section for seven seasons are shown in Chapter 4, Section 4.3.

3.3.4. Evaluation of seasonal irrigation efficiency

For irrigation to be successful, water must be applied in a controlled, carefully calculated manner. The design and operation of any irrigation system demands knowledge of the water requirements for crops at their various stages of growth and the soil moisture conditions before irrigating. Irrigation as a supplement to rainfall should therefore be scheduled to match periods when rainfall and soil water cannot meet the crop water requirements. Jackson (1977) warned that over-irrigation may cause run-off resulting in soil erosion and for the rice crop it may cause crop lodging. Under-irrigation on the other hand, may cause water deficits resulting eventually in crop water stress whose consequences may be reduction of crop yield.

The seasonal irrigation efficiency is the means of determining how irrigation water has been effective in meeting the crop water requirements and soil moisture recharge in the growing season of a crop.

irrigation efficiency is thus defined as the water required by a crop as a fraction of the water irrigated after consideration of the total effective rainfall and the recharge in soil moisture storage due to irrigation only.

The seasonal irrigation efficiency (IRR.EFF) for Mwea is calculated by use of formulae adopted from Hagan et al. (1967) and Schmueli (1973) and integrated into one form by van Gessel (1982). The integrated formula is presented as:

$$\text{IRR.EFF}\ (\%) = \frac{(ET_{(crop)} - Re - IRRds)}{IRR}\ 100 \quad \ldots .\ (10)$$

where

IRR.EFF = seasonal irrigation efficiency (percent)

$ET_{(crop)}$ = seasonal crop evapotranspiration (mm)

IRRds = seasonal total soil moisture recharge due to irrigation (mm)

IRR = seasonal total irrigation (mm)

Re = seasonal effective rainfall (mm)

The seasonal irrigation efficiency calculations and results for Mwea are shown in Chapter 4, Section 4.4.

3.3.5. Evaluation of rice-water relationships in the study area

A detailed examination to assess the association of water management to rice growth and yield is necessary at this stage. Crop grain yield, generally a criterion for judging treatment performance, is used here to assess the impact of seasonal water application in Mwea. This will enable the previous obtained results to be interpreted in terms of the degree of association between seasonal water management and rice water requirement. This is done at specific periods of the rice growth stages and should also depict how these water management activities influence the rice grain yield.

To find out the relationships between water management and rice crop, a simple linear regression model is used. This model is defined by Gomez and Gomez (1976) as a test of the degree of association between two variables. The general simple linear regression model is presented as:

$$Y_i = \beta_o + \beta_1 X_i + U_i, \; i = 1, 2 \ldots\ldots, n \quad (11)$$

where

Y_i = dependent variable

β_o and β_1 = intercept and slope terms for the regression equation respectively.

X_i = independent variable

U_i = random disturbance

The following are the important properties of the simple linear regression model used in this study:

3.3.5. (a) Properties of linear regression model

In the simple linear regression equation, it is assumed that for every fixed value of X_i, the U's are random quantities independently distributed with mean equal to zero and a common variance denoted by σ^2.

The regression parameters β_0 and β_1, are estimated by the method of least squares which involves minimizing the sum of squares of the residuals of $S(\beta_0, \beta_1)$ where

$$S(\beta_0, \beta_1) = \sum_{i=1}^{n} U_i^2 = \sum_{i=1}^{n} (Y_i - \beta_0 - \beta_1 X_i)^2 \quad \ldots\ldots (12)$$

The estimated values of β_0 and β_1 that minimize $S(\beta_0, \beta_1)$, denoted by b_0 and b_1 respectively, are given by the equations:

$$b_1 = \frac{= \sum_{i=1}^{n} (Y_i - \bar{Y})(X_i - \bar{X})}{\sum_{i=1}^{n} (X_i - \bar{X})^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

and

$$b_0 = \bar{Y} - b_1\bar{X} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

where $\bar{Y} = \frac{\sum_{i=1}^{n} Y_i}{n}$ and $\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n}$

n being the number of observations.

Based on the assumption that U's, the random disturbances, are normally distributed, the quantities b_o and b_1 are unbiased estimates of β_o and β_1, respectively whose variances are:

$$\mathrm{Var}(b_1) = \frac{S^2}{\sum_{i=1}^{n} (X_i - \bar{X})^2} \quad \ldots\ldots\ldots\ldots\ldots (15)$$

$$\mathrm{Var}(b_o) = S^2 \left[\frac{1}{n} + \frac{\bar{X}^2}{\sum_{i=1}^{n} (X_i - \bar{X})^2} \right] \ldots\ldots\ldots\ldots (16)$$

where

$$S^2 = \frac{\sum_{i=1}^{n} (Y_i - b_o - b_1 X_i)^2}{n-2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (17)$$

Thus corresponding to the i^th observation, the response value, Y_i, predicted by the linear regression model is given as:

$$Y_i = b_o \pm b_1 X_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)$$

which is the regression line whose Y - intercept is b_o and b_1 is the gradient of the regression line.

3.3.5. (b) Further investigation of linear regression and assumptions

In order to validate the obtained linear regression equation (18), correlation analysis is necessary. This analysis is done to test the goodness-of-it of the regression equation for the research data.

The correlation coefficient, r, computed for X and Y is defined by Chatterjee and Price (1977) as:

$$r = b_1 \frac{S_x}{S_y} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

Where

$$S_x = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n-1}} \quad \ldots\ldots\ldots\ldots \quad (20)$$

and

$$S_y = \sqrt{\frac{\sum_{i=1}^{n} (Y_i - \bar{Y})^2}{n-1}} \quad \ldots\ldots\ldots\ldots\ldots \quad (21)$$

and the obtained value of r is always in the range -1 to 1, thus $-1 \leqq r \leqq 1$.

The correlation coefficient, r, explains the strength and direction of the linear relationship between Y_i and X_i, that is, if r is large, there is a strong linear relationship between Y_i and X_i and vice versa.

In this study, linear regression equations relating rice water requirements to seasonal applied water, and the seasonal rice yields to water management activities are done for Mwea Irrigation Settlement.

The obtained regression equations are tested for linearity by the method of Analysis of Variance (ANOVA) which is explained by Tabel 3.8.

Table 3.8: Analysis of Variance Table

Source of Variation	Degrees of freedom (D.F.)	Sum of Squares (S.S.)	Mean Squares (M.S.)
Accounted for by regression	1	$\sum_{i=1}^{n}(\hat{Y}_i-\bar{Y})^2$	$\frac{\sum_{i=1}^{n}(\hat{Y}_i-\bar{Y})}{1}$
Unaccounted for by regression (residuals)	n-2	$\sum_{i=1}^{n}(Y_i-\hat{Y}_i)^2$	$\sum_{i=1}^{n}(Y_i-\hat{Y}_i)^2/n-2$
Accounted for by mean (Total)	n-1	$\sum_{i=1}^{n}(Y_i-\bar{Y})^2$	

Source: Draper and Smith (1981)

The analysis of variance apportions the variability of the dependent variable Y into a variability accounted for by regression equation and a variability unaccounted for by the regression (see Table 3.8).

The analysis of variance table for research data in this study is subjected to a test of significance of the linear regression. The F-test statistic is the most appropriate significant test after the analysis of variance table has been generated. The F-test statistic with 1 and n-2 degrees of freedom at α is given by:

The obtained regression equations are tested for linearity by the method of Analysis of Variance (ANOVA) which is explained by Tabel 3.8.

Table 3.8: Analysis of Variance Table

Source of Variation	Degrees of freedom (D.F.)	Sum of Squares (S.S.)	Mean Squares (M.S.)
Accounted for by regression	1	$\sum_{i=1}^{n}(\hat{Y}_i-\bar{Y})^2$	$\frac{\sum_{i=1}^{n}(\hat{Y}_i-\bar{Y})}{1}$
Unaccounted for by regression (residuals)	n-2	$\sum_{i=1}^{n}(Y_i-\hat{Y}_i)^2$	$\sum_{i=1}^{n}(Y_i-\hat{Y}_i)^2/n-2$
Accounted for by mean (Total)	n-1	$\sum_{i=1}^{n}(Y_i-\bar{Y})^2$	

Source: Draper and Smith (1981)

The analysis of variance apportions the variability of the dependent variable Y into a variability accounted for by regression equation and a variability unaccounted for by the regression (see Table 3.8).

The analysis of variance table for research data in this study is subjected to a test of significance of the linear regression. The F-test statistic is the most appropriate significant test after the analysis of variance table has been generated. The F-test statistic with 1 and n-2 degrees of freedom at α is given by:

The obtained regression equations are tested for linearity by the method of Analysis of Variance (ANOVA) which is explained by Tabel 3.8.

Table 3.8: Analysis of Variance Table

Source of Variation	Degrees of freedom (D.F.)	Sum of Squares (S.S.)	Mean Squares (M.S.)
Accounted for by regression	1	$\sum_{i=1}^{n}(\hat{Y}_i-\bar{Y})^2$	$\frac{\sum_{i=1}^{n}(\hat{Y}_i-\bar{Y})}{1}$
Unaccounted for by regression (residuals)	n-2	$\sum_{i=1}^{n}(Y_i-\hat{Y}_i)^2$	$\sum_{i=1}^{n}(Y_i-\hat{Y}_i)^2/n-2$
Accounted for by mean (Total)	n-1	$\sum_{i=1}^{n}(Y_i-\bar{Y})^2$	

Source: Draper and Smith (1981)

The analysis of variance apportions the variability of the dependent variable Y into a variability accounted for by regression equation and a variability unaccounted for by the regression (see Table 3.8).

The analysis of variance table for research data in this study is subjected to a test of significance of the linear regression. The F-test statistic is the most appropriate significant test after the analysis of variance table has been generated. The F-test statistic with 1 and n-2 degrees of freedom at α is given by:

$$F(1,\ n-2,\ \alpha) = \frac{\sum_{i=1}^{n}(Y_i-\bar{Y})^2/1}{\sum_{i=1}^{n}(Y_i-\bar{Y}_i)/n-2} \quad \ldots\ldots\ldots\ldots\ldots(22)$$

where α is the level of significance.

The obtained F-value is compared to given F-value from the F-distribution tables with 1 and n-2 degrees of freedom at α significance level to determine if the mean square explained by the linear regression is large enough in comparison to the residual mean square (M.S.). This effects a decision on whether the regression is due to a 'real' effect rather than to random sampling.

Thus if the obtained F-value is greater than the given F-value from F-distribution table at α, then there is a significant linear relationship between X and Y.

The practical significance of the regression is measured by the squared correlation coefficient (r^2) which is obtained from ANOVA table as:

$$r^2 = \sum_{i=1}^{n}(\hat{Y}_i-\bar{Y})^2 \Big/ \sum_{i=1}^{n}(Y_i-\bar{Y})^2 \quad \ldots\ldots\ldots\ldots (23)$$

which is used as an explanation of the total variability of Y explained by the fitted linear regression.

The simple linear regression equation obtained for Mwea with rice variables as the dependent variables and water related variables as the independent ones are subjected to F-test statistic at $\alpha = 0.10$ and the results are discussed in the next chapter of this work.

However, there are some assumptions made when using the simple linear regression which sometimes may give invalid conclusions about X and Y. The major assumption of this model is that the relationship between X and Y is perfectly linear. This assumption does not hold in crop-water relationships due to the numerous other factors which influence crop growth and yield. In view of this limitation, the data in this study will be subjected to non-parametric tests to ascertain whether there may be other non-linear relationships between crop variables and water management activities.

3.4. Research limitations

The time and finances available for this research did not allow for a complete coverage of the Mwea Irrigation Settlement. A sample (Mwea Section) of the Irrigation Settlement was selected for data extraction which forms the basis of this study.

Some data, mainly meteorological, specifically relative humidity and windrun were missing for most of the selected rice seasons. This data was required to estimate rice water requirement (ETrice) and its inavailability limited the rice seasons to seven which is a relatively small sample. However, without an alternative, the small sample of seven seasons had to be relied upon in the water balance calculations and also in the estimation of the degree of association between rice crop variables and water management activities.

Another limitation was the lack of soil data, that is the agrohydrological characteristics of Mwea Vertisols. This was overcome by use of laboratory tests done by van Gessel (1982) on the area's Vertisols.

An agro-climatological model (Pan Evaporation method) was used to estimate rice water requirements (ETrice) and as noted by Sarraf (1971), most analytical models in agro-climatology depend on the accuracy of meteorological data. Meteorological data according to his view, sometimes have error margins of order 20%. This is due to errors in measurement. However, the error magnitude even with measurements of the estimated variable(s) could be the same. Hence, use of models to estimate variables in agro-climatology are only as good as the actual observations.

Some data, mainly meteorological, specifically relative humidity and windrun were missing for most of the selected rice seasons. This data was required to estimate rice water requirement (ETrice) and its inavailability limited the rice seasons to seven which is a relatively small sample. However, without an alternative, the small sample of seven seasons had to be relied upon in the water balance calculations and also in the estimation of the degree of association between rice crop variables and water management activities.

Another limitation was the lack of soil data, that is the agrohydrological characteristics of Mwea Vertisols. This was overcome by use of laboratory tests done by van Gessel (1982) on the area's Vertisols.

An agro-climatological model (Pan Evaporation method) was used to estimate rice water requirements (ETrice) and as noted by Sarraf (1971), most analytical models in agro-climatology depend on the accuracy of meteorological data. Meteorological data according to his view, sometimes have error margins of order 20%. This is due to errors in measurement. However, the error magnitude even with measurements of the estimated variable(s) could be the same. Hence, use of models to estimate variables in agro-climatology are only as good as the actual observations.

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Results of the Evaluation of the Crop Water Requirements of Rice (ETrice)

The results of the analysis of rice evapotranspiration in Mwea presented as ten-day totals over the entire growing season are summarized in Table 4.1 for seven seasons. These results are estimated by use of the Pan Evaporation method as already demonstrated in Section 3.3.1.

The ten-day variations of rice evapotranspiration in each season, as the crop advances in growth and development, are clearly indicated in Table 4.1. The highest evapotranspiration rates were found to be between 50 and 70 days after transplanting. This is also the period when the rice crop is flowering and when the formation of grain commences and the period of maximum water requirement by the crop.

Seasonal rice evapotranspiration for the seven seasons as seen from the table varied from 619mm to 795mm with an average of 691mm and a standard deviation of 56.5mm. The average ETrice, based on the data of the seven seasons, is shown in Figure 11. This figure shows the deviations of ETrice for the ten-day periods from the calculated averages. The seventh ten-day period has the largest deviation (20.5mm). Overall, the figure indicates that seasonal ETrice on

Table 4.1: Summary of the seasonal rice evapotranspiration in Mwea Irrigation Settlement for seven seasons in 10-day periods (mm/10 days)

10-day period	1	2	3	4	5	6	7	8	9	10	11	12	Total
Season													
1970	44	35	32	60	52	72	94	82	90	42	50	54	707
1971	48	57	62	69	81	76	95	73	55	71	59	49	795
1972	58	48	72	72	65	65	62	48	53	43	50	42	678
1973	48	54	69	59	74	67	74	56	58	49	46	43	697
1974	38	44	45	63	78	58	45	45	52	55	51	45	619
1981	44	53	61	72	51	83	90	61	65	48	43	51	722
1982	35	40	58	65	55	85	44	61	55	44	31	48	621
Mean	45	47	57	66	65	72	72	61	61	50	47	47	691
Standard Deviation	6.9	7.4	13	5	11.7	9.1	20.5	12.2	12.4	9.4	8.0	4.0	56.5

Source of data: Calculations from Pan evaporation data obtained from Mwea Irrigation Settlement.

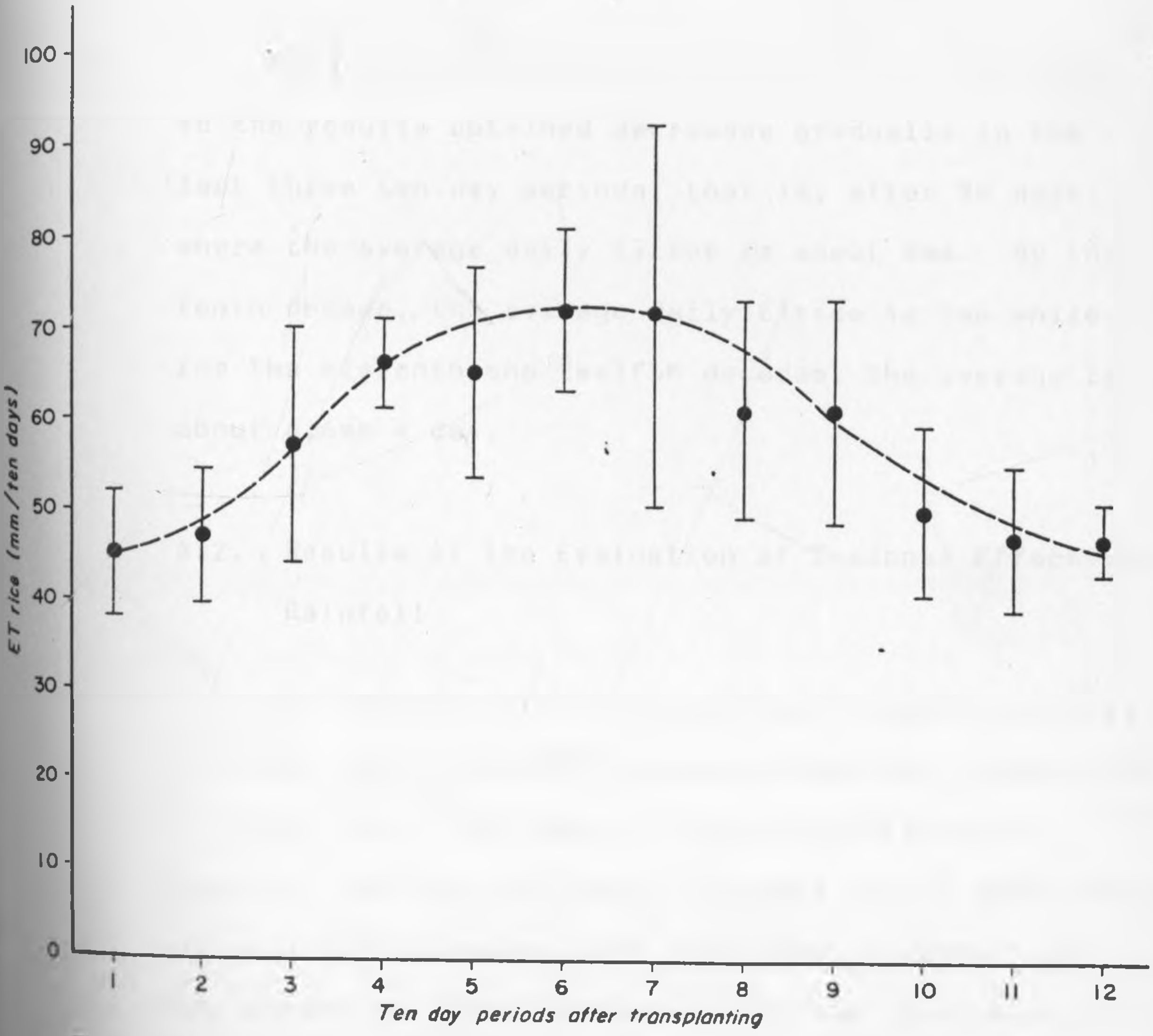


Fig. 11 RICE EVAPOTRANSPIRATION FROM TRANSPLANTING TO HARVESTING BASED ON SEVEN SEASONS' DATA FROM MWEA IRRIGATION SETTLEMENT.

ten-day basis is variable and that decision on irrigation scheduling should not be based on previous season's ETrice. This is due to the dependence of ETrice on weather conditions.

Rice evapotranspiration in the area, according to the results obtained decreases gradually in the last three ten-day periods, that is, after 90 days where the average daily ETrice is about 6mm. By the tenth decade, the average daily ETrice is 5mm while for the eleventh and twelfth decades, the average is about 4.6mm a day.

4.2. Results of the Evaluation of Seasonal Effective Rainfall

The seasonal effective rainfall results obtained for Mwea during the rice growing season are summarized in Table 4.2. The amount of seasonal effective rainfall in Mwea was found to depend on the distribution of rainfall throughout the rice growing season and the extent to which irrigation met the rice water requirement. Effective rainfall during the seven seasons also depended on how the seasonal rainfall replenished the soil water at successive ten-day periods of the seasons.

The highest percentage of effective rainfall for the seven seasons was 92% for both 1970 and 1971 seasons. This high percentage was partly due to low seasonal rainfall for the two seasons, 158mm and 164mm respectively. This means that most of the rainfall went to meet the deficiency in rice evapotranspiration after irrigation and the rest was stored in the soil or flooded the bunded paddy fields.

Another factor which contributed to the high effective rainfall percentage was the temporal distribution of the rainfall which was even over the two seasons. As such, the rain water was utilized by the crop without losses to overflow.

The lowest percentage of seasonal effective rainfall was found to be 44% in the 1974 season. Although the seasonal rainfall was 198mm, its distribution by ten-day periods was uneven, where most of the rainfall was from 60 days after transplanting. Before 60 days, high amounts of irrigation water were applied and by the period of 70 days, the bunded paddy fields had been flooded to maximum (375mm). Hence most of the rainfall after the 70 days for this season was ineffective and consequently, the low seasonal effective rainfall.

Table 4.2: Summary of calculated seasonal effective rainfall in Mwea Irrigation Settlement during the rice growing season

Season	1970	1971	1972	1973	1974	1981	1982
Gross rainfall (mm)	158	164	436	338	198	284	492
Effective rainfall (mm)	146	151	306	193	88	169	271
Proportion of gross rainfall which is effective (%)	92	92	70	57	44	60	55

For the remaining four seasons, the seasonal effective rainfall is seen to have been more than 50% of the gross seasonal rainfall from which it can be inferred that over a half of the rainfall is effective. This indicates that in Mwea Irrigation Settlement, more than a half of the seasonal rainfall during the rice growing season is utilized by the paddy or stored in the soil and as such less than a half of the gross seasonal rainfall is not required for most seasons.

4.3. Results of the Evaluation of Cumulative Soil-Water Balance

The seasonal cumulative soil-water balance calculations of Mwea Irrigation Settlement were done using equation (6) [Chapter 3]). The soil moisture characteristics used in these calculations were shown in Table 3.4 and the details of the procedure of calculations were explained in Section 3.3.3.

The seasonal cumulative soil-water balances of Mwea for the seven seasons are now shown in Tables 4.3 (a) to 4.3 (g) where all the values are in millimetres for ten-day increments.

Tables 4.3(a)-4.3(g): Calculated seasonal cumulative soil-water balances of Mwea Irrigation Settlement on ten-day basis

Table 4.3(a)

1970

10-day period	IRR_i+R_i	S_{i-1}	$(ET_{rice})_i$	SP_i	S_i	OF_i	$IRR_i+R_i-ET_{rice_i}$
1	78	175	44	5	204	0	34
2	63	204	35	7	225	0	28
3	53	225	32	9	236	0	21
4	141	236	60	9	308	0	81
5	70	308	52	15	311	0	18
6	64	311	72	15	288	0	-8
7	84	288	94	13	265	0	-10
8	85	265	82	12	256	0	3
9	61	256	90	11	216	0	-29
10	98	216	42	8	264	0	56
11	28	264	50	12	230	0	-22
12	1	230	54	9	168	0	-53
Seasonal Total	826		707	125		0	119

Table 4.3(b)

1971

10-day period	IRR_i+R_i	S_{i-1}	$(ET_{rice})_i$	SP_i	S_i	OF_i	$IRR_i+R_i-ET_{rice_i}$
1	81	175	48	5	203	0	33
2	50	203	57	7	189	0	-7
3	60	189	62	6	181	0	-2
4	151	181	69	5	258	0	82
5	61	258	81	11	227	0	-20
6	80	227	76	9	222	0	4
7	60	222	95	9	178	0	-35
8	67	178	73	5	167	0	-6
9	111	167	55	4	219	0	56
10	30	219	71	8	170	0	-41
11	29	170	59	4	136	0	-30
12	23	136	49	1	109	0	-26
Seasonal Total	803		795	74		0	8

Table 4.3(c)

1972

10-day period	IRR_i+R_i	S_{i-1}	$(ET_{rice})_i$	SP_i	S_i	OF_i	$IRR_i+R_i-ET_{rice_i}$
1	73	175	58	5	185	0	15
2	57	185	48	6	188	0	9
3	67	188	72	6	177	0	-5
4	76	177	72	5	176	0	4
5	116	176	65	5	222	0	51
6	158	222	65	9	306	0	93
7	122	306	62	15	351	0	60
8	95	351	48	18	375	5	47
9	84	375	53	20	375	11	31
10	50	375	43	20	362	0	7
11	17	362	50	19	310	0	-33
12	0	310	42	15	253	0	-42
Seasonal Total	915		678	143		16	237

Table 4.3(d)
1973

10-day period	IRR_i+R_i	S_{i-1}	$(ET_{rice})_i$	SP_i	S_i	UF_i	$IRR_i+R_i-ET_{rice_i}$
1	83	175	48	5	205	0	35
2	44	205	54	7	188	0	-10
3	107	188	69	6	220	0	38
4	100	220	59	9	252	0	41
5	96	252	74	11	266	0	25
6	70	266	67	12	257	0	3
7	134	257	74	11	306	0	60
8	174	306	56	15	375	34	118
9	84	375	58	20	375	6	26
10	60	375	49	20	366	0	11
11	9	366	46	19	310	0	-37
12	0	310	43	15	252	0	-43
Seasonal Total	961		697	150		40	264

Table 4.3(d)
1973

10-day period	IRR_i+R_i	S_{i-1}	$(ET_{rice})_i$	SP_i	S_i	UF_i	$IRR_i+R_i-ET_{rice_i}$
1	83	175	48	5	205	0	35
2	44	205	54	7	188	0	-10
3	107	188	69	6	220	0	38
4	100	220	59	9	252	0	41
5	96	252	74	11	266	0	25
6	70	266	67	12	257	0	3
7	134	257	74	11	306	0	60
8	174	306	56	15	375	34	118
9	84	375	58	20	375	6	26
10	60	375	49	20	366	0	11
11	9	366	46	19	310	0	-37
12	0	310	43	15	252	0	-43
Seasonal Total	961		697	150		40	264

Table 4.3(e)

1974

10-day period	IRR_i+R_i	S_{i-1}	$(ET_{rice})_i$	SP_i	S_i	OF_i	$IRR_i+R_i-ET_{rice_i}$
1	79	175	38	5	211	0	41
2	51	211	44	8	210	0	7
3	90	210	45	8	247	0	45
4	100	247	63	10	274	0	37
5	80	274	78	12	264	0	2
6	69	264	58	12	263	0	11
7	45	263	45	12	251	0	0
8	30	251	45	11	225	0	-15
9	45	225	52	9	209	0	-7
10	22	209	55	8	168	0	-33
11	20	168	51	4	133	0	-31
12	0	133	45	1	87	0	-45
Seasonal Total	631		619	100		0	12

Table 4.3(f)

1981

10-day period	IRR_i+R_i	S_{i-1}	$(ET_{rice})_i$	SP_i	S_i	OF_i	$IRR_i+R_i-ET_{rice_i}$
1	84	175	44	5	210	0	40
2	72	210	53	8	223	0	21
3	64	223	61	9	217	0	3
4	118	217	72	8	255	0	46
5	69	255	51	11	262	0	18
6	109	262	83	12	276	0	26
7	60	276	90	13	233	0	-30
8	215	233	61	9	375	3	154
9	64	375	65	20	354	0	-1
10	40	354	48	19	327	0	-8
11	39	327	43	16	307	0	-4
12	25	307	51	15	266	0	-26
Seasonal Total	959		722	145		3	237

Table 4.3(g)

1982

10-day period	IRR_i+R_i	S_{i-1}	$(ET_{rice})_i$	SP_i	S_i	OF_i	$IRR_i+R_i-ET_{rice_i}$
1	65	175	35	5	200	0	30
2	81	200	40	7	234	0	41
3	60	234	58	9	227	0	2
4	111	227	65	9	262	0	46
5	80	262	55	12	275	0	25
6	136	275	85	13	313	0	51
7	168	313	44	15	375	47	124
8	86	375	61	20	375	5	25
9	67	375	55	20	367	0	12
10	89	367	44	19	375	18	45
11	27	375	31	20	359	0	-4
12	24	359	48	19	316	0	-24
Seasonal Total	994		621	168		70	373

The cumulative soil-water balance results show that in most of the ten-day periods, the rice water requirement (ETrice) was met by rainfall and irrigation but in most cases, there was over-application of water. The surplus water was stored in the bunded paddy fields although the magnitude of deep percolation below the root zone (30cm) increased with surplus water (Tables 4.3(a) to 4.3(g).

In some ten-day periods, there were overflows such as the 8th and 9th periods in 1972 and 1973. The highest overflow was during the seventh period in 1982 (47mm). This was due to the high amount of rainfall in the previous ten-day period (136mm) and at the 7th ten-day period, irrigation was done which was unnecessary. At this 7th ten-day period of 1982 season, 167mm of rainfall were received still making irrigation unnecessary. This was the reason for high amount of overflow.

The 1970 and 1971 seasons had no overflows at all but this does not indicate that there was no over-irrigation. It could be argued that irrigation and rainfall met the rice water requirement as much as possible without extreme surplus water to the paddy fields. Over-irrigation on the other hand could occur even without overflow depending on the level of flooding the paddy fields according to the requirements of the crop.

Nevertheless, the 1971 season was the only season out of the seven seasons, which had correct water application for rice agriculture where the amount of water in the paddy fields (S_i) matched the water requirements of Mwea paddy fields.

Application of water into the paddy fields of the area should be scheduled according to the rice water requirements, the amount of rainfall previously received and the existing soil moisture conditions. This reduces the risk of over-irrigation and avoids the problem of overflows.

4.4. Results of the Evaluation of Seasonal Irrigation Efficiency

The results of the seasonal irrigation efficiency in Mwea for seven seasons are summarized in Table 4.4. As it is obvious that seasonal irrigation efficiency is influenced by the method and scheduling of irrigation, the seasonal irrigation efficiency of Mwea from the calculations considered the scheduling. The interval of irrigation schedule should conform to the field water requirement if high efficiency is to be attained.

In the 1982 season, the irrigation efficiency was very low (46%). This was due to poor scheduling without consideration of effective rainfall to assess the field water requirement. Due to the poor scheduling, as seen from Table 4.3(g), it led to 70mm of overflow. In this season, the rice water requirement was 621mm while effective rainfall was 271mm. Hence, of the 503mm of irrigated water, only 117mm was useful.

Irrigation in the 1982 season was concentrated in the first five ten-day periods while in the sixth and seventh periods, there was no irrigation. This is the peak period for water requirement by rice.

In the 1971 season, the seasonal irrigation efficiency was 83%, the highest of the seven seasons. This high irrigation efficiency is attributed to low effective rainfall (151mm) and high seasonal rice water requirement (795mm). The scheduling of irrigation and low rainfall within the season led to the high irrigation efficiency as confirmed from Table 4.3(b) where it is seen that there was no overflow and the soil moisture did not exceed 225mm.

The overall irrigation efficiency from the seven seasons was above 60% for six seasons which is the suggested irrigation efficiency of furrow irrigation in paddy fields (Sarraf, 1971).

4.5. Results of the Evaluation of Rice-water Relationships in Mwea

The previous sections of this Chapter have considered the seasonal rice evapotranspiration and

Table 4.4: Summary of Seasonal Irrigation Efficiency Calculations for Mwea during the rice growing seasons

Season	ETrice (mm)	Re (mm)	IRRds (mm)	IRR (mm)	IRR.EFF. (%)
1970	707	115	151	668	66
1971	795	151	110	639	83
1972	678	306	22	479	73
1973	697	193	83	623	67
1974	619	88	131	597	59
1981	722	169	101	665	61
1982	621	271	117	503	46

applied water (irrigation and rainfall) separately. In this section, the relationships between rice evapotranspiration and applied water are investigated. The rice grain yields and other water related variables are analysed for the purpose of validating the previously postulated hypotheses.

4.5.1. Rice evapotranspiration and seasonal applied water

Rice water requirement, (ETrice), is the main environmental characteristic which sets the rice crop apart from other cereals since the crop thrives under flooded conditions. The rice evapotranspiration values obtained by Pan Evaporation method for Mwea compare well with those obtained from Thailand by Oldeman and Frere (1982), in Philippines by Moorman and Breemen (1978) and the standard rice evapotranspiration as indicated by Doorenbos and Kassam (1979).

Thus it was considered logical to subject rice evapotranspiration results to further analyses. The comparison between the seasonal rice evapotranspiration and the seasonal rainfall show that rainfall is far much below ET_{rice}. With such an observation, there is a need for supplementary irrigation in Mwea during the rice growing season to meet the rice evapotranspiration and to flood the paddy fields.

Due to this need for irrigation, it was found necessary to consider the gross amount of applied water (irrigation and rainfall) as the two important sources of water for rice agriculture in Mwea. Figures 12(a)-12(g) show the seasonal rice evapotranspiration and the total applied water on ten-day basis during the rice growing season.

The figures show that there are certain periods when the rice water requirement exceeded the applied water (deficits). However, these do not necessarily indicate rice water stress since the available soil water, as shown in Tables 4.3(a) to 4.3(g), is not depleted to wilting point at any period.

For the seven considered seasons, the deficits towards the end of the seasons, according to Williams and Joseph (1970), are desirable as this is the time of rice ripening when excess moisture may spoil the process of grain drying. The rice grain should be harvested at a moisture content of 15%.

An attempt to investigate the seasonal applied water and the water requirement by rice in the area was necessary in order to determine the significance of seasonal applied water to rice evapotranspiration. Figure 13 shows the regression graph of the difference between applied water and the rice water requirement with the seasonal applied water on a ten-day period basis.

KEY TO FIGURES 12a–12g

- - - - Rice evapotranspiration (ET_{Rice})
—— Irrigation and rainfall
▨ Water deficit

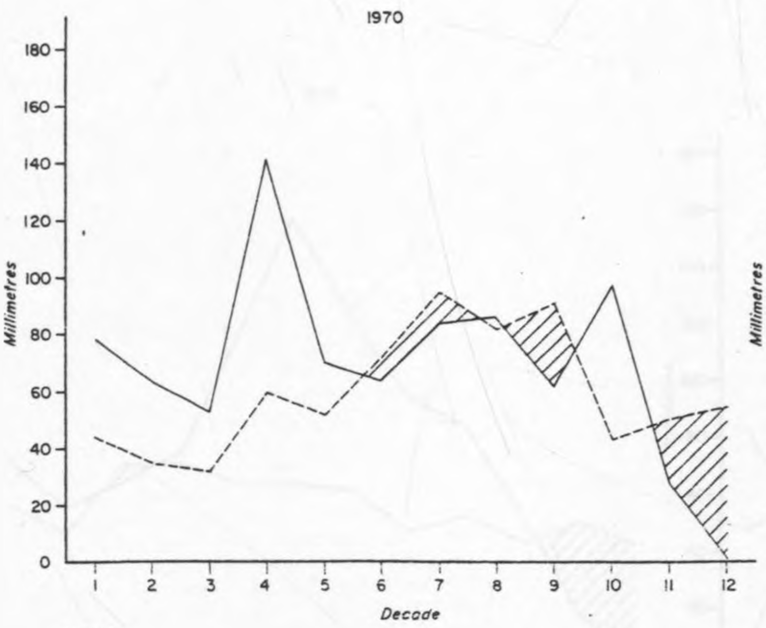


Fig.12a

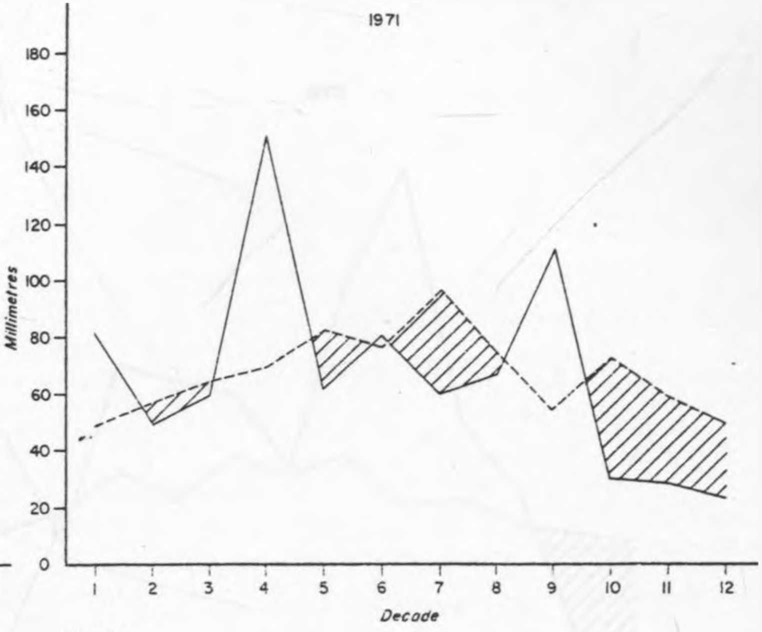


Fig.12b

Fig. 12a–12g SEASONAL DISTRIBUTION OF TEN-DAY APPLIED WATER AND RICE EVAPOTRANSPIRATION IN MWEA FOR SEVEN SEASONS

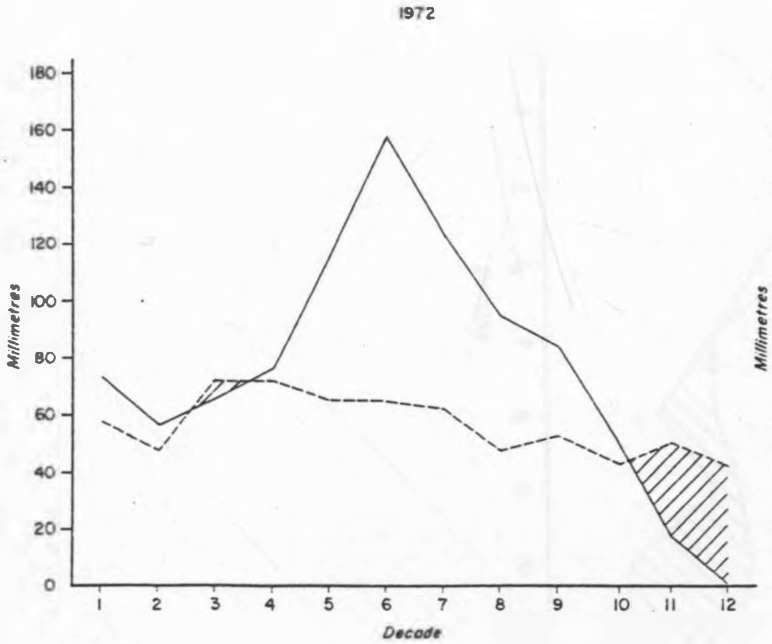


Fig. 12c

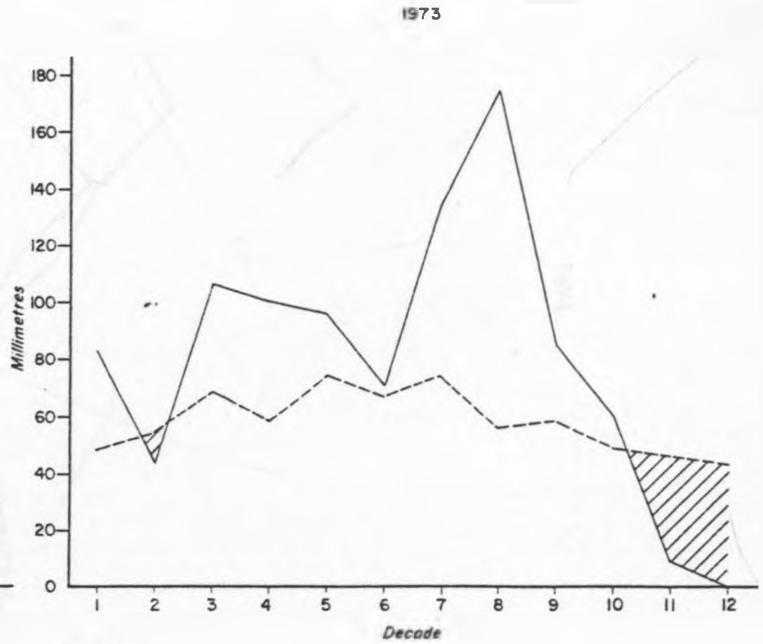


Fig. 12d

1974

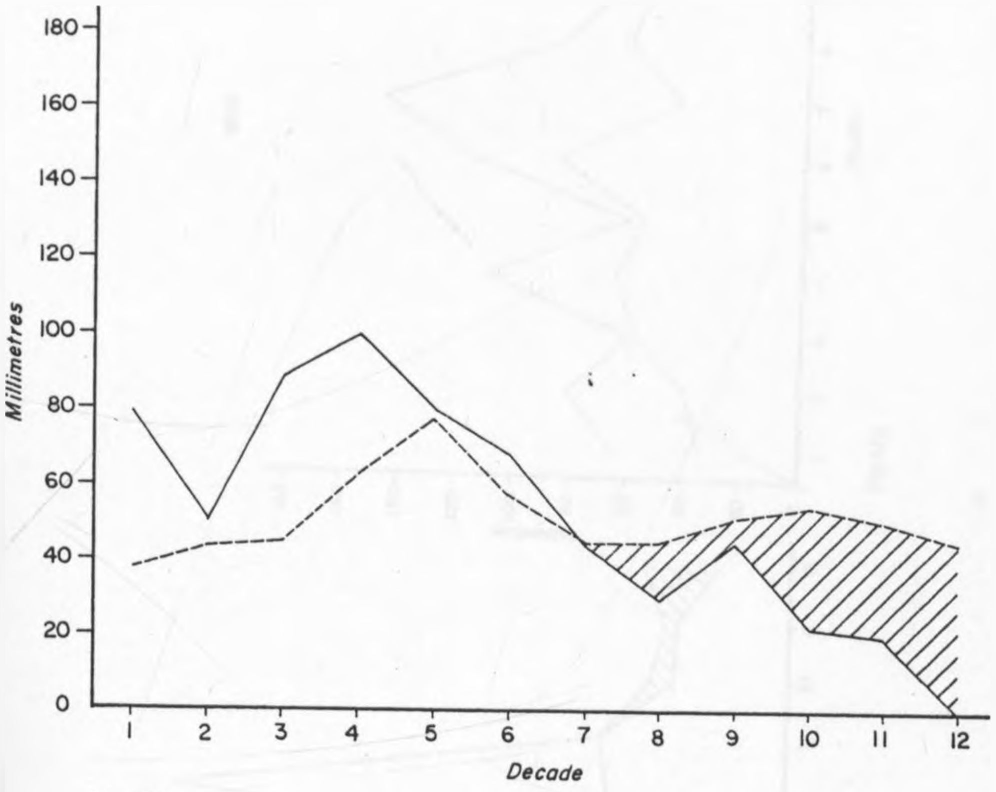

Millimetres
180
160
140
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
11
12
Decade

Fig. 12e

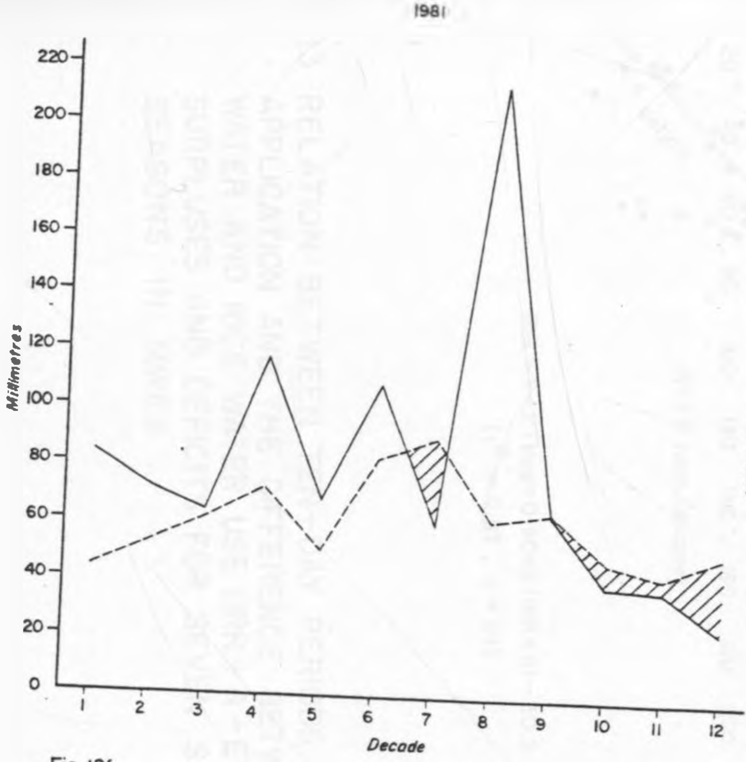


Fig. 12f

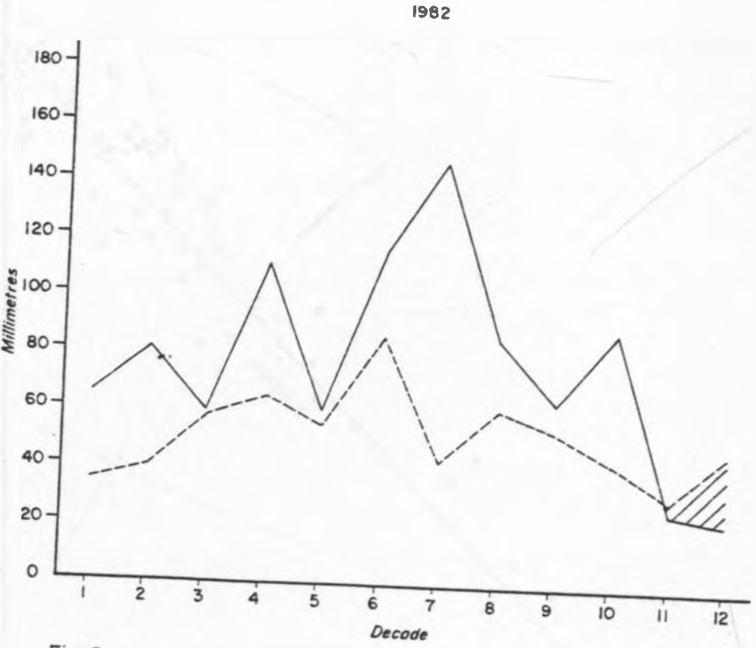


Fig.12g

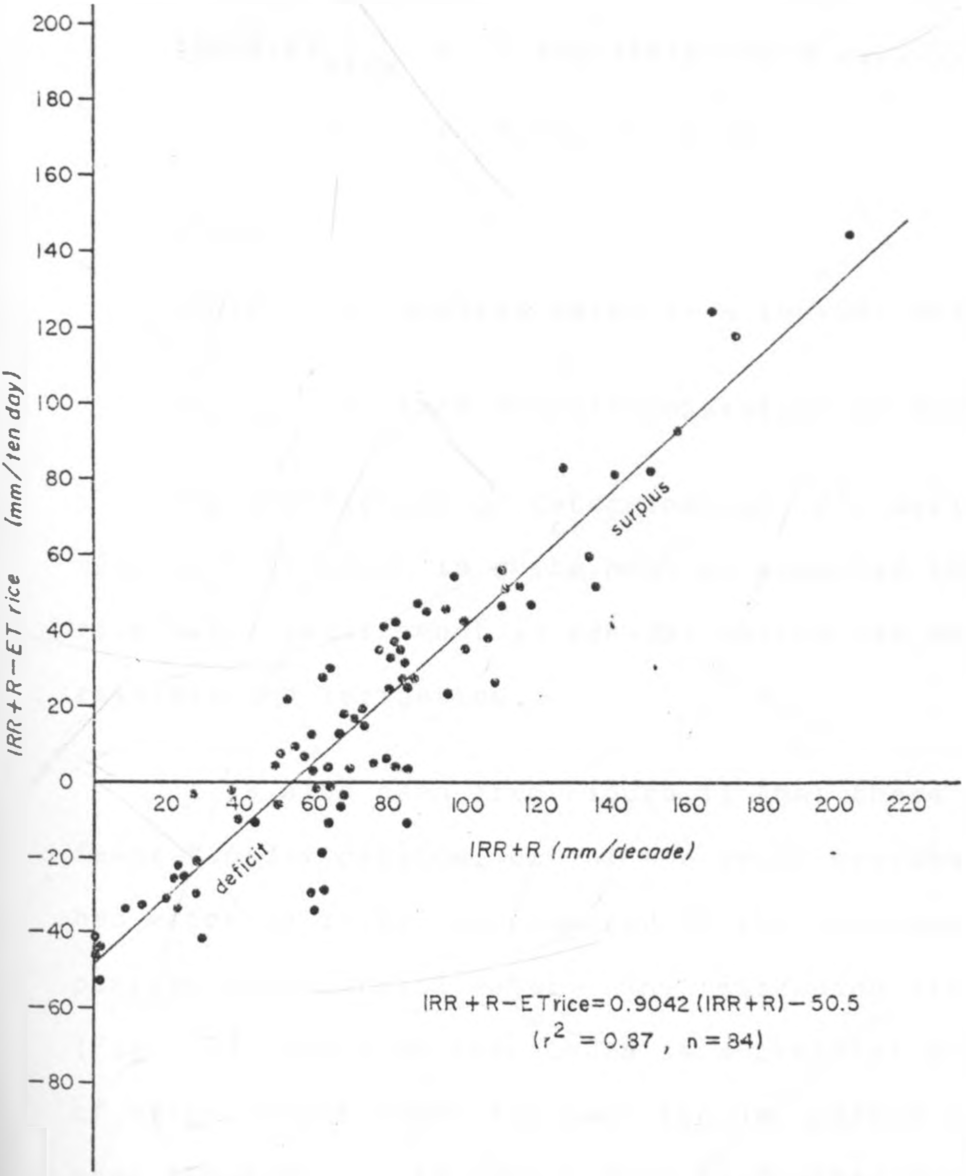


Fig. 13 RELATION BETWEEN TEN-DAY PERIODS OF WATER APPLICATION AND THE DIFFERENCE BETWEEN APPLIED WATER AND RICE WATER USE (IRR + R − ET rice) INDICATING SURPLUSES AND DEFICITS FOR SEVEN SELECTED SEASONS IN MWEA

The linear regression equation is as follows:

$$IRR+R-ET_{rice} = 0.904(IRR+R)-50.5 \quad \ldots\ldots\ldots\ldots \quad (24)$$

$$r = 0.93, \quad n = 84$$

where

$IRR+R$ = applied water in a ten-day period (mm).

ET_{rice} = rice evapotranspiration in millimetres.

The coefficient of determination, r^2, derived from (24) is 0.87 which is quite high as expected that the rice water requirement in ten-day period was met by rainfall and irrigation.

It is also seen from Figure 13 that there were fewer ten-day periods, out of the seven seasons, that had water deficits, as compared to the numerous periods with surplus water. The regression line (Fig. 13) indicates that there is a critical amount of water (about 56mm) for each ten-day period even when $IRR+R-ET_{rice}$ is zero. This is further supported by the seasonal ten-day average of ET_{rice}, indicated in Table 4.1. where the average for ten-day periods is about 58mm. Hence, to minimise wastage of water and to keep the crop supplied with adequate water, irrigation in Mwea Irrigation Settlement should be about 60mm.

Simple linear regression analyses to establish the degree of association between seasonal ET_{rice} and seasonal effective rainfall (Re) as well as irrigation efficiency levels gave the following results respectively:

$$ET_{rice} = 720-0.152Re \quad \ldots\ldots\ldots\ldots\ldots \quad (25)$$

$$r^2 = 0.035, \quad n = 7$$

where

ET_{rice} = seasonal rice evapotranspiration in mm.

Re = seasonal effective rainfall in mm.

and

$$ET_{rice} = 461.2+0.590\ IRR.EFF \quad \ldots\ldots\ldots\ldots \quad (26)$$

$$r^2 = 0.805, \quad n = 7$$

where

ET_{rice} is as in (25)

IRR.EFF = seasonal irrigation efficiency in mm.

Table 4.5: Analysis of variance results of rice water requirement and seasonal effective rainfall

Source of variation	Degree of freedom	Sum of Squares	Mean Squares
Accounted for by regression	1	860.9	860.9
Unaccounted for by regression	5	21458.8	4291.8
Accounted for by mean	6	22321.5	

Computed F-value = 0.20

Critical F-value at F(1, 5, 0.10) = 4.06

Table 4.6: Analysis of variance results of rice water requirement and seasonal irrigation efficiency levels

Source of variation	Degrees of freedom	Sum of Squares	Mean Squares
Accounted for by regression	1	17966.10	17966.10
Unaccounted for by regression	5	4355.33	871.1
Accounted for by mean	6	22321.43	

Computed F-value = 20.63

Critical F-value at F(1, 5, 0.10) = 4.06

As seen from tables 4.5 and 4.6, analysis of variance for effective rainfall and irrigation efficiency, at 10% risk, the F-test statistic indicates that there is no significant linear relationship between seasonal effective rainfall and ETrice. Conversely, there is a significant linear relationship between seasonal irrigation efficiency and ETrice in Mwea Irrigation Settlement.

Due to the small sample size and the assumptions of the simple linear regression model, Spearman's Rank correlation coefficient was tried on the same

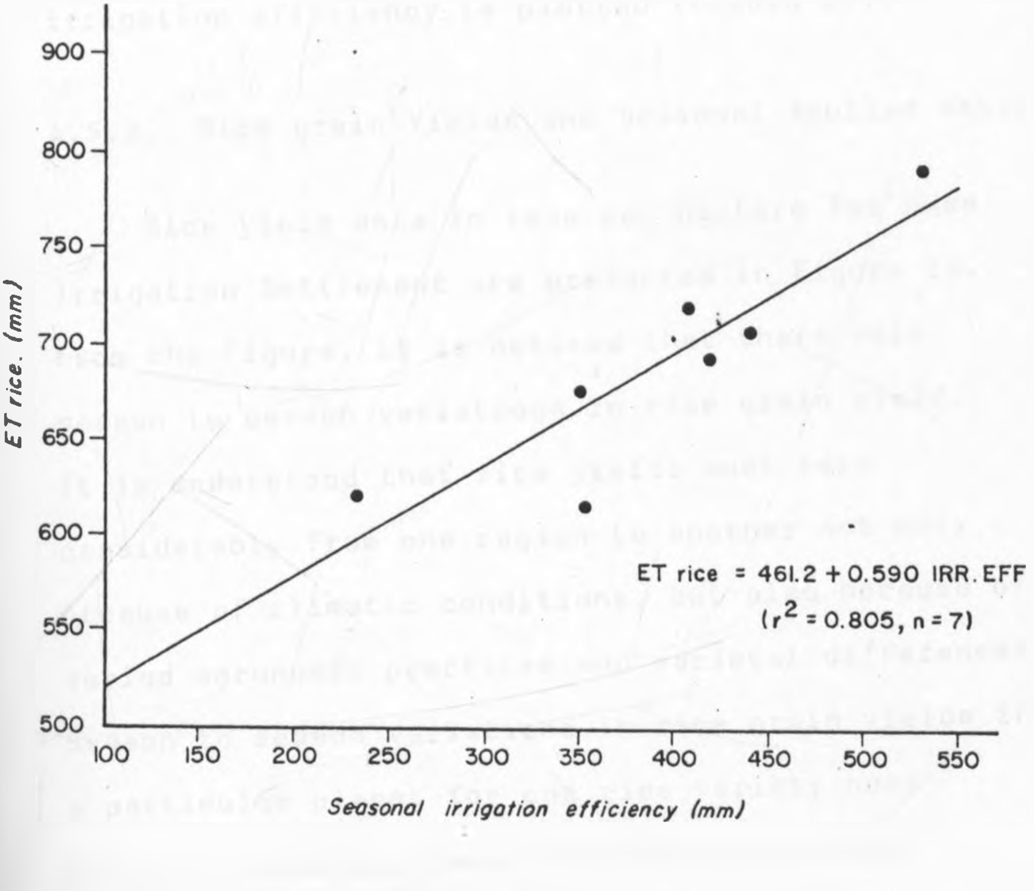


Fig. 14: RELATIONSHIP BETWEEN SEASONAL RICE EVAPOTRANSPIRATION AND IRRIGATION EFFICIENCY LEVELS

data and gave similar results at 5% risk. These results indicate that irrigation in the area is the main supplier of water in rice agriculture and without it, it would be impossible to have a successful rice crop. Simple linear regression graph for ET_{rice} and irrigation efficiency is plotted (Figure 14).

4.5.2. Rice grain Yields and Seasonal Applied Water

Rice yield data in tons per hectare for Mwea Irrigation Settlement are presented in Figure 15. From the Figure, it is noticed that there were season to season variations in rice grain yield. It is understood that rice yields must vary considerably from one region to another not only because of climatic conditions, but also because of varied agronomic practices and varietal differences. Season to season variations in rice grain yields in a particular place, for one rice variety need detailed investigations on climatic and crop maintenance factors (Robertson, 1975).

Oldeman and Suardi (1978) observed that variations of rice yields in a particular area could be attributed to the aspects of water management, specifically, insufficient water applications within the crop season. In some instances, excess flooding of paddy fields may be the cause of yield variations. Both of these aspects reduce the rice grain yield. In this study,

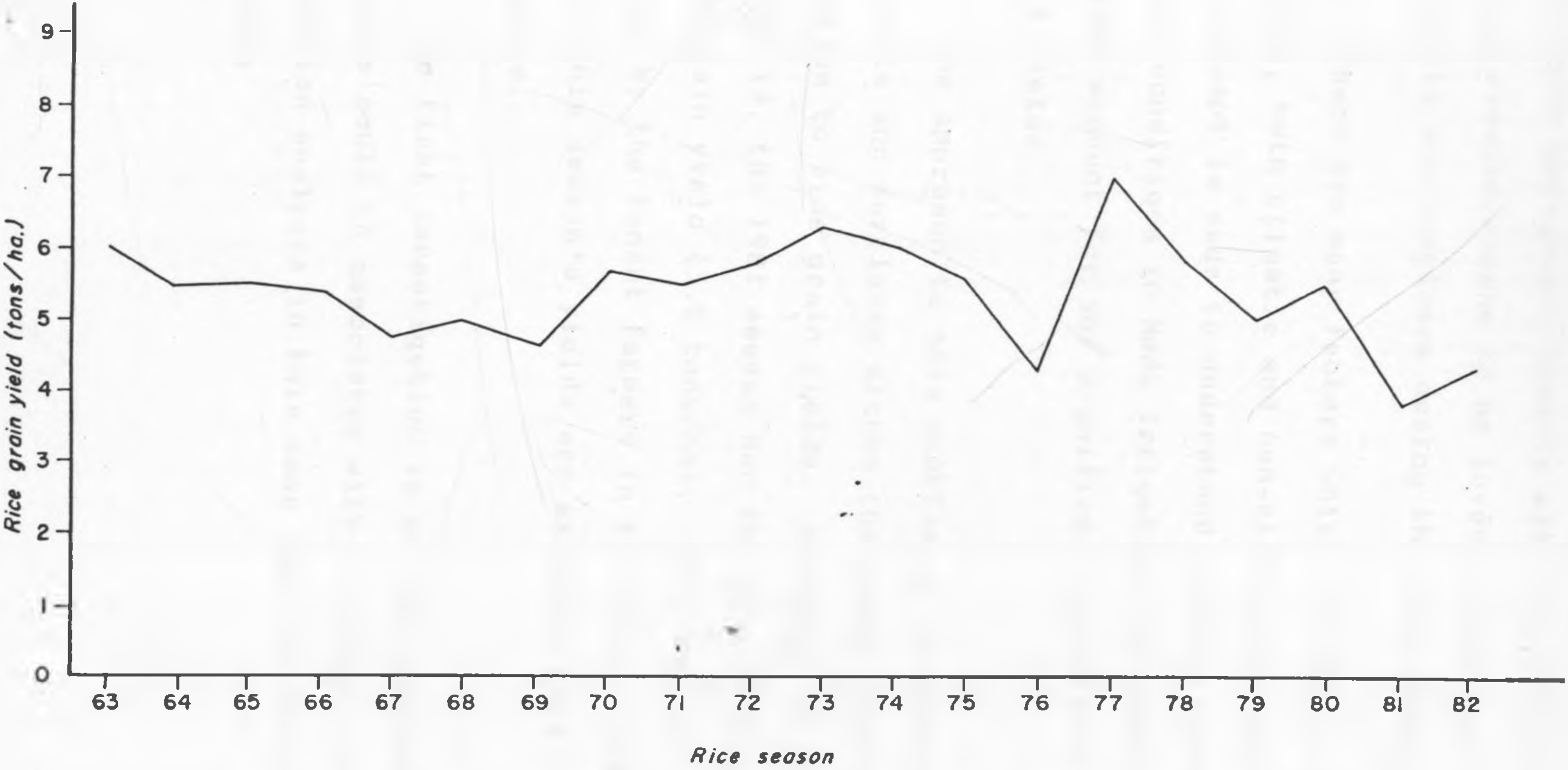


Fig. 15 SEASONAL RICE GRAIN YIELDS IN MWEA IRRIGATION SETTLEMENT FOR 20 SEASONS

the water management aspects with respect to the above considerations to be investigated are water deficits and surpluses during the rice season.

There are many factors which influence crop yields, both climatic and non-climatic, and here, an attempt is made to understand whether seasonal water conditions in Mwea Irrigation Settlement paddy fields account for any significant variations in rice yields.

The approach to this problem is to analyse water deficits and surpluses within the seven seasons in relation to rice grain yields. However, as seen from Figure 15, the 1981 season had the lowest recorded rice grain yield (3.8 tons/ha). This was due to a strike by the tenant farmers in the area. Due to this, this season's yields are excluded from the analysis.

The first investigation is on how seasonal water deficits could be associated with rice grain yields. Regression analysis in this case gave the following results:

$$Y = 5.63 + 0.001\ SD \ldots\ldots\ldots\ldots (27)$$

$$r^2 = 0.033, \quad n = 6$$

where

Y = rice grain yield (tons/ha).

SD = seasonal water deficit (mm).

Analysis of variance to test the significance of the linear regression equation above gave the results shown in Table 4.7. The coefficient of determination (r^2) in the above equation indicates that seasonal water deficits in Mwea Irrigation Settlement account for about 3% variability in rice grain yield. This means that seasonal water deficits during the crop season are not linearly related to rice grain yield.

Table 4.7: Analysis of variance results of rice grain yield and seasonal water deficit

Source of variation	Degrees of freedom	Sum of Squares	Mean Squares
Accounted for by regression	1	0.021	0.021
Unaccounted for by regression	4	0.613	0.153
Accounted for by mean	5	0.634	

Computed F-value = 0.137

Critical F-value at F(1, 4, 0.10) = 4.54

Since the computed F value is less than the critical value at $\alpha = 0.10$, there is no significant relationship between rice grain yield and seasonal water deficits in Mwea Irrigation Settlement.

Seasonal water deficits during the crop season may not be very meaningful in terms of rice grain yield. This is due to the changes in water requirement by the crop as the season advances and as such, an attempt is made to investigate the influence of water deficits at certain periods of the crop growth. Firstly, as noticed from Table 4.1 and Figure 11, the rice water requirement decreases considerably in the last twenty days. Regression analysis is therefore done on the water deficits excluding the last twenty days of the season, that is, water deficits at the first hundred days. These last twenty days are excluded because it is the period when the crop is in the process of grain drying and water deficits do not account for any change in yield. The linear regression analysis gave the following results:

$$Y = 5.83 - 0.001\,D \quad \ldots\ldots\ldots\ldots\ldots \quad (28)$$

$$r^2 = 0.04, \quad n = 6$$

Where

Y = rice grain yield (tons/ha)

D = water deficit for hundred days (mm).

As seen from the above equation, water deficits for the first hundred days of the rice crop season explains a very small (4%) variability in rice grain yield. As such, it could be argued that there is no significant association between rice grain yield and the first hundred days' water deficits. Analysis of variance (Table 4.8) is presented to confirm this.

Table 4.8: Analysis of variance results of rice grain yield and hundred days' water deficit

Source of variation	Degrees of freedom	Sum of Squares	Mean Squares
Accounted for by regression	1	0.025	0.025
Unaccounted for by regression	4	0.608	0.152
Accounted for by mean	5	0.633	

Computed F-value = 0.164

Critical F-value at F(1, 4, 0.10) = 4.54

Since the computed F-value is less than the critical value at $\alpha = 0.10$, it is concluded that there is no significant relationship between rice grain yield and water deficits for the first hundred days of the crop season.

The critical period when water deficiency has a profound reducing effect on rice grain yield is the period of heading and grain filling. In the case of Sindano, this period occurs from the fifth to ninth decades (see Figure 9). It was therefore logical to investigate water deficits at these periods to determine how they influence the crop grain yield.

Regression analysis on rice grain yield and water deficits at these periods (fifth, sixth, seventh, eighth and ninth decades) gave the following results:

$$Y = 6.00 - 0.007\ HD \quad \ldots\ldots\ldots\ldots\ldots\ldots (29)$$

$$r^2 = 0.47, \; n = 6$$

Where

Y = rice grain yield (tons/ha)

HD = water deficits from fifth to ninth decades (mm).

Analysis of variance on the regression equation (29) to test for significance gave the results presented in Table 4.9.

Table 4.9: Analysis of variance results of rice grain yield and water deficits at heading and grain filling

Source of variation	Degrees of freedom	Sum of Squares	Mean Squares
Accounted for by regression	1	0.175	0.175
Unaccounted for by regression	4	0.20	0.05
Accounted for by mean	5	0.38	

Computed F-value = 3.50

Critical F-value at F(1, 4, 0.10) = 4.54

Table 4.9 shows that the computed F-value is less than the critical F-value at $\alpha = 0.10$, so it can be concluded that the regression equation is not significant. However, the coefficient of determination from the obtained regression equation indicates that water deficits at heading and grain filling of <u>Sindano</u> rice account for about 47% variability in grain yield. This means that water deficits at these periods can .

reduce the crop grain yield considerably and as such should not be allowed to occur.

The second aspect for investigation is the seasonal surpluses. In the case of Mwea Irrigation Settlement, rice is grown in bunded paddy fields, consideration of seasonal overflow is necessary. Regression analysis on seasonal overflows and rice grain yield gave the following results:

$$Y = 5.78 + 0.003\ SF \quad \ldots\ldots\ldots\ldots\ldots \quad (30)$$

$$r^2 = 0.12, \quad n = 6$$

Where

Y = rice grain yield (tons/ha)

SF = seasonal water overflows (mm)

A table of analysis of variance for the above equation is presented (Table 4.10).

Table 4.10: Analysis of variance results of rice grain yield and seasonal water overflows

Source of variation	Degrees of freedom	Sum of Squares	Mean Squares
Accounted for by regression	1	0.046	0.046
Unaccounted for by regression	4	0.329	0.082
Accounted for by mean	5	0.375	

Computed F-value = 0.555

Critical F-value at F(1, 4, 0.10) = 4.54

The computed F-value from the regression equation is less that the critical value. Hence it could be argued that there is no significant linear relationship between rice grain yield and seasonal water overflows in Mwea Irrigation Settlement.

Owing to the small sample size in the previous analyses of the influence of water deficits and surpluses on rice grain yield, it was found necessary to try non-parametric statistics on the data. For this purpose, the Spearman's Rank correlation method was performed but even here there was no significant differences in the results from those presented.

CHAPTER 5: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1. Summary

The objective of this study was to estimate the water requirement of rice and to relate the water requirement to water supply in the paddy fields of Mwea. This was done by the cumulative soil-water balance model. The water management activities were related to rice yields by regression. Specifically, the study attempted:

- (i) estimation of water requirement of rice during the growing season by using the available meteorological data.
- (ii) examination of the seasonal effective rainfall and irrigation efficiency levels.
- (iii) assessment of the significance of water management to rice grain yields in Mwea Irrigation Settlement.

5.1.1. Estimation of rice water requirement

The available meteorological data in the area of study was used to estimate ETrice by Pan Evaporation method. It was found that the rice water requirement for the seven seasons considered varied from 795mm to 619mm with an average of 691mm and standard deviation of 56.5mm. This variability is associated with different atmospheric conditions as they are highly associated with crop water requirement.

5.1.2. Examination of seasonal effective rainfall and irrigation efficiency levels

(a) The analysis of seasonal effective rainfall revealed that effective rainfall, for the seven seasons varied from 44% to 92% of the gross seasonal rainfall. Variations in effective rainfall were found to depend partly on the distribution of rainfall within the season but to a large extent on previous irrigation depths before rainfall. This means that if in the previous ten-day period, irrigation depth was adequate to meet the rice water requirement and flood the paddy fields, then effective rainfall dropped considerably. However, the analysis demonstrated that over a half of the seven seasons had effective rainfall well over 50%.

(b) Seasonal irrigation efficiency levels for six of the seven seasons was above 60% of the total irrigation depths. This is the lower bound of irrigation efficiency for furrow irrigation method according to Sarraf (1971). As noted in this study, to attain high irrigation

(b) (cont'd)

efficiency in Mwea, irrigation should be properly scheduled depending on the previous ten-day period rainfall. The expected rainfall within the present decade and the latter ones should be considered before irrigation is planned.

Neglect of the above factors led to very low irrigation efficiency level in the 1982 season (46%). In this season, there was 70mm of water as overflow. Of the 503mm of irrigated water, only 117mm was required in the paddy fields.

5.1.3. Significance of water management to rice yields in Mwea

Evaluation of the significance of water management to rice grain yields in Mwea was done for six seasons eliminating the 1982 season which recorded the lowest grain yield due to a strike by the tenant farmers. Linear regression and analysis of variance were done on the data and it was found that seasonal water deficits and surpluses are not significantly related to rice grain yield in the area.

Water deficits at heading and grain filling periods of the six seasons was found to explain 47%

of the variability in rice grain yield. This calls for attention of water management experts in the area. Water deficits at these periods should not be allowed to occur.

5.2. Conclusions

The cumulative soil-water balance results of the seven seasons in Mwea paddy fields indicated that over-application of water in Mwea is a common practice. This brought to the surface the fact that irrigation scheduling is not in conformity with the knowledge of the likely amount of rainfall to be received within the specified periods. The other important aspects that should be considered to limit the waste of water are the soil moisture content and the water requirement by the crop.

The water balance calculations presented in Chapter 4 indicate clearly the aspects of water requirement and the water application. These are quite useful in estimating the amount of irrigation water required to avoid waste. It was noted that the 1971 season water application was the most suitable as the soil moisture content in the rootzone (30cm) was always adequate to meet the rice water requirement and there were no overflows.

Investigation of the relationship between rice water requirement and total applied water (rainfall and irrigation) showed that the water requirement by the rice crop for the entire season is linearly related to applied water. The seasonal irrigation efficiency was found to be significantly related to rice water requirement. This leads to the conclusion that irrigation in the area is necessary if rice agriculture is to be practised. This is further supported by the fact that the seasonal rainfall during the rice season is far below the water requirement of the crop.

Previous studies on rice agriculture in Mwea have not elucidated the variability of season rice yields. This study revealed that water management does not account significantly for the variability of the rice yields. As such there should be other aspects than water management which influence the rice yields in Mwea Irrigation Settlement such as those discussed in the next section.

RECOMMENDATIONS

(a) Recommendations to Government Policy makers

The economy of Kenya depends largely on agriculture and as such researches related to agriculture are of prime importance to the Government. The results obtained in this study showed that water management activities in Mwea paddy fields during the rice growing season do not account significantly for rice grain yield variations. This means that there are other factors which may be associated with these yield variations from season to season. Some of the factors could be fertilizer applications, weed control, attack of the field crop by pests or preparations of the fields before rice season.

This study recommends that the National Irrigation Board investigate the existing agronomic practices by the tenant farmers in the area to ensure that there is no neglect by the tenant farmers. During the field research period, the author noticed that irrigation controls in the main and feeder canals were left to be operated by the tenant farmers. This sometimes leads to over-irrigation due to lack of knowledge by the farmers of the field water requirements.

The water-balance model employed in this study is recommended for use in all those areas in the country where rice is grown under submerged conditions.

The simple water-balance models used to estimate effective rainfall and irrigation efficiency are also recommended for adoption by the National Irrigation Board field officers. This reduces the wastage of irrigation water since seasonal effective rainfall could be increased if irrigation scheduling is properly done with the knowledge of the likely amount of rainfall to be expected

The study recommends that irrigation headworks in Mwea Irrigation Settlement should be operated on supply schedules which conform to the field water requirements in order to reduce the wastage of water and the subsequent erosion hazard. This could be possible if a book-keeping method of the cumulative soil-water balance as presented in this study was adopted.

Agroclimatological studies depend, principally, on data from agrometeorological stations and if such studies are to give meaningful and applicable results, observations of the relevant data are a pre-requisite. It was noticed that the agrometeorological station in the study area lacks instruments for observation of data on water use by the crop (lysimeters) radiation, soil moisture content, to mention a few. The Government is advised to install such instruments in the agrometeorological stations of the Republic.

(b) Recommendations for future research

This study has contributed to the understanding of rice-climate relationship mainly in one aspect namely, the rice water requirement and water application during the crop growing season. It is realised that there are many other climatic elements such as temperatures, daylight period and solar radiation that are equally important in rice agriculture. These have not been investigated in Kenya as far as the rice crop is concerned. In most parts of the world where paddy rice is extensively grown, researches on rice crop nitrogen and light intensity responses have been done. In Kenya, these avenues have not been pursued. It would be a useful and worthwhile undertaking to study these aspects of the rice crop especially at present when the Government is looking into the possibilities of introducing upland rice varieties where water will not be as important as in submerged rice.

REFERENCES

Acland, J.D. (1971) East African Crops. Longman.

Agnew, C.T. (1982) Water availability and the development of rainfed agriculture in south west Niger, West Africa. Trans. Inst. Br. Geogr. N.S. 7., 419-457.

Arruda, H.V. and Pinto, H.S. (1980) A simplified Gamma probability model for analysis of the frequency distribution of rainfall in the region of Campinas, SP, Brazil. Agric. Meteorol., 22: 101-108.

Baier, W. (1968) Relationships between soil moisture, actual and potential evapotranspiration. Proceedings of Hydrology Symposium No. 6 Soil moisture, Ottawa, 155-204.

Braun, H.M.H. (1977) The reliability of the rainy seasons in Machakos and Kitui Districts. Miscellaneous Paper M12. Kenya Soil Survey, Nairobi.

Brown, H. and Cocheme, J. (1969) A study of the agro-climatology of the highlands of Eastern Africa. F.A.O., Unesco.

Bulanadi, J. (1968) Irrigation guide for lowland rice in Philippines. Philippines Journal of Plant Industry, 33(1-2): 95-102.

Chang, J. (1968) Climate and agriculture: An ecological survey. Aldine Publishing Company, Chicago.

Chatterjee, S. and Price, B. (1977) Regression analysis by example. John Wiley and Sons, New York.

da Mota, F.S. (1978) A dependable agroclimatological water balance. Agric. Meteorol., 19: 203-213.

Dagg, M. (1965) A rational approach to the selection of crops for areas of marginal rainfall in East Africa. E. Afr. agr. For. J., 30: 296-300.

Denmead, O.T. and Shaw, R.H. (1959) Evapotranspiration in relation to the corn crop. Agron. J., 51: 725-726.

Dastane, N.G. (1974) Effective rainfall in irrigated agriculture. F.A.O. Irrigation and Drainage Paper 25, FAO, United Nations, Rome.

Doorenbos, J. and Kassam, A.H. (1979) Yield response to water. F.A.O. Irrigation and Drainage Paper 33, FAO, United Nations, Rome.

Doorenbos, J. and Pruitt, W. (1975) Crop water requirements. F.A.O. Irrigation and Drainage Paper 24, FAO, United Nations, Rome.

Draper, N.R. and Smith, H. (1981) Applied regression analysis. John Wiley and Sons, New York.

Eagleman, J.R. (1971) An experimentally derived model for actual evapotranspiration. Agric. Meteorol., 8: 383-394.

Enyi, B.A. (1963) The effects of time of irrigation on the growth and yield of transplanted rice. J. Agric. Sc., 61(1): 115-119.

Fenner, M. (1982) Features of the rainfall at Kibwezi, Kenya. E. Afr. agr. For. J., 45: 83-91.

Francis, P. (1975) The effect of climatic factors on the production and quality of rice in Malawi. Proceedings of the E. Africa Cereals Conference, Malawi.

Franquin, P. (1978) The water-balance and the frequency period of vegetation. Proceedings of the Agroclimatological Needs of the Semi-Arid Tropics, ICRISAT, India, 100-105.

Garnier, B.J. (1972) A viewpoint on the evaluation of potential evapotranspiration. Publ. Climatol., 25: 13-24.

Ghildyal, B.P. and Jana, R.K. (1967) Agrometeorological environment affecting rice yield. Agron. J., 59: 286-287.

Giglioli, E.G. (1964) Mechanical cultivation of rice in the Mwea Irrigation Scheme. E. Afr. agr. For. J., 30: 177-179.

Glover, J., Robinson, P. and Henderson, J.P. (1954) Provisional maps of the reliability of annual rainfall in East Africa. Quart. J. Roy. Met. Soc., 80: 602-609.

Gomez, K.A. (1977) On-farm assessment of yield constraints: Methodological problems. International Rice Research Institute, Los Banos, Philippines, IRRI, 1-16.

Gomez, K.A. and Gomez, A.A. (1976) Statistical procedures for agricultural research with emphasis on rice. International Rice Research Institute, Los Banos, Philippines, IRRI.

Griffiths, J.F. (1958) Climatic zones of East Africa. E. Afr. agr. For. J., 23: 179-185.

Grist, D.H. (1959) Rice. Longman, London.

Grove, A.T. (1978) Africa. Oxford University Press.

Haggan, R., Rijov, S. and Bravel, C. (1967) Water, plant growth and crop irrigation requirements. International sourcebook on Irrigation and Drainage of Arid lands in relation to Salinity and Alkalinity. FAO, Unesco, Rome, 282-342.

Halm, A.T. (1967) Effects of water regime on the growth and composition of two rice varieties. Tropical Agriculture, 44: 33-37.

Hargreaves, G.H. (1975) Water requirements manual for irrigated and rainfed agriculture. EMPRAPA and Utah State University Publication, 75-D 158.

Hecklau, H. (1974) Irrigation farming in Kenya. Appl. Sci. and Dev., 4: 75-88.

Hills, R.C. (1974) The presentation of central tendencies in rainfall statistics. E. Afr. agr. For. J., 39: 424-432.

Houston, C.E. (1973) Comparison between pan and lake evaporation. WMO Technical Note 126: 2-4.

Inoue, E., Mihara, Y. and Tsuboi, Y. (1965) Agrometeorological studies on rice growth in Japan. Agric. Meteorol., 2: 85-107.

Jackson, I.J. (1977) Climate, water and agriculture in the tropics. Longman, London.

Kaila, A.H. (1983) A Study of evaporation pan factoring at Katumani in Kenya. M.Sc. thesis, University of Nairobi, Unpublished.

Kashasha, D.A.R. (1982) A study of effective rainfall for crop production. *M.Sc. thesis, University of Nairobi*, Unpublished.

Kharchenko, S.I. and Katz, D.M. (1972) Methods for the study of water-balance of irrigated lands and irrigation systems. *Symposium on World water balance, Vol. II*. Publ. No. 93: 452-457.

Kotter, E. (1968) Determination of water requirement of rice in Laos. *Int. Rice Comm. Newsletter*, *17(4)*: 13-20.

Kung, P. (1965) Determining water requirement of rice by field measurement in Thailand. *Int. Rice Comm. Newsletter, 14(4)*, 5-18.

Kung, P. (1966) Desirable techniques and procedures on water management of rice culture: in *Mechanization and the World's Rice Conference*... Oxford, Blackwell.

Lenga, F.K. and Stewart, I.J. (1982) Water-yield response of maize and bean intercrop. *E. Afr. agr. For. J., 5*: 103-116.

Leonard, W.H. (1948) Rice as a crop in Japan. *J. Amer. Soc. Agron., 40:* 579-602.

Lomas, J. and Lewin, J. (1974) Effects of environmenta and crop factors on the evapotranspiration rate and water use efficiency of maize. *Agric. Meteorol., 13*: 239-251.

Lourence, F.J. and Pruitt, W. (1971) Energy balance and water use of rice grown in Central Valley of California. *Agron. J., 63*: 827-732.

Manning, H.L. (1956) The statistical assessment of rainfall probability and its application in Uganda agriculture. *Proc. Roy. Soc., B144*: 460-480.

Matsushima, S. (1966) Some experiments and investigation on rice plants in relation to water in Malaysia. *Symposium Service Centre for S. East Asian studies, Kyoto University, 3:* 115-123.

McCulloch, J.S.G. and Dagg, M. (1965) Hydrological aspects of protection forestry in East Africa. *E. Afr. agric. For. J., 30*: 390-394.

Moorman, F.R. and Breemen, N. (1978) Rice, soil, water, land. Rice Res. Inst. Los Banos.

Mugah, J.O. and Stewart, I.J. (1982) Water use of Katumani composite B. maize as determined from climatic data. E. Afr. agric. For. J., 5: 92-102.

Munakata, K. (1966) Effects of temperature and light on the growth and ripening of rice. Proceeds of the Symposium on Climate and Rice, Los Banos, Philippines.

Mungai, D.N. (1985) Analysis of some seasonal rainfall characteristics in the Lake Victoria Region of Kenya. M.A. Thesis, University of Nairobi, Unpublished.

Oelke, K. and Mueller, K.E. (1969) Influences of water management and fertility on rice growth. Agron. J., 61: 51-58.

Oldeman, J.R. and Frere, M. (1982) The study of the Humid Tropics of South-East Asia. WMO Technical Note No. 179.

Oldeman, J.R. and Suardi, D. (1978) Climatic determinants in relation to cropping pattern. Symposium on crop systems and Development for the Asian Rice Farmer. I.R.R.I., Philippines.

Penman, H.L. (1948) Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. A, (London) 194: 120-145.

Penman, H.L. (1962) Weather and crops. Quart. J. Roy. Met. Soc. 88: 209-219.

Penman, H.L. (1963) Vegetation and hydrology. Technical communication No. 53. Commonwealth Agricultural Bureaux.

Pereira, H.C. and Dagg, M. (1964) Assessment of the main components of the hydrological cycle. E. Afr. agric. For. J., 27: 8-15.

Porter, P.W. (1981) Problems of agrometeorological modelling in Kenya. Interciencia Vol. 6, No. 4: 226-233.

Prescott, J.A. (1958) Climatic indices in relation to the water balance in climatology and microclimatology. Proceedings of the Canberra Symposium, UNESCO, Canberra.

Pruitt, W.O. (1960) Correlation of climatological data with water requirements of crops. Annual Report, Dept. of Irrigation, University of California, Davies: 1-99.

Rawtz, E. (1973) Gravity irrigation in Arid zone Irrigation. Ed. Yaron, B. and Vaardia, Y., 323-337.

Rijks, D. (1975) Measurements of evapotranspiration. Unpublished.

Rijtema, P.E. (1968) Derived meteorological data: Transpiration. Proceedings of the Reading Symposium. UNESCO.

Robertson, G.W. (1975) Rice and weather. WMO Technical Note, 144.

Roy, R.N. and Seetharaman, S. (1977) Rice. Fertilizer Association of India, New Delhi.

Russell, E.W. (1960) The agricultural uses of meteorological data. Proc. of the Symposium jointly sponsored by WMO and Munitalp Foundation. Ed. Bargman, D.J., 390-401.

Salter, P.J. and Goode, J.E. (1967) Crop responses to water at different stages of growth. Commonwealth Agricultural Bureaux, England.

Sarker, R.P. and Biswas, B.C. (1978) Agricultural meteorology in India: A status report. Proc. Int. Workshop on the Agroclimatological Research Needs of the Semi-Arid Tropics 1978. ICRISAT, Hydrabad, India.

Sarraf, S. (1971) Crop water requirements. F.A.O. Irrigation and Drainage Paper 13. FAO, United Nations, Rome. 31-41.

Schleusener, P.E. (1961) Pasture irrigation requirements calculated from climatological data. Transactions of the ASAE 4(1): 6-7.

Schmueli, E. (1971) The efficient use of water and agricultural research. Hecklauth B'Israel, 12(3): 54-65.

Slatyer, R.O. (1968) The use of soil water balance relationships in agroclimatology. UNESCO Arid Zone Research, 16: 15-26.

Stein, C. and Schulze, C. (1978) Landuse and development potential in arid regions of Kenya. *Appl. Sci. Dev., 12*: 47-62.

Stewart, I.J. (1972) Prediction of water production functions and associated irrigation programs to minimize crop yield and profit losses due to limited water. *Ph.D. dissertation, University of California*, Davis.

Stewart, I.J. and Hagan, R.M. (1969) Prediction effects of crop water deficits. *J. Irr. Drainage Div. ASCE Proc. Pap. 6443, 95*: 91-104.

Stewart, I.J. and Hash, C.T. (1979) Impact of weather analysis on agricultural production and planning decisions for semi-arid areas of Kenya. *J. Appl. Meteorol., 21*: 477-494.

Stewart, I.J. and Wang'ati, F.J. (1978) Research on crop water use and drought response in East Africa. *Proc. Int. Workshop on the Agroclimatological Research Needs of the Semi-Arid Tropics,'1978*. ICRISAT, Hyderabad, India.

Tanaka, A. and Parao, F.T. (1964) *Growth habits of the rice plant in the tropics and its effects on Nitrogen response*. IRRI, Los Banos, Philippines.

Thornthwaite, C.W. (1948) An approach toward a rational classification of climate. *Geog. Rev., 38*: 55-94.

Thornthwaite, C.W. and Mather, J.R. (1957) Instruction tables for computing evapotranspiration and the water balance. *Dextel Institute of Technology, Lab. of Climatology, 10:* 185-311.

Tomar, V.S. and O'Toole, J.C. (1980) Water use in lowland rice cultivation in Asia: A review of evapotranspiration. *Agricultural Water management, 3.* Elsevier Sc. Publ. Co., Amsterdam, 83-106.

van der Wal, O.A. (1981) Mwea water use study: Agronomic aspects, Ministry of Agriculture, Kenya. *I.D.R.P. Report No. 28*.

van Gessel, J.M. (1982) Mwea water use study: Management part, Ministry of Agriculture, Kenya. *I.D.R.P. Report No. 27.*

Veen, J.J. (1973) Mwea, an irrigated rice settlement. Welforum Verlag, Munchen, 121-124.

Wang'ati, F.J. (1972) Lysimeter study of water use of maize and beans in East Africa. E. Afr. agric. For. J., 37: 141-156.

Williams, C.M. and Joseph, K.T. (1970) Climate, soil and crop production in the humid tropics. Oxford University Press, Kualar Lumpur.

Woodhead, T. (1968) Studies of potential evaporation in Kenya. Water Department, Ministry of Natural Resources, Nairobi.

Woodhead, T. (1970) Confidence limits for seasonal rainfall in Kenya agriculture. Exp. Agric., 6: 81-86.

Woodhead, T. (1982) Variability of seasonal and annual rainfall in East Africa. E. Afr. agric. For. J., 5: 150-156.

APPENDIX 1A

Seasonal meteorological data for Mwea during the rice growing season in ten-day periods (7 seaso

Season: 1970

Decade	Mean Temperature (°C)	Mean Relative Humidity (%)	Rainfall (mm)	Mean Sunshine (hrs/day)	Mean Windspeed (Km/hr)	Mean Epan (mm/day)
1	21	56	0	6	84	5.6
2	21	61	13	2	82	4.2
3	20	53	1	2	74	3.5
4	22	49	1	6	100	6.2
5	21	38	0	6	88	6.0
6	23	70	1	6	115	6.4
7	24	87	14	8	122	8.3
8	24	83	1	6	110	7.2
9	24	89	20	8	109	7.9
10	22	69	78	5	87	4.5
11	22	70	28	8	85	5.2
12	22	80	1	11	85	6.6

Appendix 1A (cont'd)

Season: 1971

Decade	Mean Temperature (°C)	Mean Relative Humidity (%)	Rainfall (mm)	Mean Sunshine (hrs/day)	Mean Windspeed (Km/hr)	Mean Epan (mm/day)
1	21	50	1	6	160	6.1
2	23	53	0	8	192	7.3
3	23	54	0	8	158	7.4
4	23	48	1	7	208	7.8
5	23	45	1	8	174	8.1
6	23	40	29	8	172	7.6
7	24	70	0	9	152	8.4
8	22	73	9	8	158	6.5
9	20	65	71	6	153	4.9
10	21	48	0	10	188	7.4
11	22	68	29	7	151	6.3
12	21	70	23	7	145	5.9

Appendix 1A (cont'd)

Season 1972

Decade	Mean Temperature (°C)	Mean Relative Humidity (%)	Rainfall (mm)	Mean Sunshine (hrs/day)	Mean Windspeed (Km/hr)	Mean Epan (mm/day)
1	23	48	8	8	152	7.3
2	23	50	12	5	177	6.2
3	24	53	13	8	190	8.8
4	24	40	6	7	190	7.5
5	24	60	36	7	125	6.4
6	23	85	158	6	125	5.7
7	23	80	92	8	105	5.5
8	22	65	50	7	112	4.9
9	22	54	24	8	104	5.3
10	22	50	20	8	93	4.6
11	22	52	17	8	118	5.3
12	21	60	0	8	110	5.6

Appendix 1A (cont'd)

Season 1973

Decade	Mean Temperature (°C)	Mean Relative Humidity (%)	Rainfall (mm)	Mean Sunshine (hrs/day)	Mean Windspeed (Km/hr)	Mean Epan (mm/day)
1	24	58	0	4	200	6.5
2	22	71	4	4	185	6.5
3	23	56	27	8	170	7.7
4	24	58	0	7	144	6.2
5	24	45	56	9	161	7.9
6	23	73	10	6	185	6.7
7	24	65	54	9	160	7.4
8	23	50	144	6	122	6.0
9	22	70	4	7	117	5.8
10	22	58	30	8	127	5.5
11	21	67	9	9	126	5.5
12	20	54	0	10	117	6.1

Appendix 1A (cont'd)

Season 1974

Decade	Mean Temperature (°C)	Mean Relative Humidity (%)	Rainfall (mm)	Mean Sunshine (hrs/day)	Mean Windspeed (Km/hr)	Mean Epan (mm/day)
1	22	43	9	5	105	4.8
2	21	55	3	4	152	5.3
3	22	73	0	5	82	4.5
4	23	58	0	8	123	7.1
5	24	68	1	9	144	7.8
6	23	53	14	7	130	5.8
7	22	63	82	5	138	4.5
8	22	68	54	6	96	4.5
9	21	60	13	9	118	5.5
10	21	53	2	9	126	5.8
11	22	64	20	9	127	6.1
12	21	58	0	9	158	6.4

Appendix 1A (cont'd)

Season 1981

Decade	Mean Temperature (°C)	Mean Relative Humidity (%)	Rainfall (mm)	Mean Sunshine (hrs/day)	Mean Windspeed (Km/hr)	Mean Epan (mm/day)
1	21	51	2	3	126	5.6
2	22	54	0	4	162	6.4
3	23	41	0	7	140	6.9
4	23	48	17	6	170	7.5
5	23	40	2	5	180	5.8
6	23	68	28	9	141	8.2
7	22	79	0	5	152	8.0
8	22	79	117	8	107	5.4
9	23	56	14	9	96	6.5
10	22	86	40	8	152	4.5
11	22	88	39	5	77	4.6
12	22	80	25	7	148	5.0

Appendix 1A (cont'd)

Season 1982

Decade	Mean Temperature (°C)	Mean Relative Humidity (%)	Rainfall (mm)	Mean Sunshine (hrs/day)	Mean Windspeed (Km/hr)	Mean Epan (mm/day)
1	21	51	0	4	126	4.4
2	22	53	1	5	162	4.9
3	23	40	0	7	142	6.5
4	23	50	1	5	171	6.7
5	23	42	30	9	182	6.3
6	23	67	136	5	144	8.5
7	22	78	168	8	182	4.5
8	22	80	47	9	150	5.4
9	23	55	19	8	101	5.4
10	22	84	39	5	90	4.1
11	22	90	27	7	75	3.2
12	22	82	24	6	140	5.6

APPENDIX IB: Seasonal Rainfall data for Mwea Irrigation Settlement during the rice growing season for twenty years in 10-day periods

Sorted by Onset Date:	Cumulative								Rainfall				
Station No: 9037112	Elev. 1280m								Rainfall (mm)				
Gross rainfall for short rains season	Crop: Rice			Days: 120			No. Periods: 12			Period Days: 10			
Transplanting Date	Rainfall Amounts												Total
	1	2	3	4	5	6	7	8	9	10	11	12	
04/08/70	0.0	12.9	14.2	15.5	15.5	16.3	30.1	30.9	50.4	128.6	156.5	157.3	157.3
04/08/76	1.2	1.2	12.8	13.8	19.4	63.3	110.4	133.3	133.0	180.3	201.5	268.3	269.3
04/08/68	4.9	9.0	9.0	9.0	9.3	12.6	13.9	86.3	205.7	245.2	432.5	585.3	585.3
05/08/66	0.0	0.0	9.0	8.0	13.1	16.5	24.9	40.3	187.5	285.8	285.2	289.9	289.9
08/08/80	22.1	23.7	23.7	23.7	23.7	23.7	24.2	27.1	164.7	297.7	363.7	363.7	363.7
10/08/81	1.8	2.1	2.1	18.8	20.3	48.7	48.7	165.8	178.7	219.5	258.9	283.5	283.5
10/08/65	9.4	9.4	9.9	10.7	18.8	25.4	45.2	62.4	222.4	345.8	388.6	388.7	399.7
10/08/67	9.0	12.5	28.8	28.8	28.8	48.1	100.1	233.7	288.7	328.8	384.4	394.7	394.7
10/08/77	6.0	6.0	6.0	24.6	24.7	24.7	28.1	52.7	173.8	249.6	412.3	417.1	417.1
10/08/63	2.3	6.4	6.4	6.4	21.2	43.6	62.5	97.4	114.3	237.1	293.7	345.6	345.6
11/08/82	0.0	1.0	1.0	2.3	32.3	168.7	336.6	383.1	401.8	440.8	468.3	492.1	492.1
12/08/79	2.0	3.0	7.3	7.3	7.3	14.7	19.7	48.3	240.3	268.1	269.1	273.6	273.6
13/08/64	39.9	39.9	50.1	60.5	60.5	78.3	216.1	243.6	248.8	264.8	355.3	356.0	356.0
14/08/69	0.3	2.1	2.1	2.1	2.6	12.8	20.4	23.7	55.2	170.6	132.9	215.7	215.7
21/08/78	0.0	20.8	20.8	48.5	48.6	126.7	312.8	342.3	375.2	409.5	427.2	464.6	464.6
22/08/75	0.0	2.9	6.0	51.9	55.3	78.8	164.1	164.1	212.3	221.6	239.5	239.9	239.9
28/08/73	0.0	3.6	30.6	30.6	86.5	96.5	150.8	295.2	299.0	329.3	338.2	338.3	338.3
31/08/72	7.8	19.9	33.3	39.0	74.8	233.1	325.0	374.8	398.7	418.8	435.3	435.6	435.6
31/08/74	8.7	11.2	11.6	11.6	12.2	26.4	107.9	162.3	175.7	177.9	197.7	197.7	197.7
01/09/71	0.8	0.8	1.2	2.1	3.0	32.2	32.2	41.6	112.4	112.4	140.9	164.2	164.2

APPENDIX 1B (continued)

Sorted by onset data Non-cumulative Rainfall. Dates and totals saved in file
Station. No. 9037112 Elev. 1280m Rainfall (mm)

Gross rainfall for short rains season Crop: Rice Days: 120 No. periods: 12 Period days: 10

Transplanting Date	Rainfall Amounts 1	2	3	4	5	6	7	8	9	10	11	12	Total
04/08/70	0.0	12.9	1.3	1.3	0.0	0.8	13.8	0.8	19.5	78.9	27.9	0.8	157.3
04/08/76	1.2	0.0	11.6	1.0	5.6	43.9	47.1	21.9	0.7	47.3	21.2	67.8	269.3
04/08/68	4.9	4.1	0.0	0.0	0.3	3.3	1.3	72.4	119.4	38.5	187.3	152.8	585.3
05/08/66	0.0	0.0	9.0	0.0	3.1	4.4	8.4	15.4	147.2	98.3	0.0	4.1	289.9
08/08/80	22.1	1.6	0.0	0.0	0.0	0.0	0.5	2.9	137.6	133.0	66.0	0.0	363.7
10/08/81	1.8	0.3	0.0	16.7	1.5	28.4	0.0	117.1	13.9	39.8	39.4	24.6	283.5
10/08/65	9.4	0.0	0.5	0.8	8.1	6.6	19.8	17.2	160.0	123.4	42.8	1.1	389.7
10/08/67	9.0	3.5	16.3	0.0	0.0	19.3	52.0	133.6	55.0	40.1	65.6	0.3	394.7
10/08/77	6.0	0.0	0.0	18.6	0.1	0.0	3.4	24.6	121.1	75.8	162.7	4.8	417.1
10/08/63	2.3	4.1	0.0	0.0	14.8	22.4	18.9	34.9	16.9	122.8	31.6	76.9	345.6
11/08/82	0.0	1.0	0.0	1.3	30.0	136.4	167.9	46.5	18.5	39.3	27.4	23.8	492.1
12/08/79	2.0	1.0	4.3	0.0	0.0	7.4	5.0	28.6	192.6	28.2	0.0	4.5	273.6
13/08/64	39.9	0.0	10.2	10.4	0.0	17.8	137.8	26.5	6.2	16.0	60.5	30.7	356.0
14/08/69	0.3	1.8	0.0	0.0	0.5	10.2	7.6	3.3	31.5	115.4	22.3	22.8	215.7
21/08/78	0.0	20.8	0.0	27.7	0.0	78.1	186.1	29.5	32.9	34.3	17.7	37.4	464.6
22/08/75	0.0	2.9	3.1	45.9	3.4	23.5	85.3	0.0	48.2	9.3	17.9	0.4	239.9
28/08/73	0.0	3.6	27.0	0.0	55.9	10.0	54.4	144.3	3.8	30.3	8.9	0.1	338.3
31/08/72	7.8	12.1	13.4	5.7	35.8	158.3	91.9	49.8	23.9	20.1	16.5	0.3	435.6
31/08/74	8.7	2.5	0.4	0.0	0.6	14.2	81.5	54.4	13.4	2.2	19.8	0.0	197.7
01/09/71	0.8	0.0	0.4	0.9	0.9	29.2	0.0	9.4	70.8	0.0	23.5	23.3	164.2

APPENDIX 1B (continued)

Unsorted File	Non-cumulative	Rainfall	Dates and totals saved in file
Station No., 9037112	Elev: 1280m		Rainfall (mm)

Gross rainfall for short rains season Crop: Rice Days 120 No. periods: 12 Period days: 10

Transplanting Date	Rainfall Amounts 1	2	3	4	5	6	7	8	9	10	11	12	Total
10/08/63	2.3	4.1	0.0	0.0	14.8	22.4	18.9	34.3	16.9	122.8	31.6	76.9	345.6
13/08/64	39.9	0.0	10.2	10.4	0.0	17.8	137.8	26.5	6.2	16.0	60.5	30.7	356.0
10/08/65	9.4	0.0	0.5	0.8	8.1	6.6	19.8	17.2	160.0	123.4	42.2	1.1	389.7
05/08/66	0.0	0.0	9.0	0.0	3.1	4.4	8.4	15.4	147.2	98.3	0.0	4.1	289.9
10/08/67	9.0	3.5	16.3	0.0	0.0	19.3	52.0	133.6	55.0	40.1	65.6	0.3	389.7
04/08/68	4.9	4.1	0.0	0.0	0.3	3.3	1.3	72.4	119.4	39.5	187.3	152.8	585.3
13/08/69	0.3	1.8	0.0	0.0	0.5	10.2	7.6	3.3	31.5	115.4	22.3	22.8	215.7
04/08/70	0.0	12.9	1.3	1.3	0.0	0.8	13.8	0.8	19.5	78.2	27.9	0.8	157.3
01/09/71	0.8	0.0	0.4	0.9	0.9	29.2	0.0	9.4	70.8	0.0	28.5	23.3	164.2
31/08/72	7.8	12.1	13.4	5.7	35.8	158.3	91.9	49.8	23.9	20.1	16.5	0.3	435.6
28/08/73	0.0	3.6	27.0	0.0	55.9	10.0	54.4	144.3	3.8	30.3	3.9	0.1	338.3
31/08/74	8.7	2.5	0.4	0.0	0.6	14.2	81.5	54.4	13.4	2.2	19.8	0.0	197.7
22/08/75	0.0	2.9	3.1	45.9	3.4	23.5	85.3	0.0	48.2	9.3	17.9	0.4	239.9
04/08/76	1.2	0.0	11.6	1.0	5.6	43.9	47.1	21.9	0.7	47.3	21.2	67.8	269.3
10/08/77	6.0	0.0	0.0	18.6	0.1	0.0	3.4	24.6	121.1	75.8	162.7	4.8	417.1
21/08/78	0.0	20.8	0.0	27.7	0.1	78.1	186.1	29.5	32.9	34.3	17.7	37.4	464.6
12/08/79	2.0	1.0	4.3	0.0	0.0	7.4	5.0	28.6	192.6	28.2	0.0	4.5	273.6
08/08/80	22.1	1.6	0.0	0.0	0.0	0.0	0.5	2.9	137.6	133.0	66.0	0.0	363.7
10/08/82	1.8	0.3	0.0	16.7	1.5	28.4	0.0	117.1	13.9	39.8	39.4	24.6	283.5
11/06/82	0.0	1.0	0.0	1.3	30.0	136.4	167.9	45.5	18.5	39.5	27.4	23.8	492.1

APPENDIX 1B (continued)

Unsorted File Cumulative Rainfall Dates and Totals saved in file

Station No. 9037112 Elev. 1280m Rainfall (mm)

Gross rainfall for short rains season Crop: Rice Days:120 No. periods: 12 Period days: 10

Transplanting Date	Rainfall Amounts 1	2	3	4	5	6	7	8	9	10	11	12	Total
10/08/63	2.3	6.4	6.4	6.4	21.2	43.6	62.5	97.4	114.3	237.1	298.7	345.6	345.6
13/08/64	39.9	39.9	50.1	60.5	60.5	78.3	216.1	243.6	248.8	264.8	325.3	356.0	356.0
10/08/65	9.4	9.4	9.9	10.7	18.8	25.4	45.2	62.4	222.4	345.8	382.6	389.7	389.7
05/08/66	0.0	0.0	9.0	9.0	12.1	16.5	24.9	40.3	187.5	285.8	285.2	289.9	289.9
10/08/67	9.0	12.5	28.8	28.8	28.8	48.1	100.1	233.7	288.7	328.8	394.4	394.7	394.7
04/08/68	4.9	9.0	9.0	9.0	9.3	12.6	13.9	86.3	205.7	245.2	432.5	585.3	585.3
14/08/69	0.3	2.1	2.1	2.1	2.6	12.8	20.4	23.7	55.2	170.6	192.9	215.7	215.7
04/08/70	0.0	12.9	14.2	15.5	15.5	16.3	30.1	30.9	50.4	128.6	156.5	157.3	157.3
01/09/71	0.8	0.8	1.2	2.1	3.0	32.2	32.2	41.6	112.4	112.4	140.9	164.2	164.2
31/08/72	7.8	19.9	33.3	39.0	74.8	233.1	325.0	374.8	398.7	418.8	435.3	435.6	435.6
28/08/73	0.0	3.6	30.6	30.6	86.5	96.5	150.9	295.2	299.0	329.3	358.2	338.3	338.3
31/08/74	8.7	11.2	11.6	11.6	12.2	26.4	107.9	162.3	175.7	177.9	197.7	197.7	197.7
22/08/75	0.0	2.9	6.0	51.9	55.3	78.8	164.1	164.1	212.3	221.6	239.5	239.9	239.9
04/08/76	1.2	1.2	12.8	13.8	19.4	63.3	110.4	132.3	132.0	180.3	201.5	269.3	269.3
10/08/77	6.0	6.0	6.0	24.6	24.7	24.7	28.1	52.7	173.8	249.6	412.3	417.1	417.1
21/08/78	0.0	20.8	20.8	48.5	48.6	126.7	312.8	342.3	375.2	409.5	497.2	464.6	464.6
12/08/79	2.0	3.0	7.3	7.3	7.3	14.7	19.7	48.3	240.9	269.1	269.1	273.6	273.6
08/08/80	22.1	23.7	23.7	23.7	23.7	23.7	24.2	27.1	164.7	297.7	363.7	363.7	363.7
10/08/81	1.8	2.1	2.1	18.8	20.3	48.7	48.7	165.8	179.7	219.5	258.9	283.5	283.5
11/08/82	0.0	1.0	1.0	2.3	32.3	168.7	336.6	383.1	401.6	440.9	468.3	492.1	492.1

APPENDIX 2A

Available seasonal irrigation data in ten-day periods from Mwea Irrigation Settlement - Values in millimetres

Decade	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
1	78	80	65	83	70	85	80	75	80	86	60	82	65
2	50	50	45	40	48	40	85	80	70	68	72	72	80
3	52	60	54	80	90	54	65	70	100	100	80	64	60
4	140	150	70	100	100	60	70	108	80	70	95	101	110
5	70	50	80	40	80	65	80	60	50	65	90	67	50
6	63	51	0	60	69	50	105	75	20	58	80	81	0
7	70	60	30	80	45	45	60	68	0	60	100	60	0
8	84	58	45	30	30	79	75	0	40	95	120	88	40
9	41	40	60	80	45	84	63	0	25	30	0	50	48
10	20	30	30	30	20	20	30	40	15	20	0	10	50
11	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	668	639	479	623	597	582	713	576	480	652	697	675	503

APPENDIX 2B

Rice grain yields (tons/ha) in Mwea for 20 season (1963-1982)

Season	Grain Yield
1963	6.0
1964	5.5
1965	5.5
1966	5.4
1967	4.8
1968	5.0
1969	4.7
1970	5.7
1971	5.5
1972	5.8
1973	6.3
1974	6.0
1975	5.5
1976	4.3
1977	7.0
1978	5.8
1979	5.0
1980	5.5
1981	3.8
1982	5.3