EVALUATING THE TECHNICAL PERFORMANCE OF KIBIRIGWI SPRINKLER IRRIGATION SYSTEM

BY

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of

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1990

Declaration

I declare that this is my original work and has not been submitted for a degree in any other university.

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Signature

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

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Signature

ABSTRACT

This study was to evaluate the technical performance of Kibirigwi sprinkler irrigation system in the Upper Tana Basin, Kenya. Development of irrigation in this area is constrained by water availability and not land availability. The available water resources therefore need to be utilized as efficiently as possible. In this study, some shortcomings in, crop water management practices in the scheme, System maintenance resulting mainly to pressures and water losses in the system and low sprinkler performance efficiencies.

On average, the christiansen uniformity coefficient was 77 percent, sprinkler application efficiency was 70 percent, distribution uniformity was 64 percent, potential application efficiency of the low quarter was 65 percent and the application efficiency of the low quarter was 56 percent. The pressures and discharge imbalances in the system were caused by multiple leakages in the distribution network, mainly at the control valves, pipe junctions, hydrants and connections of the portable irrigation equipments at the farms. Irrigation water was insufficiently filtered and the remaining sediments had caused sprinkler nozzle diameters to wear by an average of 9.1 percent.

An alternative irrigation schedule responsive to the prevailing weather conditions and the type of crop growing in the season was proposed. This was to replace the existing schedule of an application duration of 10 hours and an irrigation interval of 7 days for all the crops. If farmers would follow the developed irrigation schedule in this study and in addition have pipe leaks in the distribution network, at the gate valves and at pipe connections at the farms repaired, the irrigation efficiency of the scheme would greatly improve.

Though the scheme experiences water shortages during some periods in the year, the shortages cannot be attributed to inadequate river discharge during these periods. River flow analysis showed that the water flowing past the water abstraction point was much higher than the required scheme irrigation discharge throughout the year.

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LIST OF ABBREVIATIONS

CU	Christiansen Uniformity Coefficient
DU	Distribution uniformity
AELQ	Application efficiency of the low quarter
PELQ	Potential efficiency of the low quarter
m	Meter
cm	centimeter
mm	millimeter
ha	hectare
s	second
l/s	litres per second
mm/h	millimeters per hour
mm/day	millimeters per day
r	rainfall
E_0	potential evaporation
ETcrop	crop evapotranspiration
Ep	evaporation from class A pan
pvc	polyvinylchloride
GI	galvanised Iron
R.G.S.	river gauging station
K.I.S.	Kibirigwi Irrigation Scheme
KIFCO	Kibirigwi Irrigation Farmers Cooperative Society
WMO	World Meteorological Organisation
MAFF	Ministry of Agriculture, Fisheries and Food
HMSO	Her Majesty's Stationery Office
MOWD	Ministry of Water Development

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ETcrop	crop evapotranspiration
Ep	evaporation from class A pan
pvc	polyvinylchloride
GI	galvanised Iron
R.G.S.	river gauging station
K.I.S.	Kibirigwi Irrigation Scheme
KIFCO	Kibirigwi Irrigation Farmers Cooperative Society
WMO	World Meteorological Organisation
MAFF	Ministry of Agriculture, Fisheries and Food
HMSO	Her Majesty's Stationery Office
MOWD	Ministry of Water Development

1 INTRODUCTION

1.1 General Background

Kenya's population is estimated to rise to 37 million by the year 2008 according to sessional paper no. 1 of 1986 (GOK,1986). To feed this population, horizontal and vertical expansion of agricultural production will be required. Irrigation will therefore gain prominence in Kenya's agricultural efforts to boost crop production both in the marginal and high potential areas if it is to contribute significantly to increases in irrigated area and in production per hectare.

The current irrigated area in Kenya is 36,660 hectares while the total irrigable area is 539,500 hectares (KARI, 1987). This indicates quite a high irrigation potential remains unexploited.

Since 1977, small-scale irrigation development, which is being emphasized by the government in the medium and low potential areas of Kenya, has been slow but steady; with preference being given to rehabilitation of already existing projects (GOK,1986). Small-scale irrigation now accounts for 16 percent of the irrigated area in the country (KARI,1987). The main crops grown are; maize, rice and horticulture.

1.2 Justification of the study

Kibirigwi Irrigation Scheme is a pilot scheme and careful monitoring has to be done to see if its example can be followed and multiplied. A number of studies have been carried out over the years, often stressing on the economic, financial and management aspects of the scheme (Arao and Hourtman,1980;

Alphen, 1980; Leeuw, 1982; Njihia,1982; Ekirapa,1984; Mwanjila,1984; Makanga,1986; Mugwanja and Mwangi,1987).

Makanga (1986) revealed that the scheme was experiencing water shortages in the dry months of the year. This shortage was unexpected because the design was made to cater for crop water requirements in the dry season, particularly the period from December to March.

The following three factors can contribute to water shortages in the irrigation schem.

i) **River flow adequacy**

The river flow rates in the dry periods of the year might be less than the design flow rate at the intake weir. Excessive abstraction of water upstream of the intake could reduce the water levels in the river during the dry season possibly to the extent of affecting the water abstraction for the scheme.

ii) **Under-estimation of Scheme irrigation discharge**

Water requirements for the scheme could have been under-estimated in the design due to the cropping pattern and evapotranspiration values used and recommended for the scheme.

iii) **Water Conveyance Losses**

Discharge and head losses in the distribution network if occuring would reduce the performance of the sprinklers by lowering their operating pressures, discharge and precipitation rates as required by the manufacturers and in the design. The magnitude of the losses had not been established at the time of this study.

1.3 Objectives and Scope of study

1.3.1 Objectives

This study had the following objectives:

i) To determine if the irrigation water supply to the scheme is adequate for the currently grown crops around the year;

ii) To determine if the irrigation distribution and application system is performing as designed;

iii) To determine if there were losses in irrigation water through run-off in the fields during irrigation.

iii) To recommend strategies to improve the technical performance of the sprinkler irrigation system.

1.3.2 Scope of study

The method of study covered the following aspects:

i) Analyse sprinkler performance from collected data on precipitation, discharge, operating pressures, and nozzle diameters at sufficient representative irrigation plots in the scheme.

ii) Perform infiltration tests in the scheme area and check whether sprinkler precipitation rates were causing run-off during irrigation.

iii) Obtain, the cropping pattern as recommended by the scheme management for the farmers and climatological data recorded in the irrigation scheme in order to evaluate the monthly crop water requirements for the scheme.

iv) Determine the soil moisture characteristics in the scheme to use in determining a suitable irrigation interval.

1.4 **Research study area**

The study area was Kibirigwi irrigation Scheme. The scheme is located in the Upper Tana Basin. The Irrigation Scheme is in Kirinyaga District along the Sagana-Nyeri road about 100 Km from Nairobi (fig.1).

According to Ilaco (1971) a total area of nearly 271,000 hectares is suitable for irrigation in Upper Tana Basin making it the largest single basin with the biggest potential for irrigation development in Kenya. Eighty two percent of the soils in this Basin are Nitosols and the rest are vertisols according to FAO/UNESCO classification. Nitosols have high infiltration rates and are therefore more suitable for sprinkler irrigation than for surface irrigation. With this realization, the Tana and Athi Rivers Development Authority (TARDA) in 1975 initiated the Kibirigwi Irrigation Scheme as a pilot Scheme towards the irrigation development within the Upper Tana Basin which is constrained by water availability and not land (World Bank and Netherlands Government, 1987).

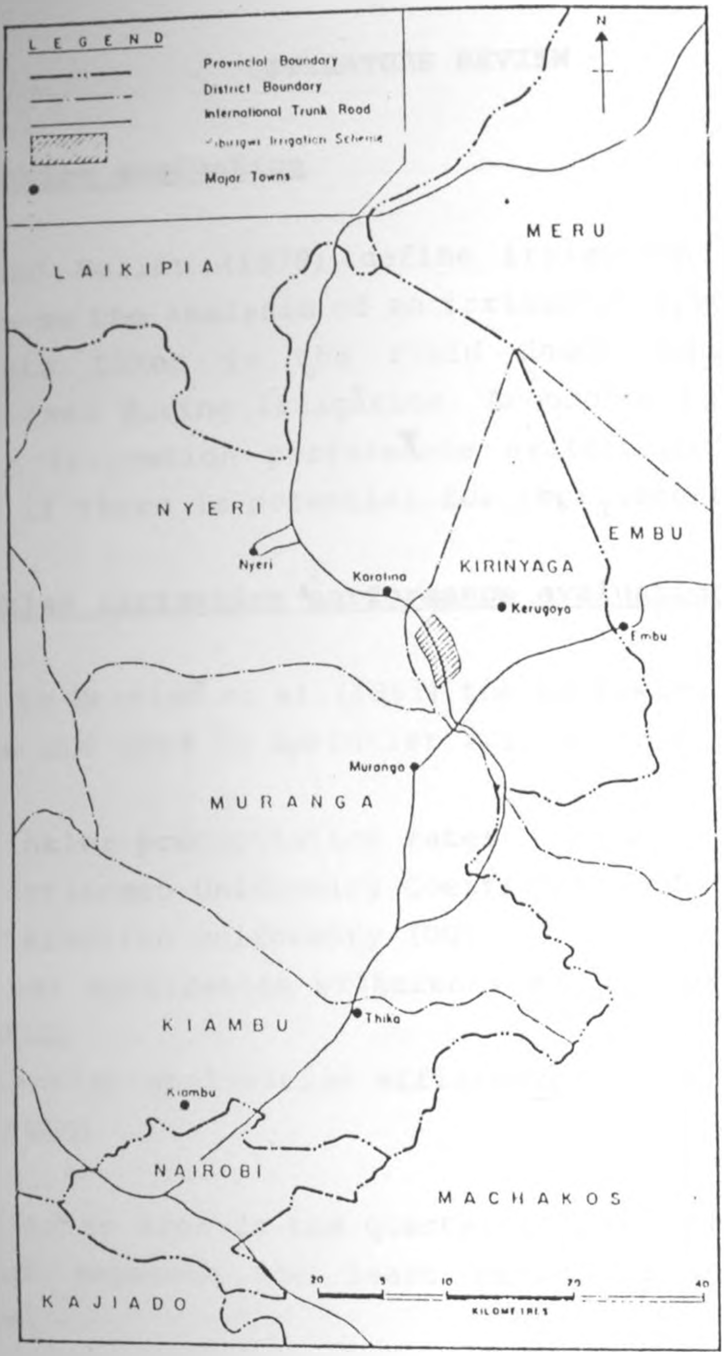

Figure 1. Location of Kibirigwi Irrigation Scheme

2 LITERATURE REVIEW

2.1 Irrigation evaluation

Merriam and Keller (1979) define irrigation performance evaluation as the analysis of an irrigation system based on measurements taken in the field under conditions and practices used during irrigation. According to Merriam et al.(1983), irrigation performance evaluation is done to determine if there is potential for improvement.

2.2 Sprinkler irrigation performance evaluation

According to Merriam et al.(1983) the following performance parameters are used in sprinkler irrigation evaluation.

i) Sprinkler precipitation rates
ii) Christiansen Uniformity Coefficient (CU)
iii) Distribution uniformity (DU)
iv) Actual application efficiency of the low-quarter (AELQ)
v) Potential application efficiency of the low-quarter (PELQ)

The low-quarter area is the quarter of the total irrigated area which receives the least amount of water during irrigation.

In addition to these evaluation parameters, sprinkler precipitation rates should be less than the basic infiltration rates of the soil to avoid causing run-off during irrigation.

The parameters PELQ, AELQ, CU and DU are evaluated in field tests using catch cans to collect irrigation water from the sprinkler(s). PELQ, AELQ and DU are based on the average depth of water infiltrated or stored in the low-quarter.

through evaporation, wind drift or otherwise unaccounted due to part of the irrigation area being ungauged. The average depth of irrigation water collected in the catch cans divided by the average expected depth in the sprinkler irrigated area gives the sprinkler application efficiency.

ii) **Christiansen Uniformity Coefficient**

According to Heermann and Kohl (1983) the sprinkler irrigation industry mostly uses the Christiansen uniformity coefficient to determine the uniformity of water application and for comparing sprinkler irrigation systems.

The Christiansen uniformity coefficient, (CU), is given as:

$$CU = \left(1.0 - \frac{SUM \left|(di - \bar{d})\right|}{\bar{d}\ .\ n}\right) *100$$

Where:

CU = uniformity coefficient in percent

di = depth or volume of water collected in individual catch cans during irrigation, mm

$\bar{d}$ = average depth or volume of water collected in all the catch-cans, mm

n = total number of data

The Christiansen uniformity coefficient is a statistical representation of the precipitation pattern and shows how uniformly water is distributed by sprinklers on the soil surface (Merriam et al.,1983).

A uniformity coefficient of 100 percent means completely uniform distribution. Keller et al.(1990) states that normal distribution of irrigation water is realised when calculated CU is greater than 75 percent. A high CU is achieved with a well designed irrigation system where the sprinklers operating pressure and discharge rate are maintained at the manufacturers recommendations. The prevailing wind speeds during irrigation should be within the specified range for the particular sprinkler spacing for high uniformity coefficient values to be obtained. This, however, is an external factor which the farmer cannot control. Generally low uniformity coefficients reduce crop yields. In studies of cotton production under irrigation in the USA, Seginer as reported by Heermann and Kohl (1983) estimated that a 10 percent decrease in the uniformity coefficient value caused a net loss of $180/ha in cotton yield.

According to Wu and Gitlin (1983), Christiansen uniformity coefficient is a design criterion for sprinkler irrigation and is affected mainly by the spacing of laterals, the lateral move and the local prevailing wind speed. Wind distorts the distribution pattern of the sprinkler spray if the speed is above 2.2 m/s (Heermann and Kohl, 1983; Addink et al.1983). To maintain a desired value of uniformity coefficient at increased wind speeds, the spacings of sprinklers during irrigation are decreased according to the sprinkler manufacturer's recommendations. Though optimum sprinkler spacings to give high values of CU as desired could be calculated accurately at the design stage, it may not always be practical due to the standard pipe lengths of 6m and sometimes 9m pieces which would give either lower or higher sprinkler spacing.

iii) **Distribution uniformity**

Distribution uniformity, DU is calculated as:

$$DU = \frac{\text{Average low-quarter depth of water infiltrated (or caught)}}{\text{Average depth of water infiltrated (or caught)}} * 100$$

According to Merriam and Keller (1979) distribution uniformity is the distribution efficiency of irrigation water in the soil and it indicates the magnitude of distribution problems.

The depths of water collected in the catch cans in the test area represent the amount of irrigation water which would be infiltrated into the soil in the absence of surface runoff or ponding during irrigation. Subtracting the calculated percentage value of DU from 100, gives the percentage of irrigation water infiltrated into the soil and lost through deep percolation when the soil moisture deficit in the low-quarter area attains field capacity level (Merriam et al., 1983). From Keller et al.(1990), the relationship between CU and DU can be approximated by:

$Cu = 1.0 - 0.63\ (1.0 - DU)$.

If a Cu value greater than 75 percent is for a normal distribution, then satisfactory distribution uniformity (DU) values should be greater than 60 percent.

iv) **Actual application efficiency**

Actual application efficiency of the low-quarter, AELQ, is calculated as:

$$AELQ = \frac{\text{Average low-quarter depth of water infiltrated and stored}}{\text{Average depth of water applied by the sprinklers}} * 100$$

Merriam et al.(1983) reports that the average low-quarter irrigation depth infiltrated and stored in the root zone for performance evaluation tests is taken as the average depth of the lowest one-fourth of the total measured values of irrigation water collected in the catch cans placed on the ground surface in the sprinkler irrigated area. Each of these values represents an equal unit of area.

The AELQ values indicate both the uniformity of water distibution and adequacy of irrigation. Under irrigation is observed when the low-quarter value is less than the soil be used to compare irrigation systems or methods. According to Keller et al.(1990) low PELQ values indicate poor system design and low values of AELQ relative to the potential efficiency for a given field indicate irrigation system management or operational problems.

2.3 Irrigation water requirement

Heermann (1985) gives a method of calculating the net irrigation water requirement during a crop growing season as;

$In = ET - Re - Gw - Ws$

Where:

In = net irrigation water requirement, mm/month
ET = Evapotranspiration requirement, mm/month
Re = Effective rainfall, mm/month
Gw = The water contribution from a high water-table
Ws = available stored soil moisture

Where the water-table is deep, the ground water contribution in the water balance method would be negligible. This would also be true for the available stored soil moisture during the dry months.

i) Effective rainfall

Dastane (1974) defines effective rainfall as that part of the total rainfall received in an area during a crop growing season which is partly or wholly available for the crop evapotranspiration needs.

Among the methods available to determine the effective rainfall is a simple empirical one by the United States Department of Agriculture, Soil Conservation Service (Burman et al.,1983) where the average monthly total effective rainfall is related to the average monthly total rainfall by the mean monthly total consumptive use (Table 1). This method was used to calculate the effective rainfall in this study.

Table 1. Average monthly effective rainfall as related to mean monthly rainfall and mean monthly consumptive use

Monthly mean rainfall mm	Mean monthly consumptive use mm													
	25	50	75	100	125	150	175	200	225	250	275	300	325	350
	Mean monthly effective rainfall mm													
12.5	7.5	8.0	8.7	9.0	9.2	10.0	10.5	11.2	11.7	12.5	12.5	12.5	12.5	12.5
25.0	15.0	16.2	17.5	18.0	18.5	19.7	20.5	22.0	24.5	25.0	25.0	25.0	25.0	25.0
37.5	22.5	24.0	26.2	27.5	28.2	29.2	30.5	33.0	36.2	37.5	37.5	37.5	37.5	37.5
50.0	25	32.2	34.5	35.7	36.7	39.0	40.5	43.7	47.0	50.0	50.0	50.0	50.0	50.0
62.5	at 41.7	39.7	42.5	44.5	46.0	48.5	50.5	53.7	57.5	62.5	62.5	62.5	62.5	62.5
75.0		46.2	49.7	52.7	55.0	57.5	60.2	63.7	67.5	73.7	75.0	75.0	75.0	75.0
87.5		50.0	56.7	60.2	63.7	66.0	69.7	73.7	77.7	84.5	87.5	87.5	87.5	87.5
100.0		at 63.7	63.7	67.7	72.0	74.2	78.7	83.0	87.7	95.0	100	100	100	100
112.5			70.5	75.0	80.2	82.5	87.2	92.7	98.0	105	111	112	112	112
125.0			75.0	81.5	87.7	90.5	95.7	102	108	115	121	125	125	125
137.5			at 122	88.7	95.2	98.7	104	111	118	126	132	137	137	137
150.0				95.2	102	106	112	120	127	136	143	150	150	150
162.5				100	109	113	120	128	135	145	153	160	162	162
175.0				at 160	115	120	127	135	143	154	164	170	175	175
187.5					121	126	134	142	151	161	170	179	185	187
200.0					125	133	140	145	158	168	178	188	195	200
225					at 197	144	151	160	171	182				
250						150	161	170	183	194				
275						at 243	171	181	194	205				
300							175	190	203	215				
325							at 287	198	213	224				
350								200	220	232				
375								at 331	225	240				
400									at 372	247				
425										250				
										at 412				
450	25	50	75	100	125	150	175	200	225	250				

Source: Burman et al. (1983)

When using table 1, it should be noted that where it is indicated, for example, at 41.7 and a mean monthly consumptive use of 25 mm, then the effective rainfall is 25mm. Other values of rainfall greater than 41.7 mm have an effective rainfall of 25 mm. 41.7 mm in this case is therefore the cut-off value. If the rainfall is 40 mm, then the effective rainfall will be calculated by interpolation.

ii) Crop water requirement

Open water evaporation (E_0) is the maximum rate of evaporation from an extended water surface under certain climatic conditions. It was previously used to estimate crop water requirements (ETcrop).

Doorenbos and Pruitt (1977) defines reference crop evapotranspiration (ET_0) as the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height actively growing, completely shading the ground and not short of water. The reference crop evapotranspiration is closer to the normal agricultural situation with dry footed crops. The main difference is in the albedo (20 - 28 % for crops, 15 - 8 % for water).

Crop evapotranspiration (ETcrop) is the actual rate of evapotranspiration from an area planted with a certain crop at a given time. According to Wright (1985) ETcrop is the rate of evapotranspiration in relation to all causative factors of plant cover, stage of growth, soil conditions, particularly as they affect evaporation directly or the availability of water for uptake by the roots, and the climatic factors as they affect the energy and mass exchange process.

In irrigation, interest is on ETcrop which according to Doorenbos and Pruitt (1977) can be obtained from reference crop evapotranspiration, ET_0, and the crop factor, K_c, by the following expression; $ETcrop = K_c * ET_0$.

ET_0 is reasonably estimated by the following methods: Jensen-Haise, Penman, Blaney-Criddle and the pan evaporation. Jensen - Haise method relates ET_0 to the relevant climatic parameters by the following expression as given by Heermann (1985):

$ET_0 = 0.0096\ (T + 8.7) * Rs$

Where,

ET_0 = reference crop evapotranspiration, mm/day

T = mean daily air temperature, ^{0}c

Rs = daily solar radiation, Ly/day

The disadvantage of this equation as found by Allen (1985) is that it greatly under-estimates lysimeter measurements of ET_0. It has the major advantage in that it requires temperature and solar radiation data only as its input.

The Penman method is the most accurate of the methods mentioned above for calculating open water evaporation. It requires data on temperature, humidity, wind and either sunshine or radiation (Wang and Hagan, 1981). All the other components can be derived from these data.

Doorenbos and Pruitt (1977) gave a modified Penman equation to determine ET_0. It involves a revised wind function term. The method uses mean daily climatic data since day and night time weather conditions considerebly affect the level of evapotranspiration, an adjustment for this is included.

The form of the equation used in the Penman method is:

$ET_0 = c\ (W \cdot R_n + (1 - W) \cdot f(u) \cdot (e_a - e_d))$

where,

$(W \cdot R_n)$ is the radiation term, and

$(1 - W) \cdot f(u) \cdot (e_a - e_d)$ is the aerodynamic term.

ET_0 = reference crop evapotranspiration, mm/day

W = temperature related weighting factor

R_n = net radiation in equivalent evaporation, mm/day

$f(u)$ = wind related function

$(e_a - e_d)$ = difference between the saturated vapour pressure at mean air temperature and the mean actual vapour pressure of the air, both in mbar

c = adjustment factor to compensate for the effect of day and night weather conditions

To use the Penman equation the following meteorological data is needed; mean air temperature, sunshine duration, mean relative humidity or dewpoit temperature, wind run and solar radiation. The altitude and latitude should also be known.

Doorenbos and Pruitt (1977) gives tables for, calculating $f(u)$ values for wind run at 2m height, $(1-W)$ and W values as related to temperature and altitude, and adjustment factor C. The net radiation R_n, is the difference between all incoming and outgoing radiation. It can be measured or calculated from solar radiation or sunshine hours, temperature and humidity data.

According to Wright (1985), the Blaney-Criddle empirical formula is based on a simple correlation between ET_0, temperature and daylight factors with the estimating accuracy limited due to the dependence on only a few variables. The Blaney-Criddle equation as expressed by Doorenbos and Pruitt (1977) is;

$$ET_0 = c * (p(0.46T + 8)), \text{ mm/day}$$

where,

ET_0 = reference crop evapotranspiration in mm/day for the month considered

T = mean daily temperature in °c over the month considered.

p = mean daily percentage of total annual daytime hours obtained for a given month and latitude. These values are available from Doorenbos and Pruitt (1977).

c = adjustment factor which depends on minimum relative humidity, sunshine duration and day time wind estimates.

The Blaney-Criddle method was developed for hot and dry Western U.S.A. and is empirical. It is therefore only used accurately in areas with similar climatic conditions. The method is widely used due to its relative simplicity. Only temperature is needed in the use of this method.

Doorenbos and Pruitt (1977) in their analysis of the Blaney-cridle equation found it to be inaccurate in some conditions. Two of these which are relevant to kenyan situation are:

i) Equatorial conditions where temperatures remain fairly constant while other weather parameters change.

ii) At high altitudes due to the fairly low mean daily temperatures even though day-time radiation levels are high.

The study area lying on the equator and the altitude being high although Doorenbos and Pruitt did not set the lower limit of altitude, the Blaney-cridle equation was found to be unsuitable for use here.

The Jensen-Haise and the Penman equations are radiation dependent. This parameter was not available from the

Kibirigwi meteorological station records. The two methods therefore could not be used in this study.

The pan evaporation method was used to estimate ET_0. The method is simple and requires only the pan evaporation data (Heermann,1985). According to Doorenbos and Pruitt (1977), evaporation pans provide measurement of integrated effect of radiation, wind, temperature and humidity on evaporation from a specific open water surface. Plants respond similarly to the same climatic conditions.

With the pan evaporation data,

$ET_0 = Epan * K_p$, mm/month

Where:

Epan = Pan Evaporation, mm/month

K_p = Pan coefficient

$ET_{crop} = K_c * ET_0$

where K_c = Crop factor

According to Doorenbos and Pruitt (1977), a class A pan placed in short green cropped area, at a medium mean Relative humidity of 40-70 percent, light wind speed of less than 175 km/day and at a windward side distance of green crop of 10 m has a pan coefficient value of 0.75. Since these conditions of the class A pan location are similar to those at the site of Kibirigwi Meteorological Station (Appendix VI), the pan coefficient value of 0.75 was used in the calculations of ETcrop. The crop factors vary with the type of crop and it's growth stages. Doorenbos and Pruitt (1977) give the four stages of crop development as;

i) **Initial stage**

This covers the period from germination to early growth stage when the soil surface is not or is hardly covered by the crop. The ground cover is less than 10 percent.

ii) **Crop development stage**

This is the period of attainment of effective ground cover. At this stage, the ground cover is approximately 70-80 percent.

iii) **Mid-season stage**

This is the period from attainment of effective full ground cover to the time the crop starts maturing.

iv) **Late season stage**

This is the period from end of Mid-season stage to full maturity or harvest. Table 2 gives examples of crop factors during the crops development stages.

Table 2: Crop factors and lengths of the growth stages,days, of some selected crops

stages of growth	crop type			
	tomato	capsicum	onions	cabbage
Initial stage	10(0.45)[1]	25(0.40)	15(0.50)	25(0.45)
Crop development	25(0.75)	35(1.03)	30((0.75)	30(0.75)
Mid-season stage	35(1.15)	25(1.03)	35(1.03)	25(1.03)
Late-season stage	35(0.85)	45(0.85)	40(0.88)	15(0.95)
Length of growth season (days)	105	130	120	95

Source: Doorenbos and Kassam (1979).

To attain full development potential, the crop should not be subjected to moisture stress in any of the growth stages during the season. However, designing an irrigation system for the maximum ETcrop, using the maximum crop factor, would leave the system operating below capacity for the longest part of the crop season when the water requirement is less than that of the peak.

Weighted crop factors in irrigation system design become necessary noting that the crop water requirement increases gradually from germination to a maximum during the season and then drops. The weighted crop factor ensures that the crop water requirements is met during the greater part of the crop season. This reduces the system peak irrigation demand and consequently the cost of supplying irrigation water and at the same time not compromising too much on the ETcrop needs for the greater part of the crop season.

---

[1] .The numbers in brackets represent the crop factors for the growth stages

Table 2: Crop factors and lengths of the growth stages,days, of some selected crops

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2.4 Irrigation schedule

Rao et al.(1987) define irrigation scheduling as determining the timing and amount of irrigation for a given crop during the growth season. Irrigation intervals and application durations should therefore be correct during the crop growth season. To schedule irrigation, factors to consider according to Rao et al.(1988) are:

i) crops grown and their seasons
ii) climate
iii) soil moisture characteristics
iv) available water supply

The recommended irrigation schedule for Kibirigwi is an application duration of 10 hours and irrigation interval of 7 days irrespective of the crop, its stage of growth and the season (Anonymous, 1988; Leeuw, 1982; Mugwanja et al.(1987). This is clearly not in line with Rao's recommendations above. It might result to water stress or excess irrigation and reduced crop yields for some of the crops grown. Information on the crops grown, their seasons, climatic conditions and soil moisture characteristics is necessary in irrigation scheduling.

Knowledge of crop root depths is also required in irrigation management because besides extracting nutrients and moisture from the soil, the absorptive capacity of a plant is determined by the distribution and depth of the root system (Schuurman and Goedewaagen,1971). Lambert et al.(1981) noted also that roots restricted from fully developing consequently limits soil water and nutrient availability to the plants and affect its development.

Common among the methods used to determine plant root depths and the one used in this study is that by Schuurman and Goedewaagen (1971) where the crops root depth in the field is determined by digging a profile wall tangential to the plant. This method is simple, quick and require only hand tools as opposed to others which need complicated laboratory analysis.

2.5 Soil characteristics

Important characteristics of a soil in sprinkler irrigation evaluation are the soil moisture holding capacities and the infiltration rates.

2.5.1 Soil moisture holding capacity

The total available soil moisture to the plants is the depth of water held in the plant root zone between field capacity and the permanent wilting point of a soil (Doorenbos and Kassam,1979; Skaggs et al.,1983).
Soil moisture deficit (SMD) is defined by Merriam et al., (1983) as the depth of water required to change a specific depth of soil from its present soil moisture status to field capacity level. Similarly, the management allowable deficit (MAD) is the allowable soil moisture depth in the plant root zone that corresponds to a desired management allowed crop water stress before application of irrigation. According to Shaw (1985) the maximum soil moisture deficit for a plant is when the soil moisture in root zone is depleted up to the permanent wilting point level.

Experimental findings reported by Stegman et al.(1983), indicate that yields of many crops are near their maximum when root zone available water is not depleted by more than 40 percent of the maximum soil moisture deficit (SMD) between irrigations. Exceptions to this is where a crop requires water stress management at some stages in the growth period to produce desired yield and quality levels.

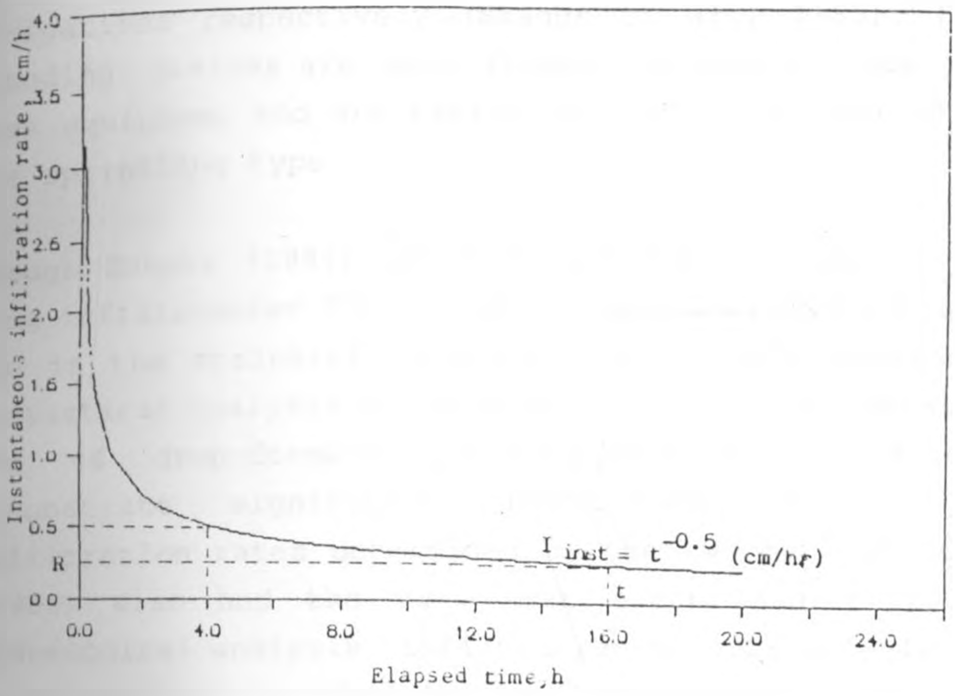
The field capacity is selected at water contents in equilibrium of 1/10 bar for sandy soil and 1/3 bar for fine textured soils and the permanent wilting point at 15 bar for both type of soils (Skaggs et al.,1983). The National Agricultural Research laboratories, at Kabete, has adopted these equilibrium points in the analysis of soil moisture contents (Hinga et al.,1980).

Soil moisture content measurements are in three categories Viz. Sampled, in-situ and remote (Stafford, 1988). In the sampled system, the soil moisture measuring technique is laboratory based. This technique is reasonably accurate and is more widely used due to its simplicity and the availability of the equipments required. It was therefore used in this study.

2.5.2 **Infiltration**

Infiltration is the process in which water soaks into or is absorbed by the soil and the rate of water entry into a soil is the infiltration rate. This rate decreases with increase in infiltration opportunity time (Skaggs et al.,1983) and result to a constant after a sufficiently long time of infiltration.

Irrigation water applied in excess of the infiltration capacity of the soil become available for surface storage and or run-off (Knight, 1983). In a good sprinkler irrigation design, the sprinklers' precipitation rates should always be less than the intake rate of the soil (fig.2) to prevent run-off occurring or water to stand on the soil surface during irrigation (Clothier et al., 1983). As noted by Slack (1980), determination of infiltration characteristics of a soil is therefore important when studying performance of sprinkler irrigation systems.



R, - basic infiltration rate

t - Irrigation water application duration beyond which run-off occurs

Fig. 2: Average infiltration rate of soil against elapsed time

Though infiltration theory does not describe infiltration under field conditions adequately (Clemmens, 1983) empirical infiltration equations have been devised for practical use. The Kostiakov infiltration equation used in this study is the most widely used of the empirical equations for most infiltration test purposes.
This is because the equation fits infiltration data for most of the soils reasonably well (Clemmens, 1983). This equation is of the form;

$$Icum. = K * t^{a},$$

where:

Icum.= cumulative depth infiltrated; (mm)

t = time of infiltration; (h)

and a, K are constants.

The infiltration rate, $Iinst. = K*a*t^{(a-1)}$.

Measurements of infiltration recommended for irrigation purposes are the use of a sprinkling infiltrometer and flooding infiltrometer for sprinkler and furrow or flood irrigations respectively (Skaggs et al., 1983). However flooding devices are more frequently used as they require less equipment and are easier to install and operate than the sprinkling type.

Though Bouwer (1984) cautions against the use of double ring infiltrometer for infiltration measurements meant for use in the sprinkler contexts, Neff (1983) reports that statistical analysis of 50 double-ring infiltrometer tests and 44 drop-forming infiltrometer tests failed to demonstrate significant differences in the final infiltration rates determined by the two methods. Amerman (1983) also had the view that except for purposes of hydrological analysis, infiltration measurements for other uses could be accomplished by point measurement method. Infiltration measurements in this study were therefore done with a double-ring infiltrometer.

2.6 **River flow analysis**

When a river is the source of irrigation water, its flow analysis becomes necessary at the design stage to determine if water could be supplied during the irrigation season with a certain probability of exceedance (Chow,1964). During the irrigation season, the source of water is considered adequate when the available amount exceeds that required for irrigation (MAFF,1977). The design discharge for irrigation project is based on a flow with 80 percent exceedance probability of occurence which is considered a fair approximation of a drought flow for irrigation purposes (MOWD,1986).

To use a river as a reliable source of water supply, analysis of low flows should be done to determine the nature of the drought (WMO,1974). Drought in river flow analysis is defined as the period in which the natural river discharges are lower than those needed for water supply or other water management activity (WMO,1974).
In the analysis of low flows, if the minimum flow record far exceeds the proposed demand, further analysis becomes unnecessary but if the flow is less than the proposed demand at any one time during the period of record, further analysis is done to determine if the anticipated deficiencies in flow could be tolerated (WMO,1974). If the deficiencies are great and occur too frequently, storage could be provided to hold the high flow and release it during drought periods to meet demand (WMO,1974).

Low flow frequency and flow duration curves are the two most simple methods used in the analysis of low flows (WMO,1974). Common ways of low flow frequency analysis is by Gringorten and Weibull methods (Shaw,1985) where the plotting positions are as follows:

In Gringorten method;

$$P(x) = \frac{r - 0.44}{N + 0.12}$$

and in Weibull;

$$P(x) = \frac{r}{N + 1}$$

where for both,

$P(x)$ = the probability of exceedance of flow event

r = the rank order of the event

N = the number of the flow events

However, these are not suitable for data of less than 20 years record (Shaw,1985) and could therefore not be used in this study.

Chow (1964) defines flow duration curve as a plot of the magnitude of river flows against corresponding per cents of time the flows are exceeded. On logarithmic probability paper, the flow duration curve generally plots nearly as a straight line particularly in the middle portion (WMO,1974). This curve is considered to represent hydrograph of the average year with its flow arranged in order of magnitude (Chow,1964). According to WMO (1974), flow duration curves of daily discharges show the per cent of time that the flow of a river is greater than given amounts regardless of continuity in time. The curve though has the weakness in that it deals only with discrete values of flow and reveals nothing about the sequence of low flows nor whether they occured consecutively over a few weeks or were scattered throughout the year (Hudson and Hazen, 1964). The river flow analysis was done by the flow duration curve method.

3. MATERIALS AND METHODS

3.1 Kibirigwi Irrigation Scheme

i) Site Description

The scheme has an area of approximately 100 hectares. It extends for a length of 8 Km and a width of 1 Km along the Sagana- Karatina road. The general scheme layout is shown in Figure 3.

ii) Climate

The average annual rainfall of Kibirigwi irrigation scheme area is estimated to be 1250 mm. The rainfall distribution is bi-modal. The long rains season (March-May) and the short rains season (October-December) account for 53 and 31 percent respectively of the average annual rainfall (Oswago, 1979).

The period from June to September is relatively dry but January and February are the driest months of the year; both dry periods account for 12 and 4 percent of the mean annual rainfall.

The average potential evaporation (E_0) is estimated to be in the order of 1900 mm (Oswago,1979). The May-August period has less evaporation per month compared to the period from September to March. With the estimated average annual rainfall (r) of 1250 mm and annual potential evaporation of 1900 mm, the r/E_0 ratio is 66 percent. The probability that the average rainfall in the long and short rains is less than 2/3 E_0 is 1 and 56 percent respectively (Oswago, 1979). For a seasonal crop of about 90 days growing period, the water deficit is low in the long rains season but quite considerable during the short rains season.

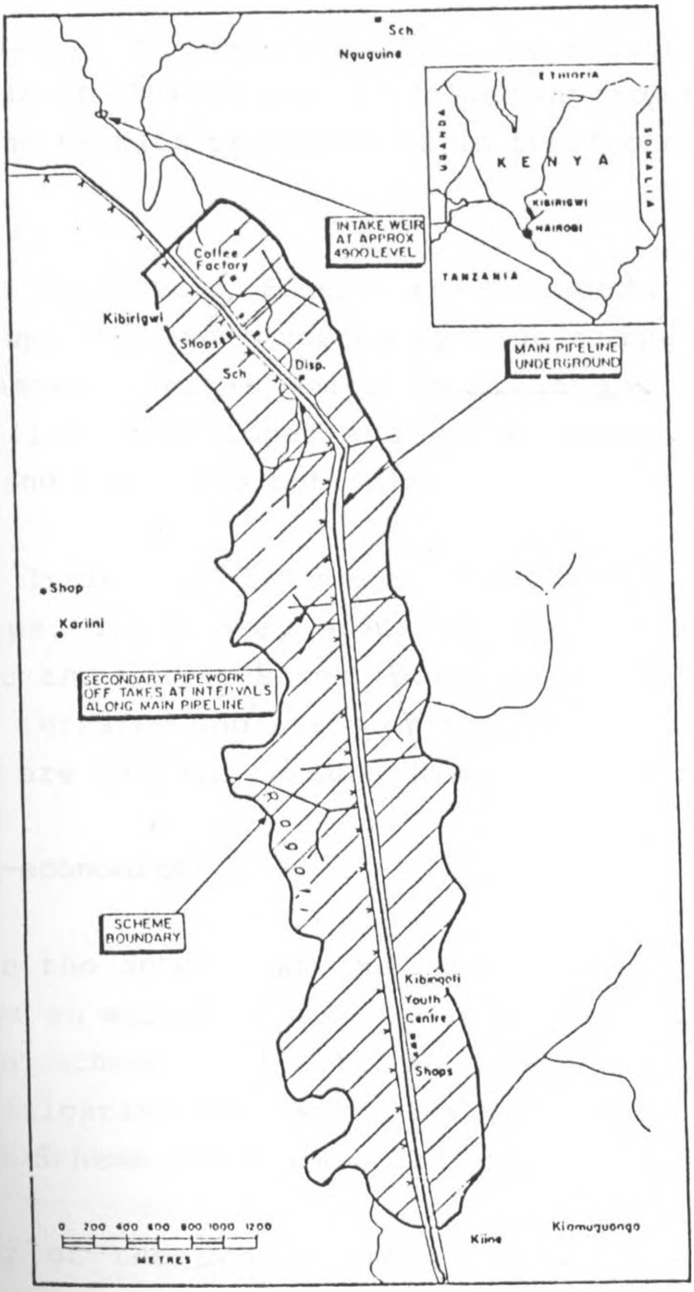


Fig. 3: Kibirigwi Irrigation Scheme

iii) **Geology and Soils**

The irrigation scheme area rests on Pleistocene to Recent olivine basalt (Thiba basalt). Colluvium from biotite gneisses and olivine basalts predominates in the footslopes and valley sides.

Kibirigwi Irrigation Scheme is situated in a relatively lowlying upland area bordered by high ridges on both sides. Major geomorphological units found in and around the area include hills, footslopes and valley sides, uplands, river terraces and riverrine bottomlands.

Kibirigwi Irrigation Scheme can be divided into five broad soil groups. These are: soils of the hills, soils of the footslopes and valley sides, soils of the uplands, soils of the river terraces and soils of the riverline bottomlands. The soils are clay in texture (Oswago, 1979).

iv) **Socio-economics**

Farmers in the scheme own the land on which they farm. They have signed an agreement with the government through Kibirigwi Irrigation Scheme (K.I.S.), as the water undertaker, to perform irrigation duties and becoming members of Kibirigwi Irrigation Scheme Cooperative Society,KIFCO, (Makanga, 1986).

Harvesting of the scheme crops is done twice a week and marketing is done through KIFCO. The farmers have permitted and authorized KIFCO to deduct money received from the sales of their horticultural produce to cover some of the costs of running the irrigation scheme.

The crops grown in the scheme are; coffee, maize, beans, bananas and english potatoes on the non-irrigated part of the farm, and horticultural crops like tomatoes, onions, cauliflower, lettuce, cucumber, courgette, capsicum and bobby beans on the irrigated plots with rotation whenever possible (Anonymous, 1988). Farmers are given farm inputs on credit basis. They apply freely for these inputs though a supply schedule is prepared on a monthly basis in order to balance production.

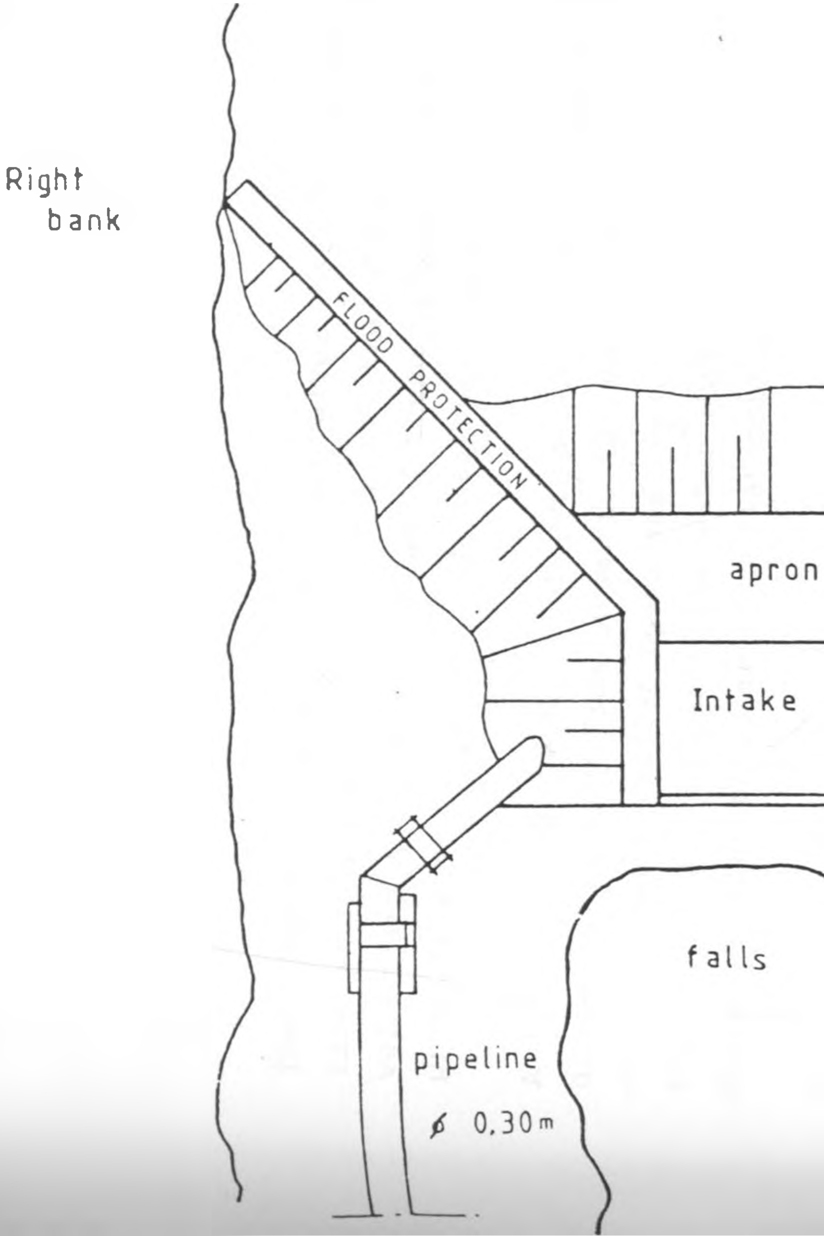
The scheme management and four extension officers from the Ministry of Agriculture visit the farmers throughout the planting, cultivation and harvesting periods to guide them in the best way of performing these operations.

About 280 farms are situated within the scheme boundaries. Out of this, only 270 are in the irrigation programme. The average farm size is 1.8 ha. The gross command area is about 482 ha out of which 94 ha or about 20 percent are irrigated. All the 270 farms in the irrigation scheme are members of KIFCO. Farmers outside the irrigation programme are registered as outgrowers (Makanga, 1986).

v) **Irrigation System Hydraulics**

Irrigation water for Kibirigwi scheme is from Ragati river. A weir across the river diverts water to an intake box and is conveyed by pipe through gravity (fig. 4) to a filtration point and sediment is removed. The water is then conveyed still by gravity through pipes to the irrigation fields.

The main pipeline starting at the settling tanks is 7472 m long and is of Polyvinylchloride (pvc) pipes and of Galvanised Iron (GI) where it crosses a river or road. The mainline diameters are 300 mm for a length of 3858 m, 250 mm for 592 m, 200 mm for 1535 m long and 150 mm for 1487 m.


Right bank
FLOOD PROTECTION
apron
Intake
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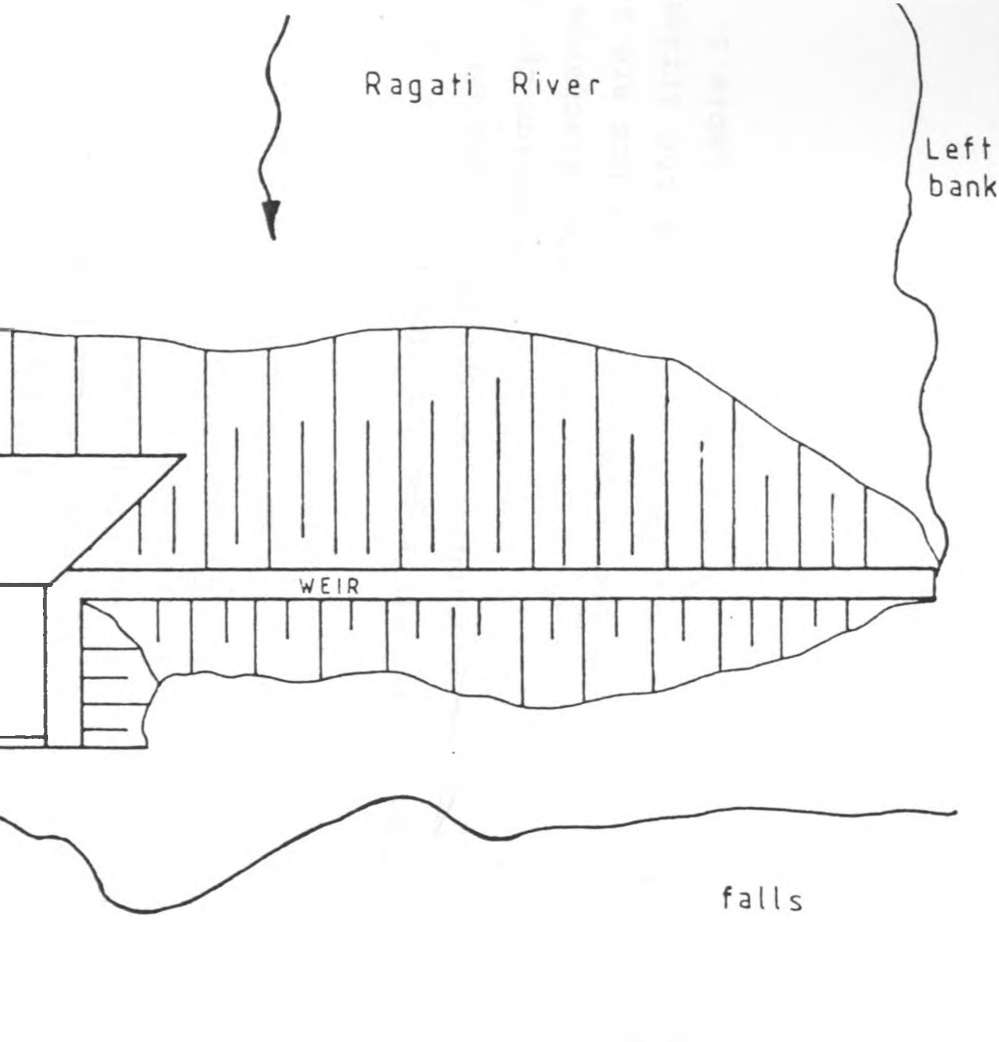
pipeline
ø 0,30 m



Scale 1 : 50

PVC pipes class B and C are used with maximum working pressures of 6 and 9 bar respectively. The end of the main pipeline is closed with a 150 mm diameter sluice valve with a 25 mm diameter hole drilled through the wedge which acts as a wash out and discharge approximately 5 l/s of water always (Bron, 1980).

There are three pressure reducing valves installed in the main line with diameters of 300 mm, 250 mm, and 200 mm. Safety valves are coupled downstream of these valves to release the pressure when the valves are malfunctioning.

A total of 25 submains of pvc pipes class B and C with diameters ranging from 50 mm to 125 mm are connected to the main line with isolating valves. Hydrants constructed along the sub-mains regulate the water supply to the farms to a maximum outlet pressure of 3.5 atmospheres.

The field supply consist of a pvc pipeline of 50 mm diameter from the hydrant to the outlet on the plot. The length of the field supply pipelines vary from 1 m to over 100 m. The outlet of these field supply lines consist of a GI stand pipe of 50 mm diameter with a 90 degrees elbow, a reducer to 25 mm, a gate valve and an adapter to the portable irrigation components described in table 3.

Irrigation water in Kibirigwi is applied by a portable sprinkler system consisting of two sprinklers spaced 18 m on the lateral and a lateral move of 12 m. The design sprinkler precipitation rate is 4.6 mm/h while the discharge and operating pressure of the recommended sprinklers are 1 m^3/h and 2.7 bar respectively. The components of the irrigation equipment for each irrigation plot is shown in table 3.

Table 3: Components of the portable irrigation equipment

ITEM	NUMBER
25 mm Brass Gate Valve	1
3 m long and 40 mm diameter flexible hose with coupling	2
Aluminium pipes with M/F Couplings (6 m and 40 mm diameter)	18
Aluminium pipes with M/M Couplings (6 m and 40 mm diameter)	3
Aluminium tee connector F/F with hop-along valve and stabilizer	1
Aluminium end cap 40 mm diameter	1
Aluminium riser pipe 25 mm diameter and average height 1.3 m, mounted with Wright rain Monitor sprinklers of nozzle diameter 3.97 mm	2

3.2 **Procedure for collecting data**

The irrigation scheme area (fig. 3) from the settling tanks at the upstream to the tail end for the purpose of this study was divided into four blocks of approximately the same size and equal number of plots. These four blocks were adopted from the scheme management's extension service organisational setup where each block was assigned to an extension officer to advise the farmers on crop husbandry techniques. Five irrigation plots were selected randomly from each of the four blocks. A total of 20 plots were therefore selected in the whole scheme.

The following was done in this study:

1. collection of sprinkler performance data
2. collection of soil data
3. collection of data on crops grown and their seasons
4. collection of meteorological data
5. collection of river discharge data

3.2.1 <u>Data on sprinkler performance</u>

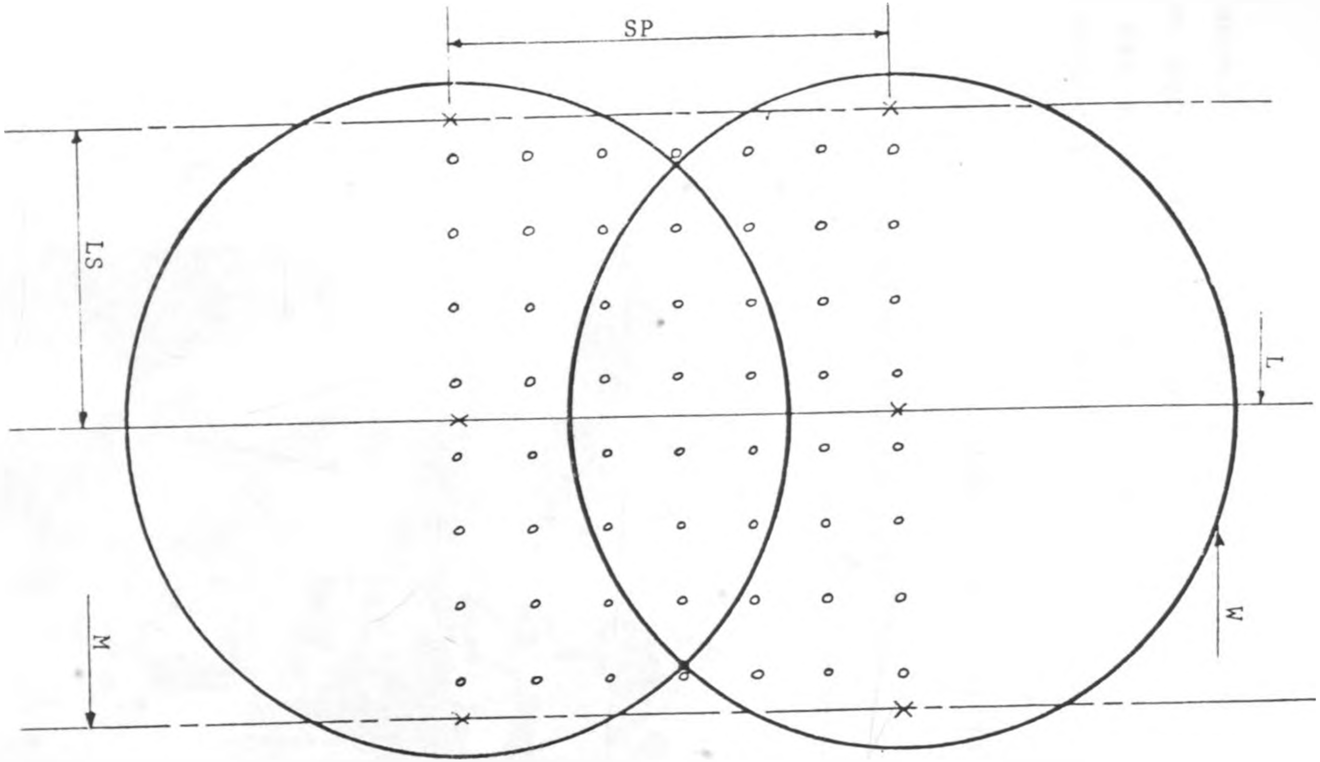
The following data were collected on sprinkler performance from the 20 randomly selected plots in the scheme:

i) **Sprinkler precipitation rates**

The portable irrigation equipment was setup and connected to the hydrant of the test plot (plate 1.). The sprinkler spacing on the lateral was 18 m. The sprinkler precipitation rates was collected with catch cans with a circular opening diameter of 8.50 cm and a height of 15.25 cm.

Plate 1: Layout of portable sprinkler system in the field with one of the catch cans in the foreground

The Catch cans were placed on the ground between the two sprinklers in a 3 m x 3 m grid pattern as shown in fig.5 using a Quick-set level, a set of ranging rods and a measuring tape.



L - Lateral position at test
W - Expected wetting pattern of sprinkler(s)
M - Next position of lateral
o - Catch cans position

x - Sprinkler position on lateral
SP - Sprinkler spacing
LS - Lateral spacing

Fig. 5, Catch can layout around the single lateral

Plate 2: Measurement of sprinkler flow rate

iv) **Test sprinkler nozzles sizes**

The diameters of the sprinkler nozzles for area computation were measured with a vernier caliper. These areas were compared with the supply nozzle areas as inscribed on the equipment and the extent of the difference of these values was attributed to the wear of the nozzles for the period they had been in use.

v) **Wind speed and direction**

The average wind speed and its direction were measured during each individual sprinkler uniformity test with an anemometer, wind vane and a prismatic compass. The wind measuring equipment (i.e. Anemometer and wind vane) was located in a clear area near but outside the sprinklers irrigated area and at a height of 2 m above the ground.

vi) **Slope of sprinkler lateral**

The slopes of the sprinkler laterals were measured with a quickset level and a levelling staff. The level differences and distances of the two sprinklers on the laterals were taken for calculation of the lateral slopes.

3.2.2 **Soil characteristics**

3.2.2.1 **Infiltration measurements**

A total of four infiltration tests were done. In each of the four extension blocks in the irrigation scheme area, one plot was randomly selected for the infiltration measurements.

The infiltration data were collected with double-ring infiltrometers of the following dimensions;

Internal diameter of outer cylinder = 54.5 cm

Internal diameter of inner cylinder = 30.0 cm

Depth of both cylinders = 25.0 cm

To measure the infiltration of the soil, the cylinders were driven concentrically into the soil to a depth of 10 cm. With a sledge hammer and a wooden plank placed on top of the cylinders, light blows were applied until the cylinders were driven to the required depth. Water was added into the cylinders and the levels of the water in both cylinders was kept at nearly 10 cm above the soil surface at start of measurements. The water was regularly added into both cylinders to minimize fluctuations of level above the soil surface during measurement.

Infiltration was measured with a stop watch, timing the rate that the free water surface in the cylinder fell every 10 mm. This depth was measured above the soil surface with a scale (ruler) stuck on the wall of the inner cylinder. Water was ponded between the two cylinders at all times during measurement to prevent edge effects and to maintain vertical flow below the inner cylinder. The sites where the tests were conducted were not pre-wet. The tests were done during the short rain season and the area was wet and therefore there wasn't need to pre-wet the site.

Cumulative infiltration depth versus time data were obtained from these tests. The length of the tests varied from three to four hours when near constant infiltration rates were obtained. The data collected was used to compute infiltration function of the soils in the area using the Kostiakov's formula.

3.2.2.2 **Soil moisture determination**

The following equipments were used to sample the soil:

i) core sampler with sample holding rings

ii) Knife

iii) Plastic bags

iv) Shovel and fork

From the 20 selected plots in the scheme area, both disturbed and undisturbed soil samples were obtained in each plot in triplicate at 0-15 cm and 40-50 cm depths from the soil surface.

The undisturbed soil was collected in cores as described below. The core sampler was driven into the soil at the required depth to fill it with soil. Care was taken not to compress the soil in the confined space of the sampler.

The sampler was removed after filling it with soil and any soil extruding beyond each end of the sample holder was trimmed with a Knife.

Disturbed soil samples at these depths were also collected and put in plastics bags.

The moisture retention was determined in the laboratory using the procedure described by Hinga et al.(1980) with the following equipments;

i) Pressure chamber with 1 and 15 bar porous ceramic plates
ii) compressed air
iii) Mercury manometer and pressure gauges
iv) soil sample rubber rings
v) soaking tray
vi) vacuum dessicator
vii) nylon cloth and rubber bands
viii) drying cans
ix) oven

The field capacity (pF 2.3) and the permanent wilting point (pF 4.2) were determined from the undisturbed and disturbed soil samples respectively. Because pore size distribution has influence on water retention at low pF, disturbed samples gives erroneous moisture retention results. Undisturbed soil cores are used though even here some error is inevitable because of the swelling and shrinking of many soils due to changes in moisture. Further, at high pF, the soil specific surface dominates the influence on water retention and the error introduced by using disturbed soil samples is negligibly small (Skaggs, et al., 1983).

The collected disturbed soil samples were crushed, passed through a 2 mm sieve before the moisture determinition.
Both the disturbed and undisturbed soil samples were saturated with water and placed on an appropriate saturated pressure plate in a pressure chamber. The pressure chamber was sealed and air pressure adjusted to 0.2 bar, equivalent to pF 2.3, for the undisturbed samples and 15 bar, equivalent to pF 4.2, for the disturbed samples respectively. The unit was observed on daily basis until water stopped draining from the soil samples when equilibrium conditions were reached. The valves were then opened to reduce pressure to atmospheric and pressure unit opened, the soil samples removed, weighed and recorded. The samples were then dried in an oven at 105^0c, cooled in a dessicator and weighed again.

The undisturbed soil was held in rubber rings placed on the ceramic plate. The soil samples in these rings was saturated by adding water carefully not to disturb the soil in the rubber rings until complete saturation was achieved.

Saturation for the undisturbed soil was obtained by placing the sample in a shallow tray of water of about 1.5 cm depth.

The percentage water content in the soil on weight basis,

$$= \frac{\text{weight of wet soil} - \text{weight of dry soil}}{\text{weight of dry soil}} * 100$$

$$= \frac{\text{weight of water in the soil}}{\text{weight of dry soil}} * 100$$

The moisture content on volume basis,
$=(D_b/D_w)$ * water content on weight basis
where,
D_b is the bulk density of the soil, and D_w is the density of water which is usually taken as 1.

3.2.3 Meteorological and cropping data

i) Meteorological data

The meteorological data collected from the Irrigation Scheme's Meteorological Station for the period 1980-1988 when the scheme had been in existence was on: rainfall, temperature, pan evaporation, and wind speed.
The pan evaporation data was used in computing the monthly reference crop evapotranspiration.

ii) Cropping data

The data required here was on the crops grown, the seasons and the crops' root depths. The scheme management's recommended cropping pattern and the amounts of farm produce delivered to KIFCO for marketing was obtained from, periodical reports on scheme performance, discussions held with the scheme management, officials of KIFCO and the extension staff of the Ministry of Agriculture at the scheme.

The pattern of the quantities of farm produce delivered for marketing for the whole scheme was compared with the recommended cropping pattern to see if the cropping pattern was followed.

The recommended cropping pattern was used to calculate the crop water requirements and with the rainfall records, the scheme irrigation requirements was also found.

The equipments used to determine the crop root depths in the field were:

i) Spade, fork
ii) Ruler, sisal rope and some nails
iii) Sack needle

To determine the crops root depths, tangential trenches were dug at distances reasonably judged from the plant and parallel to a row of the plants as recommended for horticultural and agricultural crops (Schuurman and Goedewaagen, 1971).

The tangential walls were divided into parts of equal size and these were taken as replicates. The tips of the cut roots in the walls of the trenches were mapped by covering the faces of these trenches with grid of squares, 20 x 20 cm for tomatoes and smaller for the other shallow rooted crops.
Nails were driven into the profile walls at intervals of the grid spacing. The number of roots in each grid square were counted and recorded. The depth of root spread in the profile wall was determined by the extent of root spread down the profile wall.

3.2.4 **River flow data**

The average monthly daily flows of Ragati river at River Gauging Station (R.G.S.) 4BB1, located approximately 15 Km downstream of the Kibirigwi Irrigation Scheme water intake was obtained from the Ministry of Water Development. This data was used to determine the discharge which is equalled or exceeded 4 out of 5 years or an exceedance probability of 80 percent as recommended for irrigation water supply by the Ministry of Water Development (MOWD,1986). The flow duration curve method was used for this analysis.

In the analysis, the data was grouped in convenient class intervals according to WMO (1974) and then arranged in order of their descending magnitude and per cent of time for each to be equalled or exceeded was computed as recommended by Chow (1964) and also Shaw (1985). The magnitudes of the river flows against corresponding per cents of time were plotted on logarithmic probability paper.

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4. RESULTS AND DISCUSSION

4.1 Soil characteristics

4.1.1 Soil moisture holding capacity

The amount of water available for plant growth is given as the difference in moisture content at field capacity and at wilting point. Field capacity is represented as the moisture content at pF 2.3 (0.2 bar) and wilting point as the moisture content at pF 4.2 (15 bar). The soil moisture retention data for the soil samples at depths of 0 - 15 cm and 40 - 50 cm are given in Appendix I and the averages summarised in Tables 4 and 5. The texture of the soil was clay as analysed by the Hydrometer method. The results of the analysis is in Appendix II.

Table 4: Soil moisture holding capacity at 0-15 cm depth.

Plot No.	Field capacity (percent)	Permanent wilting point (percent)	Total available soil moisture (percent)
61	26.2	19.7	6.5
324	33.0	25.0	8.0
329	32.9	21.3	11.6
346	34.7	26.5	8.2
375	30.3	22.2	8.1
396	32.5	23.9	8.6
405	34.5	24.9	9.6
470	31.2	23.7	7.5
676	32.5	22.0	10.5
482	30.9	23.4	7.5
499	32.6	24.0	8.6
531	30.1	22.6	7.5
554	30.6	25.5	5.1
360	32.0	23.2	8.8
565	32.3	23.6	8.7
569	32.0	24.0	8.0
703	31.6	24.7	6.9
708	33.2	22.6	10.6
735	32.0	23.8	8.2
1081	30.7	22.2	8.5
1172	32.0	23.4	8.7
1217	31.6	23.9	7.7
1313	31.2	23.9	7.3
K.I.S	32.8	24.8	8.0
Average	31.8	23.5	8.3

Table 5: Soil moisture holding capacity at 40-50 cm depth.

Plot No.	Field capacity (percent)	Permanent wilting point (percent)	Total available soil moisture (percent)
61	29.7	22.9	6.8
324	38.2	28.9	9.3
329	29.1	19.8	9.3
346	36.5	27.9	8.7
375	34.1	25.1	9.0
396	36.7	28.4	8.3
405	35.1	25.1	10.0
470	36.8	28.0	8.8
676	31.6	24.3	7.3
482	36.9	27.8	9.1
499	35.7	26.7	9.0
531	35.1	26.6	8.5
554	35.1	27.7	7.4
360	37.0	27.0	10.0
565	37.0	27.5	9.4
569	33.2	25.7	7.5
703	35.5	26.6	8.9
708	34.3	24.3	10.0
735	34.7	26.0	8.7
1081	32.3	24.3	8.0
117	33.6	26.7	6.9
1217	35.6	27.9	7.7
1313	33.3	25.6	7.7
kis	33.4	26.8	6.7
Average	34.6	26.1	8.5

The average total available water for plant growth at the sampled soil depths of 0 - 15 cm and 40 - 50 cm were 8.3 and 8.5 percent respectively. Though these averages showed a slight increase in soil moisture with depth, it was not a general observation in all the sampled sites.

On average, the total amount of water available in the soil at the two sample depths was 8.4 percent. This compared well with the soil moisture range of 8 - 10 percent found by Njihia (1982) in Kibirigwi Irrigation Scheme. With an average bulk density of 1.04 g/cm^3 (Oswago,1979), for clay soils at Kibirigwi Irrigation Scheme area, the average total soil moisture per m depth of soil,

= soil moisture (% w/w) x (bulk density of soil/density of water)

= 8.4 x 1.04/1

= 8.7 cm/m

Though this moisture storage capacity value of 8.7 cm/m for clay soil is low compared with the average moisture holding capacity values for silty clay and clays of 13 and 18 cm/m respectively reported by Stegman et al. (1983), it compares reasonably well with the average moisture depth of 9.1 cm/m for soils from Kibirigwi Irrigation Scheme area as reported by Alphen (1980).

The moisture holding capacity of the soils could change depending on the levels of like organic matter in it at the time of moisture determinition. This could explain the slight variation in soil moisture in this study and that determined in the past.

In this study, it was assumed that the crops are irrigated when the total available soil moisture is depleted by 40 percent. In this case, the management allowable soil moisture deficit, MAD, = 40 percent * total available soil moisture = 0.4 * 8.7 = 3.48 cm/m

4.1.2 Infiltration characteristics

The double ring infiltrometer tests data is given in Appendix III. Graphs of cumulative infiltration depth and instantaneous infiltration rates (calculated from the infiltration tests data as shown in Appendix III for test plot 569) versus time respectively were plotted. These plots are shown in Appendices III (D) - (L). The infiltration characteristics of the soil was determined by fitting the data to the kostiakov infiltration equation,

$Icum. = k*t^{a}$.

where:

Icum.= cumulative infiltration depth, mm
t = infiltration time, min
and "a" and "k" are constants determined using linear regression.

The results of the linear regression for the infiltration tests data is shown in Table 6.

A sample graph of infiltration test data for plot 569 is presented in fig. 6 where the parameters, " k" and "a" are obtained from the intercept and the slope respectively.

Table 6: Computed infiltration equations.

Plot No.	Cumulative infiltration depth, cm	Instantaneous infiltration rate, cm/min
324	$2.27t^{0.42}$ (r^2 = 0.99)	$0.95t^{-0.58}$
346	$1.81t^{0.51}$ (r^2 = 1.00)	$0.92t^{-0.49}$
569	$3.19t^{0.45}$ (r^2 = 1.00)	$1.44t^{-0.55}$
k.I.S.	$1.17t^{0.57}$ (r^2 = 0.99)	$0.67t^{-0.43}$

The infiltration data had a good fit to the Kostiakov equation as indicated by the high r^2 values of the four tests done. The power for the instantaneous infiltration rate equations ranged from 0.43 to 0.58 which was within the value of 0.50 given by the United States Department of Agriculture, Soil Conservation Service for most infiltration curve families (Hart et al.,1983).

To determine if ponding occurred during irrigation, the instantaneous infiltration rates for the soils at 10 hours irrigation application duration as reccommended (Leeuw, 1982) were calculated and compared with the measured sprinkler precipitation rates. Substituting t = 600 minutes in the instantaneous infiltration rate equations, the infiltration rates of the soils are shown in Table 7.

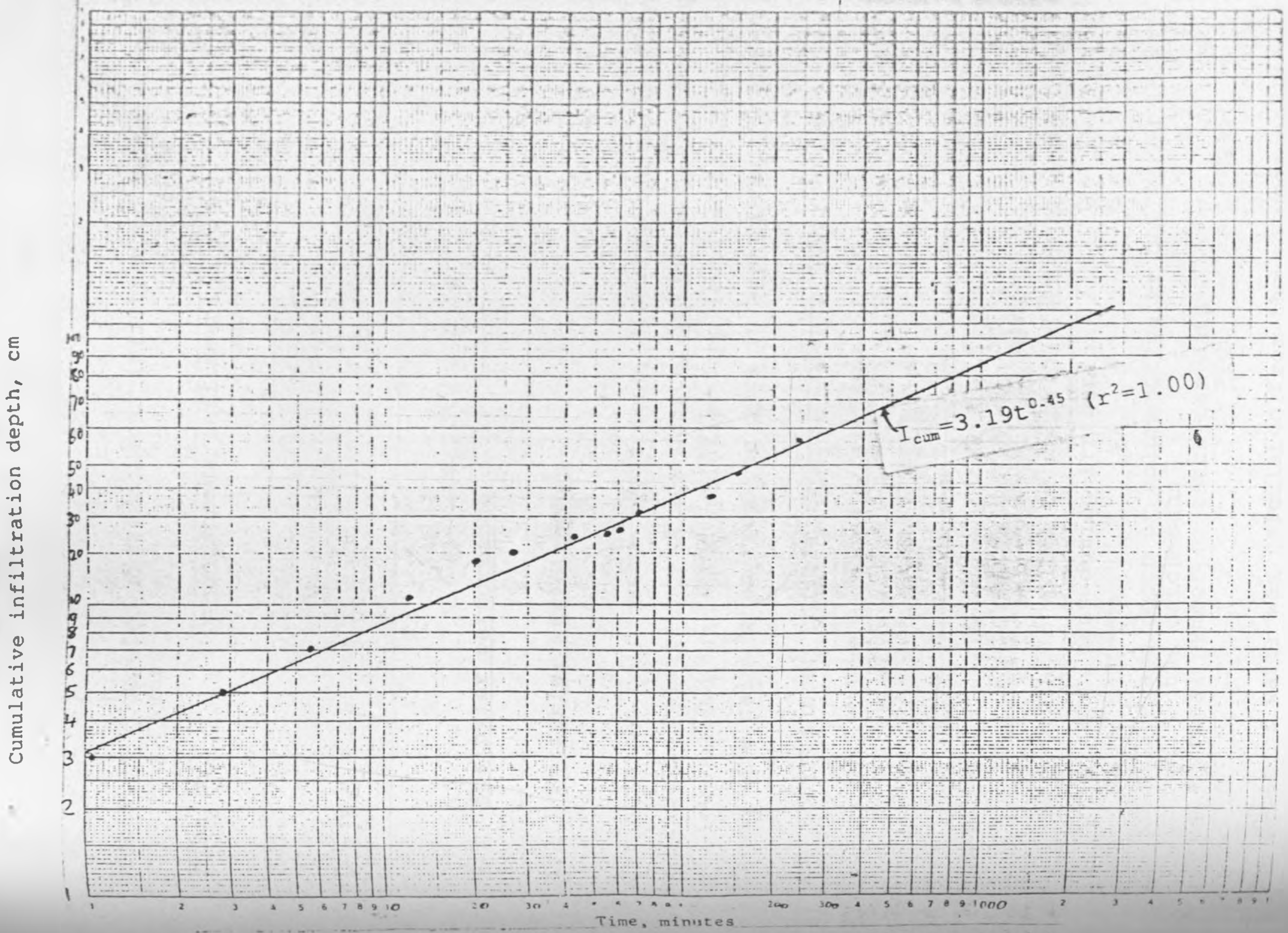

Fig. 6: Log-log plot of cumulative infiltration depth versus time

Table 7: Computed instantaneous infiltration rates after 10 hours

Plot No.	Instantaneous infiltration rate, cm/min	mm/h
324	0.023	14.0
346	0.040	24.0
569	0.030	17.8
K.I.S.	0.043	25.7

4.2 **Sprinkler performance**

4.2.1 **Sprinkler efficiencies**

Christiansen uniformity coefficient, distribution uniformity, application efficiency of low-quarter and potential efficiency of low-quarter and the sprinkler application efficiencies. These were calculated from the data in appendices IV and V.

(i) Christiansen uniformity coefficient, (CU),

$$= \left(1.0 - \frac{\mathrm{SUM}\,|(di - \bar{d})|}{\bar{d}\,.\,n}\right) * 100$$

Where:

CU = uniformity coefficient in percent

di = depth or volume of water collected in individual catch cans during irrigation

$\bar{d}$ = average depth or volume of water collected in all the catch-cans

n = total number of catch can data

The depth of water was calculated from the volumes collected in catch cans as,

$$\text{depth, di} = \frac{\text{volume collected in catch cans,ml} \times 10}{\text{cross-sectional area of the collecting cans,cm}^2}, \text{ mm}$$

(ii) Distribution uniformity,

$$DU = \frac{\text{Average low-quarter depth of water infiltrated (or caught)}}{\text{Average depth of water infiltrated (or caught)}} * 100$$

(iii) Actual application efficiency,

$$AELQ = \frac{\text{Average low-quarter depth of water infiltrated and stored}}{\text{Average depth of water applied by the sprinklers calculated from the measured discharge}} * 100$$

In this calculation, the average low-quarter irrigation depth infiltrated and stored in the root zone was taken as the average depth of the lowest one-fourth of the measured irrigation water collected in the catch cans.

(iv) Potential application efficiency,

$$PELQ = \frac{\text{average low-quarter depth of water infiltrated = MAD}}{\text{average depth of water applied}} * 100$$

The irrigation water collected in catch cans in the sprinkler performance tests are given in Appendix IV. This data was used in the above calculations with a sample calculation for test plot 396 given in Appendix V. The results of these calculations are presented in Table 8.

Table 8: Percentage sprinkler efficiencies

Plot No.	CU	DU	AELQ	PELQ	Application efficiencies
396	75	66	49	73	75
K.I.S.	84	80	63	70	68
1081	75	69	53	60	80
708	88	56	59	63	62
1313	66	55	64	73	60
735	79	69	65	77	76
360	66	61	47	51	63
405	72	55	80	83	73
499	86	78	43	51	66
554	79	69	52	67	70
565	75	64	63	66	65
1172	89	63	50	67	88
569	75	58	60	60	69
470	79	72	30	58	60
375	76	51	47	48	62
1217	73	66	60	66	68
703	70	54	55	63	70
61	70	61	60	74	65
482	85	77	63	66	82
329	*	*	*	*	*
Average	77	64	56	65	70

* Efficiency values were not calculated

For the test plot No. 329, the sprinklers were hardly rotating due to low pressure. The measured sprinkler discharge and operating pressure were very low compared to the others. There was no irrigation water collected in most of the catch cans during the test and consequently no uniformities could be calculated.

In this study, the Christiansen uniformity coefficients (CU) varied widely from 89 to 66 percent with an average of 77 percent. Only in five out of the 19 plots was the CU more than 80 percent. The CU values of less than 80 percentage in most of the plots according to Addink et al.(1983) signify poor distribution of water on the soil surface during irrigation. The wide variation in the calculated CU values was attributed largely to the variations in the operating pressures, widening of the sprinkler nozzles and high discharges. This is illustrated in the case of plot Nos. 1172 and 1313 which had the highest and lowest CU respectively. The respective operating pressures of 28 and 23 m. However, the discharge and nozzle sizes for these two plots were not significantly different.

The average calculated distribution uniformity was 64 percent. On average therefore the tests show that 36 percent of the irrigation water infiltrated into the soil is lost through deep percolation when the soil in the low-quarter area reaches field capacity level. This means also that when the irrigation application duration is designed to ensure that the soil in the low quarter area are irrigated to field capacity, the rest of the irrigation area becomes over-irrigated. This loss of irrigation water through deep percolation is quite much. Though there was no evidence of drainage problems either within the scheme area or in the surrounding areas due to the deep percolation losses, it could occur in the low lying areas in future. Nutrients also washed from the root zone by the deep percolation water if not replenished constantly would affect crop performance and lower the production of the scheme. To maintain soil fertility levels to sustain high yields with this percentage of deep percolation water during irrigation seasons is costly to the farmer because it requires seasonal additions of large amounts of fertilizers.

The average AELQ and PELQ found were 56 and 65 percent respectively. Ideally AELQ should equal PELQ for an irrigation system which is properly designed and with good water management practices. The difference between the values of PELQ and AELQ indicate that the irrigation application duration of 10 hours was too long and should be reduced. With the average sprinkler precipitation rate of 5.3 mm/h, an irrigation depth of 34.8 mm would be achieved with an application duration of 6.6 hours which is the irrigation duration when PELQ equals 100 percent. The average sprinkler application efficiency was 70 percent.

Though wind could blow the sprinkler spray in its prevailing direction and distort the wetting pattern and consequently lower the sprinkler efficiencies, it was not the case here. The wind speeds during the tests ranged from 0.5 m/s to 2.2 m/s with an average of 1.3 m/s. This speed range was low to distort the sprinkler spray because according to Addink et al.(1983), wind speeds below 2.2 m/s have little effect on sprinkler spray. The wind speed of 2.2 m/s is the limit above which the sprinkler spacings as recommended by the sprinkler manufacturers should be altered depending on that prevailing during irrigation. The design sprinkler spacings at Kibirigwi should remain as recommended in light of the measured wind speeds as they were less than 2.2 m/s in this study.

The low sprinkler performances was attributed to irregular rotational speeds of the sprinklers due to, broken or loose tension springs observed in most of the sprinkler heads, non-vertical sprinkler risers during irrigation, variations in operating pressures hence the differences in sprinkler discharges between the plots in the scheme. The irregular rotational speeds could be corrected by, replacing the worn out tension springs, use of correct nozzle sizes and operating the sprinklers at the manufacturers recommended pressures.

4.2.2 **Sprinkler parameters**

The measured sprinkler parameters were, discharges, nozzle sizes and sprinkler operating pressures. The percentage increase in sprinkler nozzle sizes were calculated. Results are shown in Table 9.

Table 9: Sprinkler parameters

Plot No.	lateral slope percent	operating pressure m	discharge l/s	sprinkler nozzle diameter, mm	nozzle area mm^2	percent increase in area	precipitation rate, mm/h Measured
708	5.9	30	0.33	4.28	14.39	13.5	5.5
1313	1.3	23	0.29	4.50	15.91	15.1	4.8
735	0.7	20	0.27	4.18	13.73	12.8	4.5
1081	0.9	38	0.35	4.48	15.77	15.0	5.8
360	2.4	52	0.41	4.00	12.57	11.6	6.8
405	0.9	18	0.25	4.33	14.70	13.9	4.2
499	0.8	28	0.41	4.25	14.19	13.3	6.8
396	5.4	25	0.29	4.20	13.86	13.0	4.8
554	0.5	30	0.31	4.43	15.42	14.6	5.2
565	0.8	38	0.32	4.45	15.56	14.8	5.3
1172	2.4	29	0.31	4.50	15.91	15.1	5.2
569	0.6	30	0.35	4.30	14.53	13.7	5.8
470	1.9	38	0.36	4.30	14.53	13.7	6.0
375	3.1	30	0.44	4.40	15.21	14.4	7.3
1217	0.5	20	0.32	6.30	31.19	151.9*	5.3
K.I.S	5.7	25	0.30	4.45	15.56	14.8	5.0
703	2.5	28	0.33	4.45	15.56	14.8	5.5
61	4.5	20	0.23	4.25	14.19	13.3	3.9
482	1.7	30	0.32	4.45	15.56	14.8	5.3
329	0.6	8	0.15	4.10	13.21	12.3	2.5
average	2.2	28	0.32	4.33	14.77	13.9	5.3

* In this particular plot, the designed Wright rain, Monitor model sprinkler nozzle sizes of 3.97 mm diameter were replaced with nozzles of 6.30 mm diameter. It was then not a representative nozzle in the scheme and was omitted in the above calculations of the averages.

4.2.2.1 **Sprinkler precipitation rates**

The sprinkler precipitation rates, SPR, were calculated from the measured discharge and sprinkler spacings as:

$$SPR = \frac{\text{discharge (l/s)} \times 3600}{\text{sprinklers irrigated area}(m^2)}, \text{ mm/hr}$$

Sprinkler irrigated area,
= Sprinkler spacing on lateral (18 m) * Lateral move (12 m)

The highest sprinkler precipitation rate in Table 9, was 7.3 mm/hr, the lowest 2.5 mm/hr and the average 5.3 mm/hr. The average precipitation rate was 15.2 percent more than the design precipitation rate of 4.6 mm/hr. The high precipitation rate results to a higher irrigation depth than the anticipated design depth for the same application duration. To apply the design irrigation depth the application duration has to be reduced by the same percentage.

The soil infiltration rates at a time equal to the irrigation application duration of 10 hours was compared with the sprinkler precipitation rates to check the sprinkler suitability to the soils. From Table 7 the lowest instantaneous infiltration rate at a time of 10 hours was 14.0 mm/hr. This was higher than the highest calculated sprinkler precipitation rate of 7.3 mm/hr. The sprinkler precipitation rates were therefore less than the final instantaneous infiltration rates of the soil for the design application duration. Ponding and consequently runoff during irrigation could not occur with this irrigation duration. The sprinklers were therefore suitable for use at the scheme.

4.2.2.2 **Sprinkler Nozzle Sizes**

The largest measured nozzle diameter was 4.50 mm and the smallest was 4.00 mm with an average of 4.33 mm. Since the original nozzle diameters were 3.97 mm, as inscribed on the sprinklers,it is clear that they had widened though to different extents. The increased diameters would give higher discharges for constant operating pressures since the discharge from a nozzle is directly proportional to the area.

The sprinkler nozzle areas were calculated as;

Area $= 22/7 * d^2/4$, mm^2

where,

d = measured diameter of the nozzle, mm.

The percentage increase in nozzle size,

$$= \frac{\text{measured area - area when supplied}}{\text{area when supplied}} * 100$$

The average calculated sprinkler nozzle area was 14.74 mm^2. This was an increase of 13.9 percent over the supply nozzle areas calculated from a diameter of 3.97 mm. This percentage increase represent the extent of nozzle wear for the 9 year period they had been in use at the scheme. The wear could be attributed to presence of sediments in the irrigation water. This was observed in most of the plots during the study where the irrigation water from the sprinklers was dirty. This was an indication that the filtration unit was inefficient in removing sediments from the river before the water was distributed for irrigation.

Regular maintenance of the filtration system could reduce the amount of sediments in the water, reduce the rate of nozzle wear and prolong their working life.

4.2.2.3 Sprinkler Operating Pressures

The measured sprinkler operating pressure head varied widely from 8 to 54 m with an average of 27 m. The designed operating pressure head was 28 m. The wide variation in the sprinkler operating pressures was suspected to distort the distribution of the spray consequently affecting their performance.

The hydraulic conditions at the sprinkler nozzle, the sprinkler rotation and air resistance met by the water after it leaves the nozzle govern the distribution of water over the field. Immediately after leaving the nozzle, gradual fragmentation of the water jet into drops starts due to turbulence, absence of a confining boundary and is enhanced by the air resistance and leads to forming even finer droplets. For a given discharge,q,the trajectory followed by the water is partly dependent on the velocity with which the water

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The big pressure range indicated that the pressure regulators in the irrigation conveyance and distribution network were not functioning as required to make the pressures uniform at the irrigation plots. Regular maintenance and calibration and where necessary replacement of the pressure regulators would correct the pressure imbalances in the irrigation pipe network. This is necessary to harmonise the performance of the sprinklers by operating them at the recommended pressures.

4.2.2.4 **Sprinkler Discharge**

The highest and lowest measured sprinkler discharges were 0.44 l/s and 0.15 l/s respectively. The average was 0.32 l/s while the design discharge was 0.28 l/s. The field lateral slopes ranged between 0.5 and 5.9 percent. These slopes were small to cause any notable differences in the measured sprinkler discharges within the irrigation plots. The variations in the sprinkler discharges within the irrigation plots was attributed to differences in the measured operating pressures and to some extent the enlarged sprinkler nozzle sizes. The measured pressures and discharges were in most cases different from those recommended by the manufacturers for the sprinkler type. Leakages in the pipe connections for the portable irrigation equipment in most plots and at the couplers to the sprinkler risers due to worn out seals was suspected to be a major cause of the losses in pressure and discharge.

For 270 irrigation plots in the scheme each operating two sprinklers simultaneously, the required average total scheme discharge,

= average sprinkler discharge * total sprinklers in the scheme

= 0.32 * 540 = 172.8 l/s.

Similarly, the design sprinkler discharge of 0.28 l/s require 150 l/s to irrigate the 270 plots. Of the 150 l/s gross design discharge, 10 l/s is allocated for domestic use in the scheme area (Bron,1979) leaving only 140 l/s for irrigation which is less than 172.6 l/s by 32.8 l/s.

With the average measured sprinkler discharge of 0.32 l/s and two sprinklers per plot, the number of irrigation plots affected by the shortage,

$$\text{Irrigation plots} = \frac{\text{discharge}}{\text{average sprinkler discharge} * \text{No. of sprinklers per plot operating simultaneously}}$$

$$= \frac{32.8}{0.32 * 2}$$

= 52 Irrigation plots.

The discharge of 140 l/s could therefore cater for irrigation of 218 plots out of the 270 which is 81 percent of the irrigated area.

With the multiple visual leakages in the irrigation distribution pipe network, mainly at the control valves, pipe junctions and connections of the portable irrigation equipments at the farmers plots, the actual percentage area irrigated with the net discharge was expected to be lower than 81 percent.

Though the gross scheme discharge as well as that in the hydrants was not determined due to lack of flow measuring equipments, it is necessary to quantify it in future.
The gross discharge for the scheme could be determined through calibration of the main-line at a suitable point below the settling tanks before the first sub-main take-off.

4.3 **Irrigation requirements**

Net irrigation, In = ETcrop - Re
where:
In = net irrigation requirement, mm/month
ETcrop = crop evapotranspiration requirement, mm/month
Re = effective precipitation for the area, mm/month

4.3.1 Crop evapotranspiration, ETcrop

Using the pan evaporation method, the recommended cropping pattern as shown in Table 10 and the pan evaporation data in Appendix VI, ETcrop was calculated as:

ETcrop = Kwc * Kp * Epan

Where:

Epan = average monthly pan evaporation, mm/month

Kp = pan coefficient (value of 0.75 was used)

Kwc = weighted crop factor in the crop season

Table 10: Kibirigwi Irrigation Scheme management recommended cropping pattern for the most grown crops

crop type	recommended growth period
Tomatoes	Dec. to Jun.
Capsicum	Jan. to Dec.
Onions	Jan. to Aug.
Cabbage	Jan. to Jun.

Weighted crop factors were calculated to have a representative value for the crop in the season.

$$\text{weighted crop factor, Kwc} = \frac{\text{Sum (Ki * Li)}}{\text{Sum (Li)}}$$

where:

Ki = crop factor at crop growth stage i

Li = length of crop growth stage i in days

As an example, the weighted crop factor for tomatoes in the growth season calculated from the values in Table 2,

$$Kwc = \frac{0.45*10 + 0.75*25 + 35*1.15 + 35*0.85}{10 + 25 + 35 + 35} = \frac{93.25}{105}$$

Kwc = 0.89

Similarly, the other weighted crop factors were calculated and are shown in Table 11.

Table 11: Average monthly ETcrop, mm/month, in the crop growth seasons

	Pan evaporation		Tomato	Cabbage	Onion	Capsicum
Month	mm/month	weighted crop factor	0.89	0.78	0.84	0.85
January	140		94	82	88	89
February	151		101	88	95	96
March	190		127	112	120	122
April	129		86	76	82	83
May	118		79	69	75	76
June	93		62	55	59	60
July	76				48	49
August	84				53	54
September	117					75
October	117					75
November	129					83
December	131		87			83

Where the crop seasons overlapped, the maximum average monthly ETcrop was selected as the critical value in the calculation of the scheme irrigation requirements.

4.3.2 **Effective Rainfall**

The mean monthly effective rainfalls was calculated by the United States Department of Agriculture, Soil Conservation Service empirical method shown in Table 1. In this calculation the mean total monthly rainfall in Appendix VI and weighted monthly ETcrop in Table 11 were used.

For example, in January, with a total average monthly rainfall of 18 mm and a weighted mean total monthly ETcrop of 94 mm and interpolating between the mean monthly total rainfall values of 12.5 and 25.0 mm the ETcrop values of 75 and 100 mm, the effective rainfall was found to be 13 mm/month. Similarly the other monthly effective rainfalls were calculated and are shown in Table 12. With the monthly ETcrop and the effective rainfall values, the net monthly irrigation requirements were determined as the difference of these two values.

Table 12: Monthly net irrigation, mm/month, for Kibirigwi scheme

Month	Total average monthly rainfall,mm	Calculated effective monthly total rainfall,mm	monthly average ETcrop, mm	Net irrigation mm
January	18	13	94	81
February	16	11	101	90
March	106	76	127	51
April	300	139	86	-
May	274	128	79	-
June	68	44	62	18
July	48	32	51	19
August	49	33	54	21
September	40	28	75	47
October	122	74	75	0
November	224	170	83	-
December	67	48	87	39

Where the mean total monthly effective rainfall exceeded the ETcrop value, there was no need for irrigation.

From Table 12,the peak irrigation demand for the scheme occurs in the month of February where

IR = ETcrop - effective rainfall

= 101 - 11

= 90 mm/month

= 3.2 mm/day

With this value of net irrigation the gross scheme discharge would be given as:

$$Q = \frac{IR}{8.64} * \frac{1}{E_f} * \frac{24}{HPD} * \frac{7}{DPW} * A$$

Where:

Q = gross irrigation scheme discharge, l/s

IR= net irrigation requirement,mm/day (3.2 mm/day)

E_f= irrigation efficiency (70 percent)

HPD = hours of irrigation application per day (10)

DPW = irrigation days per week (7)

A = area irrigated, hectares (100)

The hours of irrigation per day (HPD), irrigation days per week (DPW) and the irrigated area are the design values.

For an application efficiency of 70 percent,

$$Q = \frac{3.2 * 24 * 7 * 1 * 100}{8.64 * 10 * 7 * 0.70}$$

$$= 127 \text{ L/s}$$

This is the discharge required when irrigation is done only during the day as preferred by the farmers. However, longer irrigation durations, need less discharge, for example, an average irrigation duration of 20 hours per day require discharge of 64 l/s at the critical month assuming that the other parameters remain unchanged.

The discharge required in the critical month is less than the scheme design disharge of 140 l/s. The design discharge could adequately cater for the crop water requirement in the scheme if the design recommendations are followed and losses avoided.

However, when recommendations (cropping pattern, irrigation interval and application duration) are ignored and with poor maintenance of the irrigation system resulting to low efficiencies, the required scheme discharge is much higher than 127 l/s and the present supply would be inadequate.

4.4 **Irrigation schedule**

The irrigation schedule given here was based on the recommended cropping pattern in Table 10, the soil moisture holding capacities, the crop root depths and the sprinkler application rates found in this study.

4.4.1 **Irrigation application durations**

Irrigation application duration, hr

$$= \frac{\text{Root depth (m)} * \text{soil moisture depth replenished at irrigation, MAD, (mm/m)}}{\text{sprinkler application rate (mm/h)} * \text{application efficiency}}$$

The root depths in Table 13 are from the data given in Appendix VII on root distribution in the soil.

Table 13: Crop average root depths, determined at Kibirigwi

crop type	root depth,m
Tomatoes	1.0
Capsicum	0.7
Onions	0.3
Cabbage	0.4

These root depths were shallow compared to those in Doorenbos and Pruitt (1977) for the same crops probably due to the nature of the soils in the scheme area or due to irrigation practices at the scheme which might have affected root development. They however gave an indication of the root depths in the area.

With MAD of 34.8 mm/m, average sprinkler application rate of 5.7 mm/h, sprinkler application efficiency of 70 percent and the crop root depths, the irrigation depths and application durations in Table 14 were calculated.

For example;

tomatoes with average roots depth of 1.0 m (Table 13),

Irrigation application duration

$$= \frac{34.8 \times 1.0}{5.3 \times 0.71} = 9.4$$

$= 9$ hours (say)

Irrigation depth,
= root depth (m) x soil moisture deficit (mm/m)
= 1.0 x 34.8
= 34.8 = 35 mm (say)

Table 14: Calculated Irrigation Water Application Durations, hours, for the four mostly grown crops

crop	Average root depth, (m)	Irrigation depth (mm)	Application duration (hrs)
Tomatoes	1.0	35	9
onions	0.3	11	3
Cabbage	0.4	14	4
Capsicum	0.7	25	7

These irrigation durations range from 3 to 9 hours per day. They are then likely to be accepted by the farmers because as observed, most farmers preferred irrigating during the day due to social problems at night.

The PELQ for the individual crops calculated as already shown in the sample calculation (Appendix V), and using the root and irrigation depths, average sprinkler application rate of 5.3 mm/h and application durations in table 15 are presented below.

Table 15: Calculated PELQ with recommended irrigation application durations and MAD for the four mostly grown crops in the scheme

Crop	Recommended irrigation application duration,h	Root depth	MAD mm	PELQ %
Tomatoes	9	1.0	34.8	73.0
Onions	3	0.3	10.4	65.7
Cabbage	4	0.4	13.9	65.7
Capsicum	7	0.7	24.4	65.7

From the table, PELQ decreased slightly with the crop root depth but this change was not significant as seen from the case of onions with an application duration of 3 hours and tomatoes with 9 hours duration and PELQ values of 65.7 and 73.0 percent respectively.

4.4.2 **Irrigation intervals**

$$\text{irrigation interval} = \frac{\text{soil moisture deficit to replenish, MAD} * \text{crop root depth}}{\text{ETcrop}},$$

with MAD of 34.8 mm/m depth, root depths in Table 13 and ETcrop values in Table 11, the irrigation intervals in Tables 16, 17, 18 and 19 were calculated.

Table 16: Irrigation intervals for Tomatoes

Period of year	ETcrop		Irrigation Interval
	mm/month	mm/day	days
December	87	2.8	12
January	94	3.1	11
February	101	3.6	10
March	127	4.1	-
April	86	2.9	-
May	79	2.6	13
June	62	2.1	16
Average			12

In tables 16, 17, 18, and 19, the daily ETcrop values are calculated by dividing the monthly ETcrop values by the number of days in that month. The months considered in the calculations are those within the crops growth seasons.

Tables 14 and 16 show that the application duration for tomatoes is 9 hours and an average irrigation interval of 12 days. At the peak season with an extraction rate of 3.6 mm/day in February, the irrigation interval is 9.6 days or just 10 days. This is the minimum interval for the peak irrigation demand. During the other non peak months, the longest irrigation interval in July is 20 days or three weeks.

Table 17: Irrigation intervals for Capsicum

Period of year	ETcrop		Irrigation Interval
	mm/month	mm/day	days
January	89	2.9	8
February	96	3.4	7
March	122	4.0	6
April	83	2.8	-
May	76	2.5	-
June	60	2.0	12
July	49	1.6	15
August	54	1.8	13
September	75	2.5	9
October	75	2.5	9
November	83	2.8	-
December	83	2.8	8
Average			9

From tables 14 and 17, the average irrigation interval for capsicum was found to be 9 days at an average irrigation duration of 7 hours.

Table 18: Irrigation intervals for Onions

Period of year	ETcrop		Irrigation Interval
	mm/month	mm/day	days
January	88	2.8	4
February	95	3.4	3
March	120	4.0	3
April	82	2.7	-
May	75	2.5	-
June	59	2.0	5
July	48	1.6	7
August	53	1.8	6
Average			5

For onions average irrigation interval and application durations were 5 days and 3 hours as shown in tables 14 and 18 respectively.

Table 19: Irrigation intervals for Cabbage

Period of year	ETcrop		Irrigation Interval
	mm/month	mm/day	days
January	82	2.7	5
February	88	3.1	5
March	112	3.7	4
April	76	2.5	-
May	69	2.3	-
June	55	1.8	7
Average			5

The average irrigation interval and application duration for cabbage, given in tables 14 and 19, was on average 3 hours and 5 days respectively.

In general, these irrigation intervals showed that onions and cabbage with shallow roots require shorter irrigation intervals as opposed to tomatoes and capsicum with deeper roots.

Compared with the scheme recommended irrigation practices of an irrigation interval of 7 days and application duration of 10 hours for all the crops irrespective of the growing season (Mugwanja and Mwangi, 1987). Tomatoes and capsicum were being over-irrigated but onions and cabbage requiring short application durations and frequent irrigations were subjected to water stress when irrigated at intervals of 7 days. The application duration of 10 hours for cabbage and onions as opposed to the 4 and 3 hours required for the crops led to water losses through deep percolation.

The irrigation schedule (Tables 14, 16, 17, 18 and 19) show that a generalised irrigation interval and application duration disregarding the type of crop, its stage of growth and growing season either results in under or excessive irrigation both of which could affect crop performance. However, the irrigation schedule proposed here requires that

Table 19: Irrigation intervals for Cabbage

Period of year	ETcrop mm/month	ETcrop mm/day	Irrigation Interval days
January	82	2.7	5
February	88	3.1	5
March	112	3.7	4
April	76	2.5	-
May	69	2.3	-
June	55	1.8	7
Average			5

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The irrigation schedule (Tables 14, 16, 17, 18 and 19) show that a generalised irrigation interval and application duration disregarding the type of crop, its stage of growth and growing season either results in under or excessive irrigation both of which could affect crop performance. However, the irrigation schedule proposed here requires that the farmers keep proper records of irrigation dates in the seasons for the different crops. This is because it is different from the generally recommended interval of 7 days and application duration of 10 hours, the farmers are used to, for all the crops irrespective of the growing seasons. In terms of the scheme operation, the irrigation schedule necessitates that the scheme management educate the farmers on the need to irrigate only when necessary.

The farmers should be made aware that deep percolation losses resulting from over-irrigation is likely to leach the nutrients from the crop root zones and consequently lowering soil fertility. To maintain the soil fertility at required levels for good crop performance with unnecessary leaching is costly and it lowers the farmers profits margins. It also poses the danger of waterlogging in the low lying areas within and in the surroundings of the irrigated area.

4.5 **River flow analysis**

The river flow data in Appendix V1II, were ranked in descending order and the percent of time discharge was exceeded calculated (Table 20) and the flow duration curve plotted (fig.7).

Table 20: Flow frequencies over an 18 year period for Ragati river at R.G.S., 4BB1

Monthly daily mean discharge m^3s^{-1}	frequency	Cummulative frequency	percentage cummulative frequency
over 19.0	2	2	0.9
17.0 - 19.0	3	5	2.3
15.0 - 17.0	1	6	2.8
13.0 - 15.0	2	8	3.7
11.0 - 13.0	3	11	5.1
9.0 - 11.0	6	17	7.9
7.0 - 9.0	11	28	13.0
6.0 - 7.0	2	30	13.9
5.0 - 6.0	12	42	19.4
4.0 - 5.0	19	61	28.2
3.0 - 4.0	16	77	35.7
2.8 - 3.0	9	86	39.8
2.5 - 2.8	16	102	47.2
2.2 - 2.5	17	119	55.1
2.0 - 2.2	8	127	58.8
1.8 - 2.0	15	142	65.7
1.6 - 1.8	12	154	71.3
1.4 - 1.6	12	166	76.9
1.2 - 1.4	18	184	85.2
1.0 - 1.2	10	194	89.8
0.8 - 1.0	10	204	94.4
0.6 - 0.8	8	212	98.2
below 0.6	4	216	100

From the flow duration curve, fig. 7, the flow with exceedance probability of 80 percent used in the design of irrigation systems is 1.5 m^3/s.

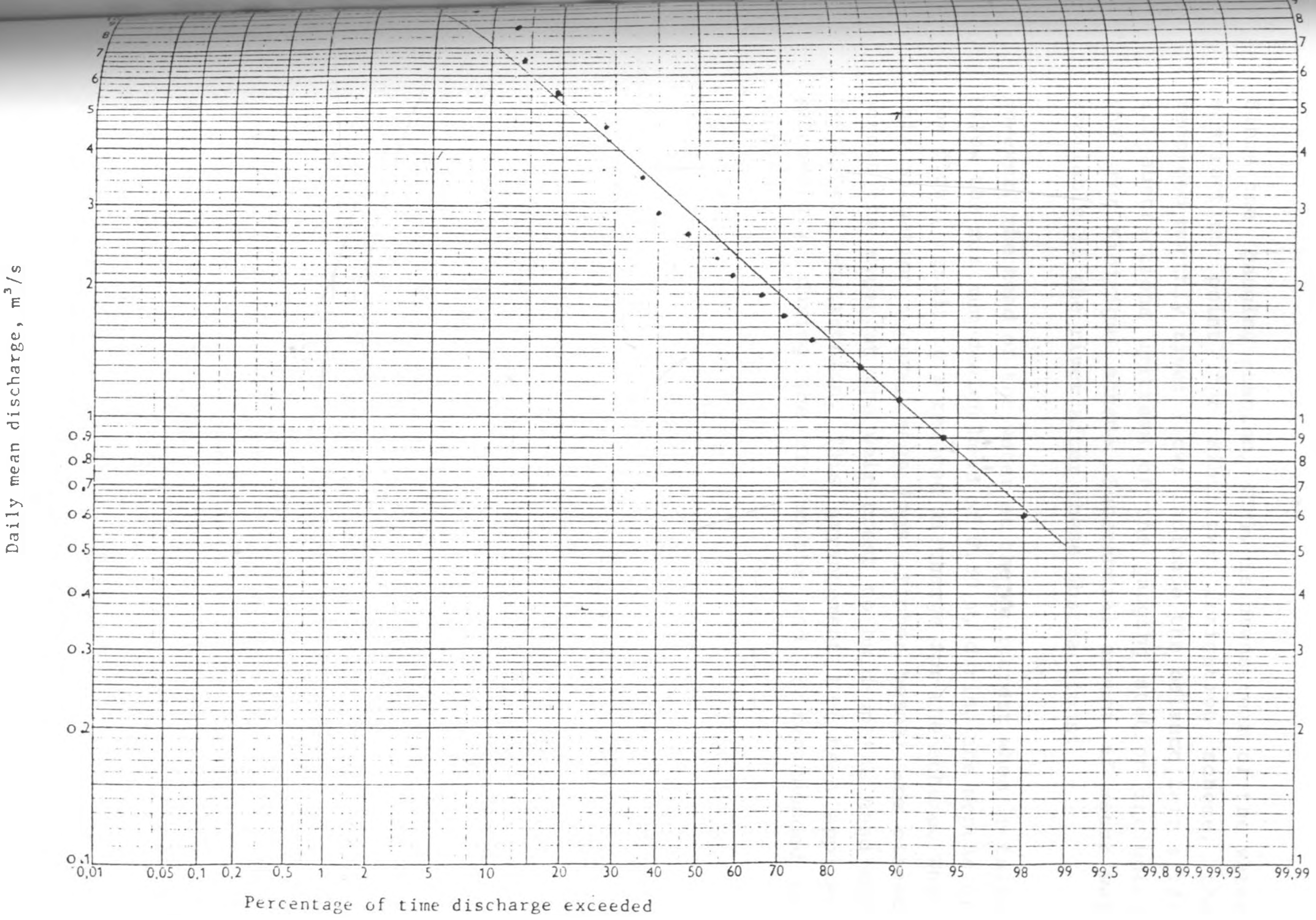

Fig.7 Flow duration curve for Ragati river at R.G.S. 4BB1

Since the gauging station, 4BB1, is downstream of the water abstraction point for Kibirigwi irrigation scheme, the recorded monthly river flows indicate the balance left after all abstractions upstream of the gauging station including that for Kibirigwi scheme. Substantial amount of water was available in the river after these abstractions.

However, the head of the water at the weir crest when it falls below the minimum design head of 0.30 m, during the months of low flows, result to a reduced discharge for the scheme. When this situation occurs, stop logs (Timber beams) are placed across the river at the weir crest to buid-up the head and facilitate abstraction. This arrangement has been applied successfully during the dry months and is recommended to continue.

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5. Conclusions and Recommendations

The following conclusions and recommendations are drawn from this study:

The sprinklers used in the irrigation scheme were suited to the soils in the scheme. This was because the final instantaneous infiltration rate for the soil at the design irrigation application of 10 hours was 14.0 mm/h which was much more than the highest calculated sprinkler precipitation rate of 7.3 mm/h. There was then no risk of ponding and consequent runoff during irrigation with this application duration.

The Christiansen uniformity coefficient (CU) was found to vary from 89 to 66 percent with an average of 77 percent. Only in 5 out of the 19 plots was the CU more than 80 percent. The low CU in most of the plots signify poor distribution of water on the soil surface during irrigation.

The average distribution uniformity (DU) was 64 percent. On average therefore when the soil just attains field capacity in the in the low quarter area, 36 percent of the water infiltrated into the soil in the rest of the sprinkler irrigated area is lost through deep percolation. This percentage loss is undesirably high. To maintain soil fertility levels for sustained high yields with this amount of deep percolation would be costly due to the constant washing of nutrients from the root zones. The average application efficiency of the low-quarter (AELQ) and potential efficiency of the low-quarter (PELQ) were 56 and 65 percent respectively. The difference between these showed that the management of the irrigation water in the scheme could be improved by reducing the design application duration of 10 hours. The average sprinkler application efficiency was 70 percent which is not low. The low and variable CU, DU and AELQ within the scheme was attributed to variations in sprinkler operating pressures and discharges within the scheme, widened sprinkler nozzle diameters and the irregular rotational speeds of the sprinklers due to broken or loose tension springs at the sprinkler heads. The low parameters were not attributed to the prevailing wind speeds in the area during irrigation as these were found to conform with manufacturers' recommendations for the measured speeds.

The sprinkler operating pressure heads varied widely from 8 to 54 m with an average of 28 m. There was no pattern of this variation in the scheme layout where-else from the upstream to the tail end of the scheme. Maintenance, calibration and regular servicing of the pressure regulators would correct the pressure imbalances in the system for the sprinklers to operate at nearly the same pressures.

The measured sprinkler discharges ranged from 0.15 to 0.44 l/s with an average of 0.32 l/s. To operate all the 540 sprinklers in the scheme simultaneously requires a total discharge of 172.8 l/s against the net design discharge of 140 l/s. 52 plots out of the total 270 plots in the scheme would therefore experience water shortage when all the sprinklers are operated at the same time. The multiple visual leakages in the irrigation distribution network, mainly at the control valves, pipe junctions, hydrants and connections of the portable irrigation equipments at the farmers plots, contributes significantly to the pressure and discharge losses in the system. These losses are due to worn out seals at the valves, broken pipes and loose pipe connections should be repaired and where necessary replaced.

The measured average sprinkler nozzle diameter was 4.33 mm. This represented an enlargement of 9.1 percent over the supply nozzle sizes of 3.97 mm diameter. The wear was attributed to the presence of sediments in the irrigation water.

Regular maintenance of the filtration system would reduce the amount of sediments in the irrigation water and reduce the rate of nozzle wear and prolong their working life. The excessively worn out nozzles should be replaced.

The rotational speeds could be corrected by replacing the worn-out springs, adjusting the tension of the loose ones and repairing and or replacing the malfunctioning pressure regulators in the irrigation system.

Crop water demand in the critical month required a discharge of 127 l/s. This should be met by the design discharge of 140 l /s. The complaints of water shortages in the scheme was then due to losses in the irrigation system due to poor maintenance of the system.

The recommended irrigation practices of an irrigation interval of 7 days and application duration of 10 hours for all the crops irrespective of the growing season resulted in over-irrigation of tomatoes and capsicum. Onions and cabbage requiring short application durations and frequent irrigations (tables 14, 18 and 19) were hence subjected to water stress. The application duration of 10 hours for cabbage and onions as opposed to the 4 and 3 hours required for the two crops respectively (table 14) leads to water losses through deep percolation because of the long irrigation duration.

In summary, the differences between the calculated values of AELQ and PELQ indicate there is potential for improving the performance of Kibirigwi scheme. The following irrigation schedule on average are therefore recommended: Tomatoes, irrigation application duration of 9 hours and interval of 12 days; for onions an irrigation application duration of 3 hours and an interval of 5 days; cabbage irrigation duration of 4 hours and an interval of 5 days while capsicum irrigation interval is 7 hours and interval of 9 days.

Since the irrigation schedule proposed for the various crops deviates from the general irrigation recommendations for the scheme, it is necessary that the farmers be educated on the need to irrigate only when necessary.

The 80 percent exceedance probability discharge for Ragati river at R.G.S. 4BB1 was 1.5 m^3/s. Because this gauging station is downstream of Kibirigwi irrigation water intake, the river had substantial discharge remaining all the year round with all the upstream abstractions.
The flactuations of the head of the water at the weir crest affect the discharge abstracted from the river and cause shortage of irrigation water for the scheme when it falls below the minimum design head of 0.30 m. Putting stop logs (Timber beams) across the river course at the weir crest to

build-up the water levels to facilitate abstraction solves this temporary problem. The gross irrigation discharge to the scheme as well as that in the Submains were not measured due to lack of flow measuring equipments. These should be measured periodically through calibration of the pipelines and especially the main-line just after the location of the settling tanks before the first sub-main take-off. Calibration of the main pipeline could be undertaken by the Kenya Bureau of Standards.

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APPENDICES

Appendix I: Soil Moisture Retention Data

(a) Soil Moisture retention data (%w/w) for Kibirigwi Soils sampled at 0 - 15 cm depth

	pF 2.3 (0.2 bar)				pF 4.2 (15bar)			
	Sampling sites				Sampling sites			
Plot No.	1	2	3	Average	1	2	3	Average
61	25.7	27.7	25.2	26.2	18.2	21.1	19.8	19.7
324	34.8	32.4	31.8	33.0	24.7	25.3	25.0	25.0
329	34.2	31.1	33.0	32.9	19.6	20.7	23.6	21.3
346	33.8	34.6	35.7	34.7	27.5	25.5	26.5	26.5
375	30.2	30.4	30.3	30.3	22.6	21.8	22.2	22.2
396	32.8	31.6	33.1	32.5	22.6	23.3	25.8	23.9
405	33.7	34.6	35.2	34.5	25.0	24.2	25.5	24.9
470	29.2	32.0	32.4	31.2	23.3	24.0	23.8	23.7
676	32.7	31.8	33.0	32.5	22.0	21.5	22.5	22.0
482	31.1	29.4	32.2	30.9	24.0	23.4	22.8	23.4
499	32.9	30.5	34.4	32.6	24.0	25.0	23.0	24.0
531	30.9	29.3	30.1	30.1	23.4	22.3	22.1	22.6
554	30.3	29.2	32.3	30.6	24.7	24.0	27.8	25.5
360	31.3	33.7	31.0	32.0	23.6	22.7	23.3	23.2
565	31.3	33.0	32.6	32.3	23.3	23.1	24.4	23.6
569	32.4	31.0	32.6	32.0	23.9	25.1	23.0	24.0
703	31.8	30.4	32.6	31.6	24.0	24.9	25.2	24.7
708	34.2	33.0	32.4	33.2	23.9	22.2	21.7	22.6
735	32.4	31.6	32.0	32.0	23.7	24.1	23.6	23.8
1081	31.8	30.5	29.8	30.7	22.7	21.6	22.3	22.2
1172	30.7	33.0	32.3	32.0	23.1	23.2	23.9	23.4
1217	32.7	31.0	31.1	31.6	23.1	24.2	24.4	23.9
1313	32.8	30.7	30.1	31.2	23.5	23.9	24.3	23.9
K.I.S	32.6	31.5	34.3	32.8	26.8	23.9	23.7	24.8

(b) Soil Moisture retention data (%w/w) for Kibirigwi Soils sampled at 40 - 50 cm depth

	pF 2.3 (0.2 bar)				pF 4.2 (15bar)			
	Sampling sites				Sampling sites			
Plot No.	1	2	3	Average	1	2	3	Average
61	30.3	28.0	30.8	29.7	23.7	21.7	23.3	22.9
324	38.2	37.8	38.6	38.2	28.6	29.2	28.9	28.9
329	28.2	29.4	29.6	29.1	20.0	19.2	20.2	19.8
346	35.2	37.7	36.6	36.5	28.3	27.4	28.0	27.9
375	35.1	34.1	33.1	34.1	25.7	24.5	25.1	25.1
396	35.5	36.8	37.8	36.7	28.1	28.8	28.3	28.4
405	35.5	34.9	34.9	35.1	25.5	26.0	23.8	25.1
470	35.5	38.0	36.9	36.8	28.4	27.5	28.1	28.0
676	33.2	28.2	334	31.6	23.4	24.5	25.0	24.3
482	37.0	37.0	36.7	36.9	28.5	28.2	26.7	27.8
499	35.3	36.2	35.6	35.7	25.7	26.9	27.5	26.7
531	35.1	35.5	34.7	35.1	27.4	27.3	25.1	26.6
554	35.1	36.0	34.2	35.1	27.9	28.6	26.6	27.7
360	37.3	37.7	36.0	37.0	27.6	26.2	27.2	27.0
565	37.5	36.3	37.2	37.0	27.7	28.0	26.8	27.5
569	33.4	35.0	31.2	33.2	26.8	25.8	24.5	25.7
703	34.1	36.0	36.4	35.5	26.7	27.2	25.9	26.6
708	34.0	35.2	33.7	34.3	24.6	23.8	24.5	24.3
735	34.2	33.6	36.3	34.7	26.0	25.5	26.5	26.0
1081	33.7	31.8	31.4	32.3	25.1	24.0	23.8	24.3
1172	33.6	33.8	33.4	33.6	26.8	27.6	25.7	26.7
1217	35.4	35.9	35.5	35.6	28.1	27.8	27.8	27.9
1313	34.0	32.7	33.2	33.3	25.3	25.0	26.5	25.6
K.I.S	34.5	33.0	32.7	33.4	26.6	27.0	26.8	26.8

Appendix II. Soil Texture Data

Mechanical analysis of soil texture

Plot no.	% sand	% silt	% clay	Texture grade
61	34	10	56	clay
324	18	24	58	clay
329	36	20	44	clay
346	16	24	60	clay
375	16	26	58	clay
396	16	24	60	clay
405	24	26	50	clay
470	16	22	62	clay
676	18	22	60	clay
482	24	26	50	clay
499	18	20	62	clay
531	20	22	58	clay
554	20	26	54	clay
360	20	22	58	clay
565	20	24	56	clay
569	18	22	60	clay
703	20	18	62	clay
708	26	26	48	clay
735	20	24	56	clay
1081	24	24	52	clay
1172	20	30	50	clay
1217	24	24	52	clay
1313	20	22	58	clay
K.I.S.	18	16	66	clay

These soil samples analysed for texture were collected at 40-50 cm depths.

Appendix III: Infiltration Tests Data

A. Infiltration data for plot Nos. 346 and 569.

On plot No. 346		On plot No. 569	
Elapsed time, minutes	Cumulative infiltration depth, Icum, cm.	Elapsed time, minutes	Cumulative infiltration depth, Icum, cm.
0.4	1.0	1.1	3.0
1.2	2.0	2.8	5.0
2.5	3.0	5.5	7.0
4.4	4.0	9.3	9.0
6.9	5.0	14.0	10.5
10.1	6.0	20.2	14.0
13.7	7.0	26.9	15.0
18.0	8.0	34.2	16.0
22.8	9.0	42.0	17.0
28.1	10.0	50.5	17.5
34.1	11.0	60.1	18.0
40.7	12.0	70.2	20.5
48.0	13.0	81.3	21.5
55.9	14.0	106.4	22.5
65.4	15.0	119.5	24.0
74.5	16.0	133.7	25.0
84.3	17.0	149.1	28.0
94.8	18.0	166.0	30.0
105.8	19.0	184.0	32.0
117.6	20.0	202.7	33.0
130.1	21.0	233.6	35.0
143.2	22.0	243.1	38.0
156.9	23.0		
171.3	24.0		
186.3	25.0		
202.1	26.0		
218.6	27.0		
235.8	28.0		
253.8	29.0		

B. Infiltration data for plot Nos. K.I.S. and 324.

On plot K.I.S.		On plot No. 324	
Elapsed time, minutes	Cumulative infiltration depth, Icum, cm.	Elapsed time, minutes	Cumulative infiltration depth, Icum, cm.
1.0	1.0	1.4	3.0
1.6	2.0	3.6	4.0
4.9	3.0	6.8	5.0
9.3	4.0	10.3	5.5
14.1	5.0	15.0	7.5
16.3	5.5	20.6	8.0
22.1	6.5	26.7	8.5
27.6	7.5	33.2	9.0
33.6	8.5	40.6	10.0
39.0	9.5	49.4	10.5
42.0	10.0	58.9	11.5
48.2	11.0	69.3	12.5
54.6	12.0	80.1	14.0
61.7	13.0	91.9	15.0
68.8	14.0	104.0	16.0
76.7	15.0	117.5	16.5
84.8	16.0	131.8	17.0
		146.4	18.5
		162.3	19.0
		178.7	20.5
		196.5	21.0
		217.4	24.0
		238.9	25.0

B. Infiltration data for plot Nos. K.I.S. and 324.

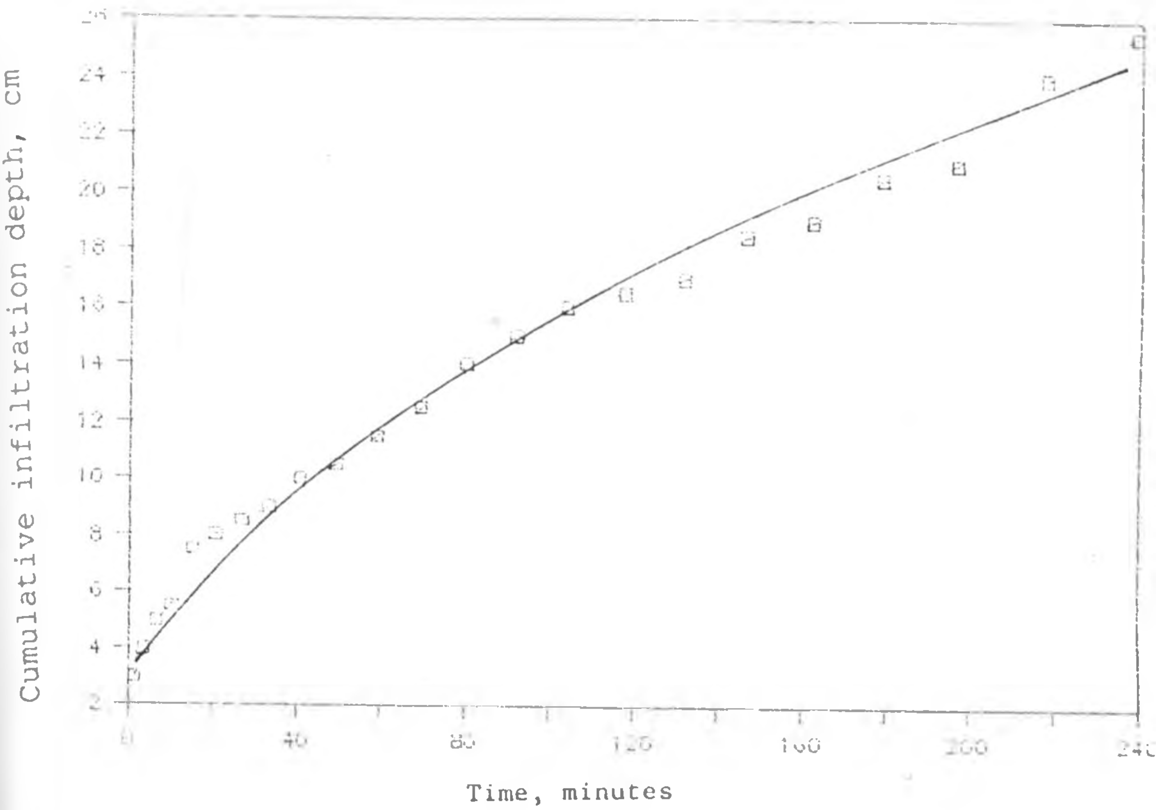
On plot K.I.S.		On plot No. 324	
Elapsed time, minutes	Cumulative infiltration depth, Icum, cm.	Elapsed time, minutes	Cumulative infiltration depth, Icum, cm.
1.0	1.0	1.4	3.0
1.6	2.0	3.6	4.0
4.9	3.0	6.8	5.0
9.3	4.0	10.3	5.5
14.1	5.0	15.0	7.5
16.3	5.5	20.6	8.0
22.1	6.5	26.7	8.5
27.6	7.5	33.2	9.0
33.6	8.5	40.6	10.0
39.0	9.5	49.4	10.5
42.0	10.0	58.9	11.5
48.2	11.0	69.3	12.5
54.6	12.0	80.1	14.0
61.7	13.0	91.9	15.0
68.8	14.0	104.0	16.0
76.7	15.0	117.5	16.5
84.8	16.0	131.8	17.0
		146.4	18.5
		162.3	19.0
		178.7	20.5
		196.5	21.0
		217.4	24.0
		238.9	25.0

C. Calculation of Instantaneous infiltration rates

Sample calculation of instantaneous infiltration rate using cumulative infiltration data for test plot 569.

Elapsed Time, min.	cumulative infiltration depth, cm	change in infiltration time, min.	Infiltrated depth cm	Instantaneous infiltration rate, cm/min.
1.1	3.0	-	-	-
2.8	5.0	1.7	2.0	1.18
5.5	7.0	2.7	2.0	0.74
9.3	9.0	3.8	2.0	0.53
14.0	10.0	4.7	1.0	0.21
20.2	14.0	6.2	4.0	0.65
26.9	15.0	6.7	1.0	0.15
34.2	16.0	7.3	1.0	0.14
50.5	17.0	7.8	1.0	0.13
60.1	18.0	16.3	1.0	0.06
70.2	20.5	10.1	1.5	0.15
81.3	21.5	11.1	1.0	0.09
106.4	22.5	25.1	1.0	0.04
119.5	24.0	13.1	1.5	0.11
133.7	25.0	14.2	1.0	0.07
149.1	28.0	15.4	3.0	0.19
166.0	30.0	16.9	2.0	0.12
184.0	32.0	18.0	2.0	0.11
202.7	33.0	18.7	1.0	0.05
233.6	35.0	30.9	2.0	0.06
243.1	38.0	9.5	3.0	0.32

III D.



ig. AIII-8: Cumulative infiltration depth versus time for test plot 324

III E.

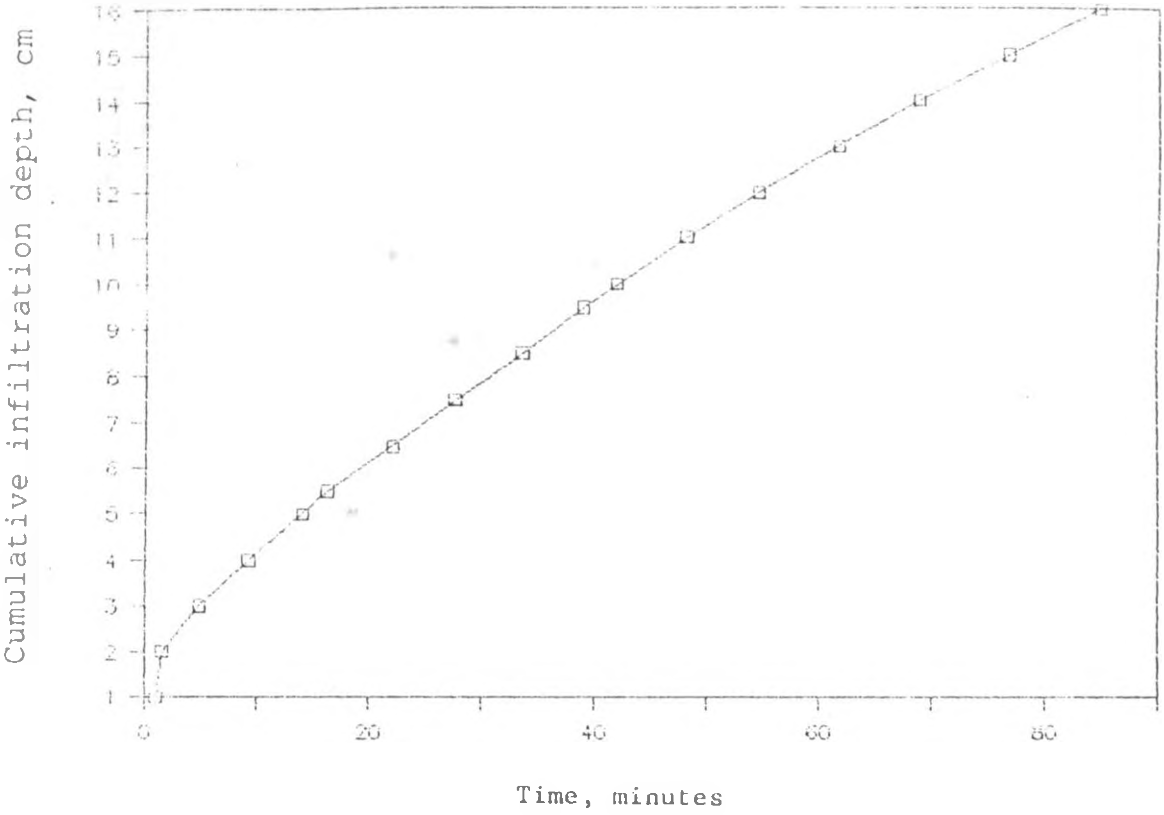


Fig. AIII-9: Cumulative infiltration depth versus time for test plot K.I.S.

III F.

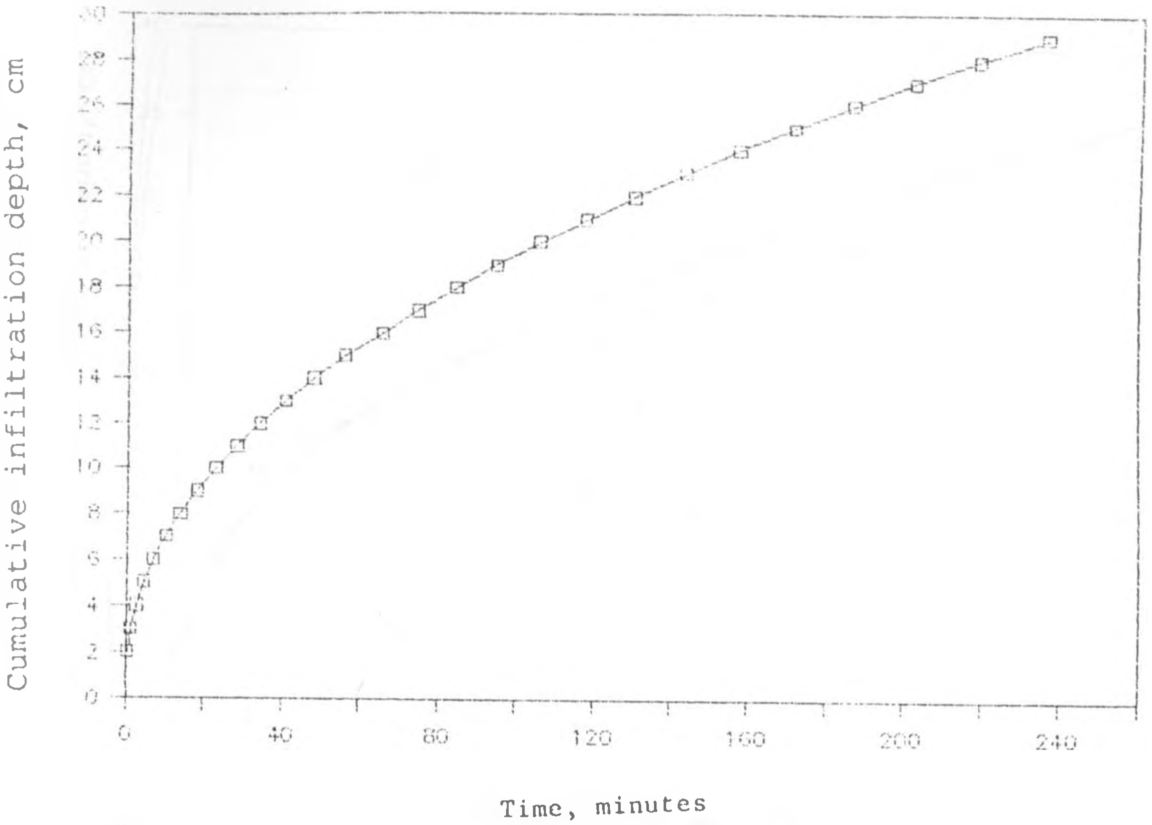


Fig. AIII-10: Cumulative infiltration depth versus time for test plot 346

III G.

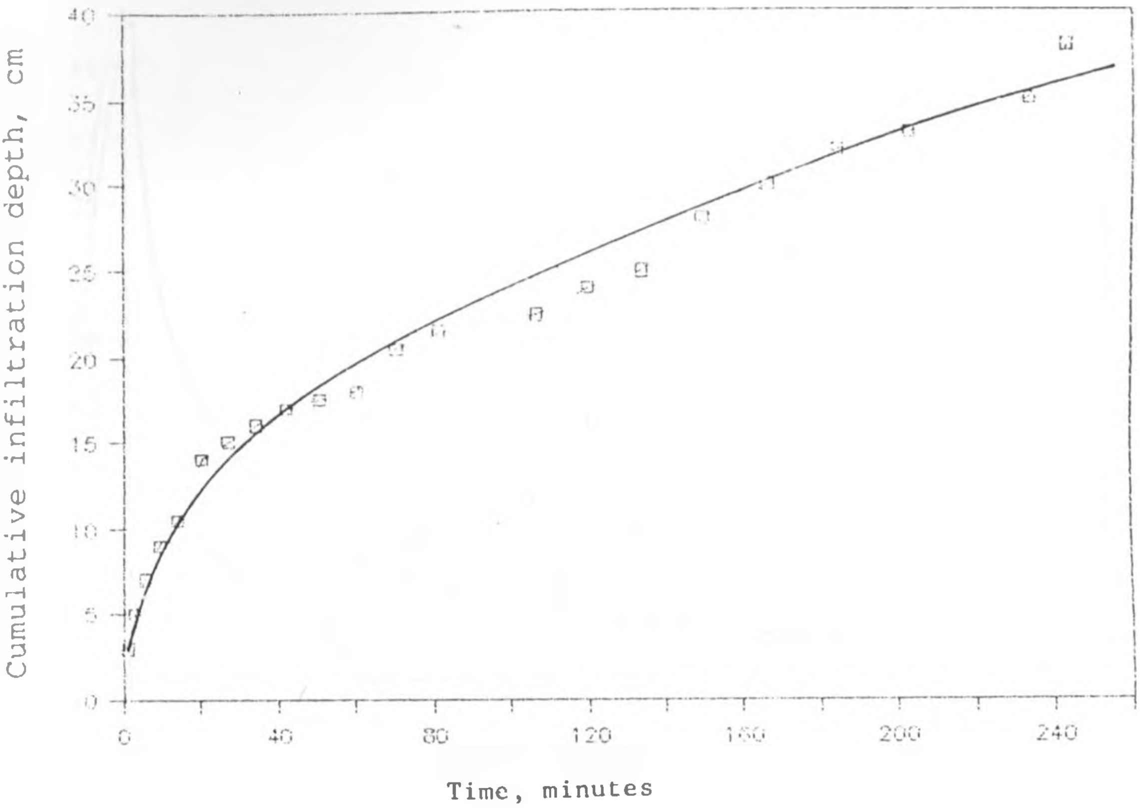


Fig. AIII-11: Cumulative infiltration depth versus time for test plot 569

III H.

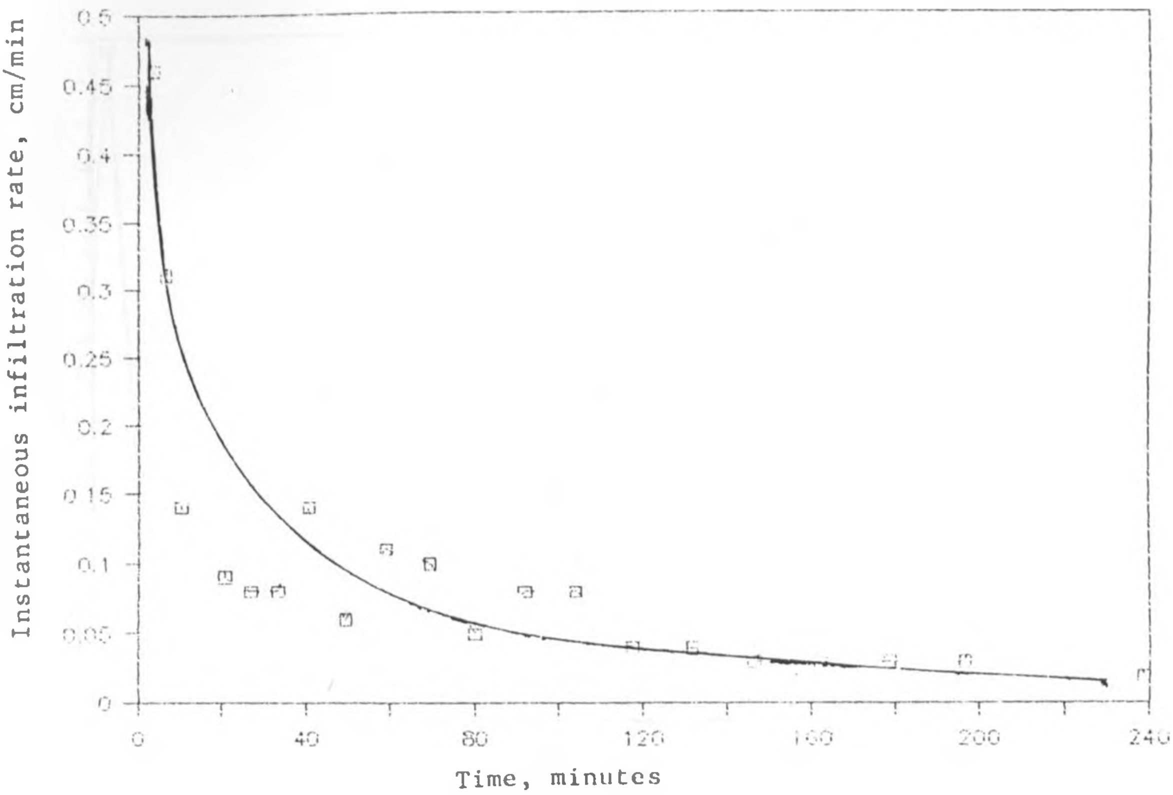


Fig. AIII-12: Instantaneous infiltration rate versus time for test plot 324

III J.

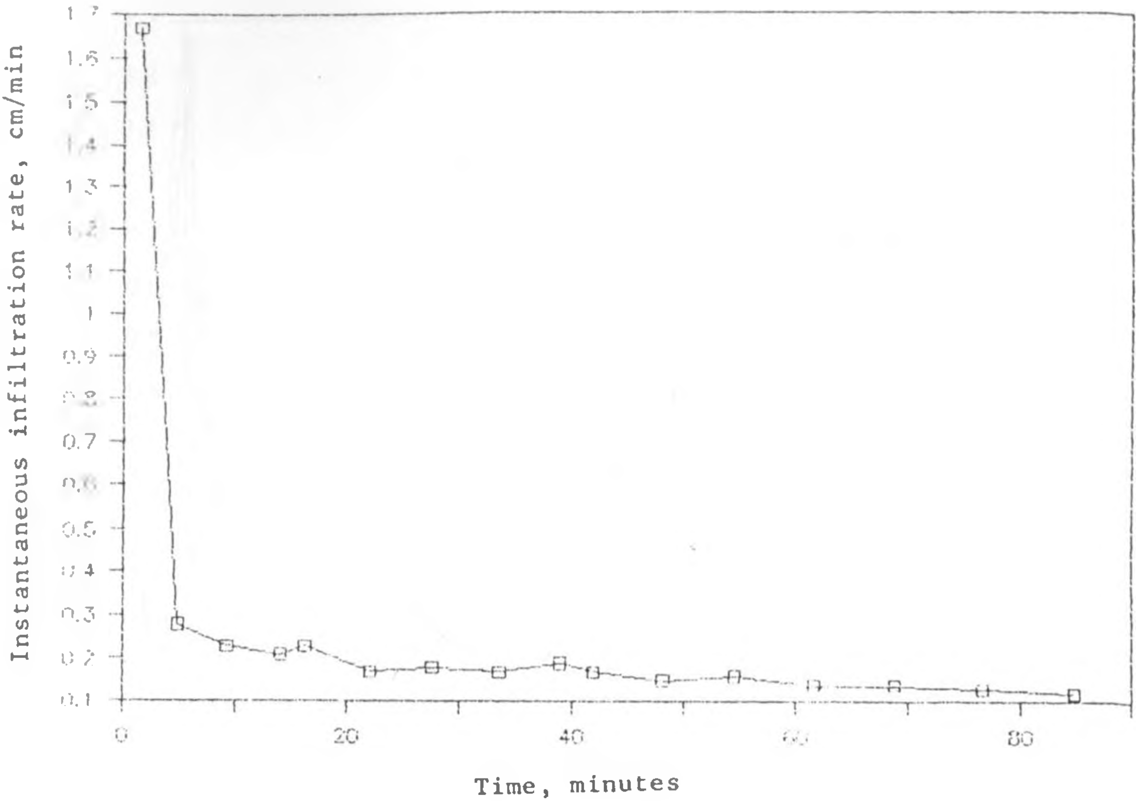


Fig. AIII-13: Instantaneous infiltration rate versus time for test plot K.I.S.

III K.

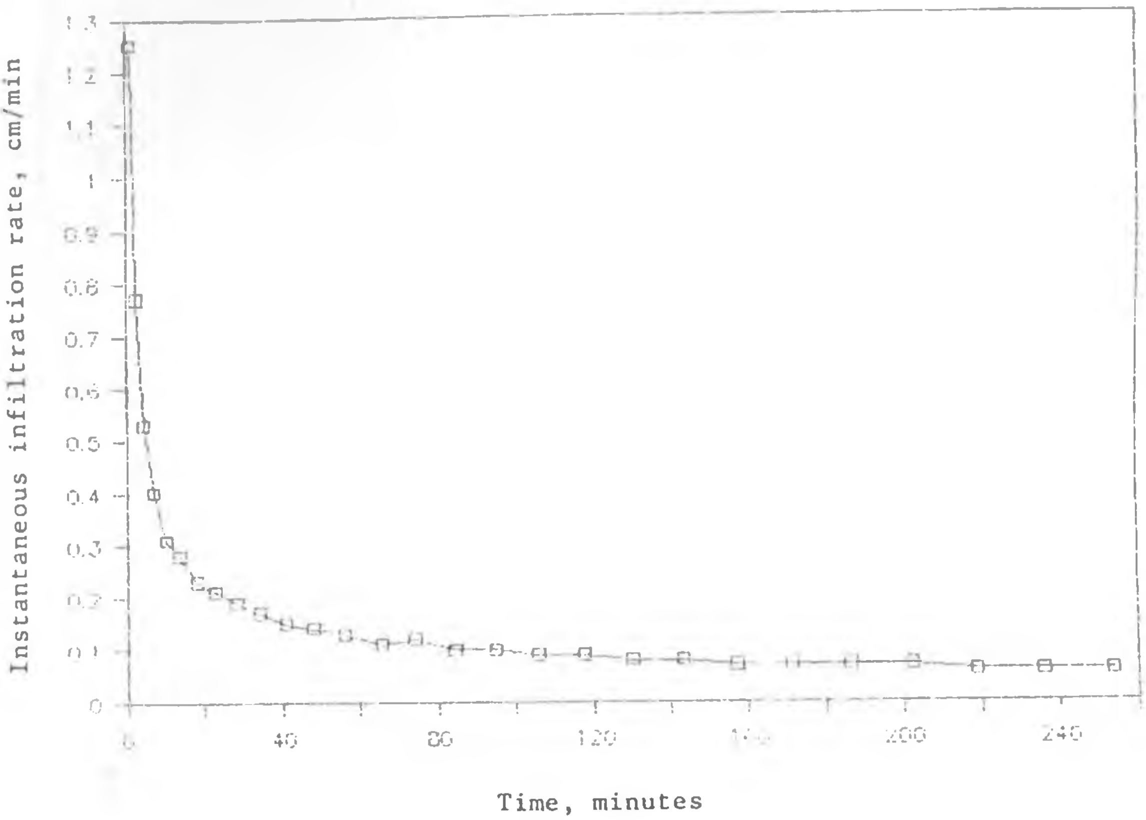


Fig. AIII-14: Instantaneous infiltration rate versus time for test plot 346

III L.

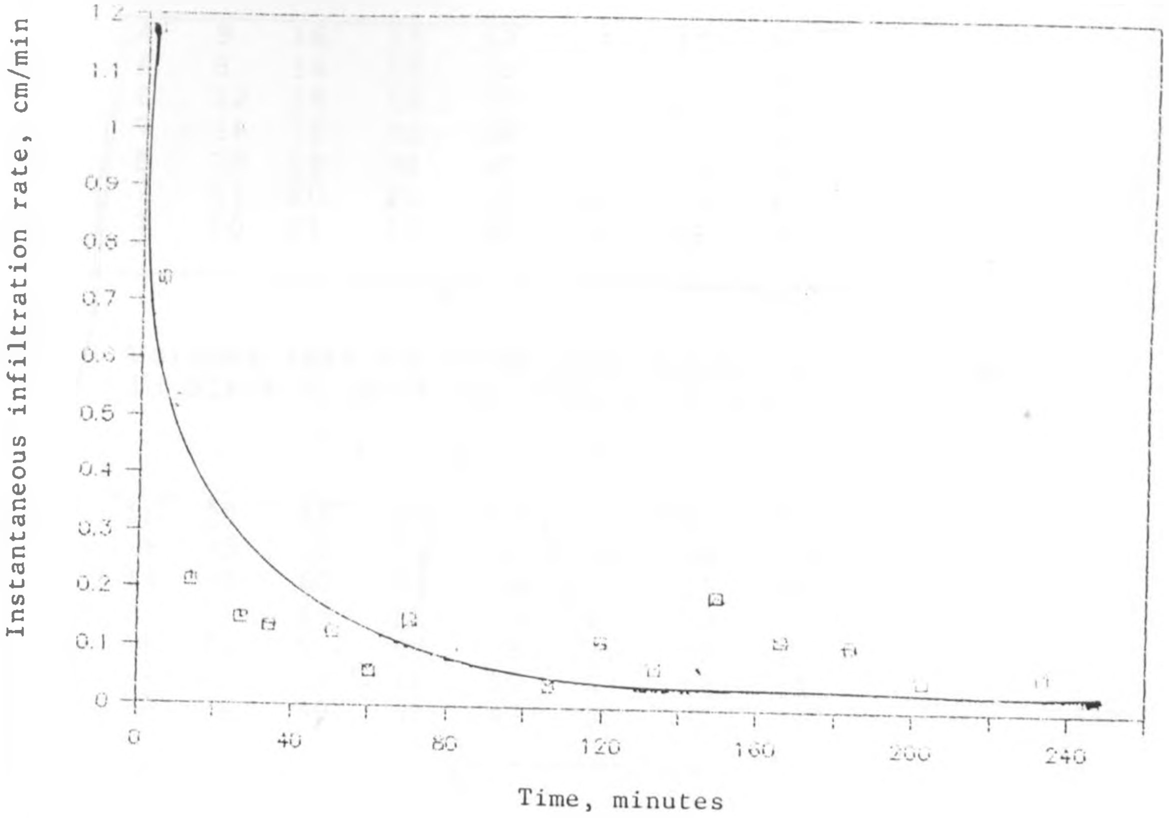


Fig. AIII-15: Instantaneous infiltration rate versus time for test plot 569

Appendix IV: Catch can volumes of Sprinkler Discharges

(A) Volumes (ml) in catch cans conducted on 5/12/88 in Block 3, plot no. 396, t = 1.5 h

x

4	9	16	15	22	14	10	5
4	8	14	16	22	11	9	4
6	12	19	19	12	7	8	3
7	16	16	30	19	13	11	4
8	10	18	34	22	35	20	9
7	14	20	25	36	25	15	8
7	10	21	30	40	19	18	9

x

(B) Volumes (ml) in catch cans conducted on 2/1/89 in Block 4, plot no. 708, t= 2.0 h

x

16	29	56	63	50	39	26	13
16	32	54	61	52	36	24	12
14	30	50	53	36	27	29	10
13	26	45	52	29	24	19	8
15	27	51	60	53	31	26	12
14	25	50	56	50	37	24	12
13	26	40	51	42	31	30	11

x

(C) Volumes (ml) in catch cans conducted on 2/1/89 in Block 4, plot no. 1313, t = 1.5 h

x

5	16	12	20	35	15	14	7
6	6	10	40	47	26	8	9
8	13	17	43	42	30	14	10
13	52	30	35	39	46	73	52
6	15	15	28	38	43	25	11
6	6	14	38	48	24	7	8
6	6	48	50	58	20	21	11

x

X- indicates the sprinkler positions during the test.

(D) Volumes (ml) in catch cans conducted on 22/1/89
in Block 4, plot no.735, t = 2 h

x

10	14	28	50	55	19	17	10
8	18	18	38	40	24	16	9
8	26	16	30	32	18	14	7
13	32	42	43	44	38	17	11
15	32	48	53	56	30	11	10
7	16	22	25	24	27	14	7
9	20	22	39	48	26	18	10

x

(E) Volumes (ml) in catch cans conducted on 29/11/88
in Block 4, plot no.1081, t = 1.5 h

x

8	16	26	28	24	22	20	7
7	14	22	28	19	16	20	6
9	22	28	30	33	27	20	9
14	28	45	58	47	48	30	14
11	30	30	42	44	40	30	13
8	22	25	23	24	25	32	9
7	20	27	28	30	22	30	9

x

(F) Volumes (ml) in catch cans conducted on 15/11/88
in Block 2, plot no. 360, t = 1.5 h

x

9	23	25	31	30	26	19	8
8	20	24	30	22	18	23	7
10	13	40	43	38	34	32	12
16	40	52	55	60	62	50	19
18	44	54	60	63	64	61	20
12	18	51	46	50	48	66	18
9	15	32	35	39	30	10	9

x

(G) Volumes (ml) in catch cans conducted on 6/12/88 in Block 3, plot no. 405, t = 1 h

x

4	7	15	18	13	22	29	21
3	6	12	17	18	18	21	19
5	12	18	12	33	25	33	23
12	26	45	41	18	34	31	20
5	14	10	24	10	22	30	17
4	8	14	13	15	9	20	14
3	4	16	16	17	31	18	15

x

(H) Volumes (ml) in catch cans conducted on 14/12/88 in Block 3, plot no. 499, t = 2.0 h

x

16	29	45	69	66	56	36	18
13	30	39	52	55	26	24	12
20	31	40	49	68	45	40	17
18	28	43	38	56	37	41	22
15	33	25	37	42	47	43	22
18	26	38	45	33	61	53	39
14	25	52	57	63	47	42	25

x

(I) Volumes (ml) in catch cans conducted on 30/11/88 in Block 3, plot no. 554, t = 1.5 h

x

7	9	19	36	33	19	14	7
4	6	25	38	35	28	22	9
8	20	34	40	37	32	26	11
10	34	16	39	39	40	16	10
12	34	38	38	41	52	36	14
8	17	19	39	34	26	22	9
8	14	23	38	29	16	9	6

x

(J) Volumes (ml) in catch cans conducted on 1/12/88 in Block 4, plot no. 565, t = 1.5 h

x

16	30	28	37	16	19	20	9
9	20	20	11	18	15	15	8
10	15	25	22	16	17	20	9
10	21	31	36	31	28	22	14
12	11	56	48	42	42	28	12
13	25	40	52	38	30	19	10
10	25	32	34	18	11	11	4

x

(K) Volumes (ml) in catch cans conducted on 1/12/88 in Block 2, plot no. 1172, t = 2 h

x

12	10	31	74	61	50	12	13
10	13	34	59	45	40	15	11
12	16	44	48	42	39	33	12
13	34	36	48	45	32	38	13
9	24	28	37	27	20	22	8
7	23	9	32	22	15	12	5
8	18	16	40	33	21	14	11

x

(L) Volumes (ml) in catch cans conducted on 8/11/88 in Block 2, plot no. 569, t = 1 h

x

7	9	24	37	28	12	6	2
9	12	28	40	29	13	5	0
8	13	31	35	30	21	22	11
9	12	28	37	31	34	21	11
14	19	29	29	27	18	10	7
10	18	19	22	21	10	11	6
5	9	9	13	9	6	9	3

x

(M) Volumes (ml) in catch cans conducted on 26/10/88 in Block 3, plot no. 470, t = 1 h

x

3	10	11	10	13	13	10	4
3	9	8	11	12	13	9	4
3	9	9	11	9	10	9	3
3	8	9	11	11	10	7	3
2	7	9	9	10	8	6	2
2	5	7	8	7	6	5	2
0	2	6	13	11	6	3	0

x

(N) Volumes (ml) in catch cans conducted on 24/10/88 in Block 2, plot no. 375, t = 1.5 h

x

15	41	42	49	38	29	19	10
12	38	31	42	29	18	15	7
6	11	20	20	18	17	16	6
7	16	19	25	24	24	12	7
6	11	17	24	25	23	16	7
10	21	20	23	19	16	15	6
8	17	27	29	25	13	10	5

x

(P) Volumes (ml) in catch cans conducted on 13/10/88 in Block 2, plot no.1217, t = 1.5 h

x

9	14	30	41	45	43	33	13
5	10	17	18	20	17	10	5
7	16	12	38	32	17	13	7
6	16	14	32	25	24	17	7
7	19	10	32	30	16	10	6
10	21	31	43	35	33	20	10
9	12	14	53	51	43	17	12

x

(R) Volumes (ml) in catch cans conducted on 29/9/88 in Block 4, plot no.K.I.S., t = 2 h

x

12	19	37	55	59	49	22	14
10	17	27	54	43	40	22	11
9	20	29	32	31	30	23	9
10	26	27	37	40	26	18	8
9	23	31	32	33	25	20	9
9	19	29	39	49	24	17	10
10	9	27	47	59	30	22	12

x

(S) Volumes (ml) in catch cans conducted on 21/1/89 in Block 4, plot no. 703, t = 1 h

x

3	7	6	13	14	10	8	4
4	5	12	16	17	10	15	5
7	10	24	29	20	18	19	6
9	20	25	37	29	27	28	9
8	16	18	38	32	30	30	10
6	15	15	26	24	22	14	7
5	9	11	28	25	18	8	7

x

(T) Volumes (ml) in catch cans conducted on 28/11/88 in Block 1, plot no. 61, t = 2 h

x

9	15	27	39	40	21	18	9
10	46	22	25	41	24	26	10
19	60	50	58	26	29	27	9
21	58	60	75	46	51	30	14
17	55	50	46	31	29	21	9
18	50	60	51	18	22	21	7
6	17	19	21	40	18	20	9

x

(U) Volumes (ml) in catch cans conducted on 16/11/88 in Block 3 plot no. 482, t = 2 h

x

8	19	28	28	27	23	13	7
8	21	24	29	26	24	21	8
10	26	30	35	31	32	25	10
9	20	26	41	42	35	29	12
10	20	22	49	44	34	28	12
10	19	23	50	45	30	25	11
9	20	20	56	47	30	22	11

x

Appendix V:

SAMPLE CALCULATION ON SPRINKLER PERFORMANCE EFFICIENCIES

The data from each performance test was mathematically overlapped to simulated infiltration from a complete irrigation at the specific move distance. This was done by super-imposing the collected data on one side of the lateral with the data on the other side of it at the corresponding distance from the lateral position. The super-imposed catch can data were used in the calculations of the sprinkler performance efficiencies.

The data collected in test plot No. 396 was used.

Combined can catch volumes
x- indicates sprinkler location

x					x
	26	23	26	20	
	26	19	23	20	
	18	19	27	20	
	26	29	27	34	
	30	45	38	43	
	43	39	45	33	
	47	29	39	39	
x					x

The values are in ml
for a test duration of
1.5 h and sprinkler
discharge $Q = 0.29$ l/s

The following calculations were done with this data.

The depth of irrigation collected in catch cans,

$$di = \frac{\text{volume collected in catch cans, ml} \times 10}{\text{cross-sectional area of the collecting cans, cm}^2}, \text{ mm}$$

The average opening diameter of the catch cans used = 8.50 cm

$$\text{Cross-sectional area of the catch cans} = \frac{3.14 * (8.50)^2}{4}$$

$$= 56.75 \text{ cm}^2$$

Volume of water collected, ml	depth of water, di, in collecting cans,mm	$\lvert di - \bar{d} \rvert$	low-quarter depths, mm
26	4.6	0.8	3.2
26	4.6	0.8	3.4
18	3.2	2.2	3.4
26	4.6	0.8	4.1
30	5.3	0.1	3.5
43	7.6	2.2	3.5
47	8.3	2.9	3.9
23	4.1	1.3	
19	3.4	2.0	sum = 25.0
19	3.4	2.0	average = 25/7
29	5.1	0.3	= 3.6
45	7.9	2.5	
39	6.9	1.5	
29	5.1	0.3	
26	4.6	0.8	
23	4.1	1.3	
27	4.8	0.6	
27	4.8	0.6	
38	6.7	1.3	
45	7.9	2.5	
39	6.9	1.5	
20	3.5	1.9	
20	3.5	1.9	
22	3.9	1.5	
34	6.0	0.6	
43	7.6	2.2	
33	5.8	0.4	
39	6.9	1.5	
sum	154.1	38.2	

average depth of irrigation collected in cacth cans,

$$\bar{d} = \frac{\text{sum of collected irrigation depths}}{\text{No. of data}} = \frac{154.1}{28}$$

$$= 5.4 \text{ mm}$$

sum $\lvert di - \bar{d} \rvert = 38.2$

sum di = 154.1

Christiansen uniformity coefficient,

$$CUC = \left(1.0 - \frac{\text{sum } |di - \bar{d}|}{\text{sum } di}\right) * 100$$

$$= \left(1.0 - \frac{38.2}{154.1}\right) * 100$$

= 75 percent

Distribution uniformity, DU,

$$= \frac{\text{average irrigation depth in low-quarter}}{\text{average irrigation depth collected in all catch cans in the test area}} * 100$$

$$= \frac{3.55}{5.38} * 100$$

= 66 percent

Application efficiency of low-quarter,

$$AELQ = \frac{\text{average low-quarter depth of water infiltrated and stored}}{\text{Average expected irrigation depth calculated from measured sprinkler discharge}} * 100$$

expected sprinkler precipitation rate,

$$= \frac{\text{discharge (l/s) x 3600 s}}{\text{sprinkler spacing(m) x move (m)}} = \frac{0.29 \text{ x } 3600}{18 \text{ x } 12} = 4.8 \text{ mm/h}$$

The average expected irrigation depth in the irrigated area,
= precipitation rate x duration of application

For a given application duration, AELQ is calculated as a ratio of the precipitation rates.

In this connection therefore,

$$AELQ = \frac{3.55}{4.8 * 1.5} * 100 = 49 \text{ percent}$$

Potential application efficiency,

$$\text{PELQ} = \frac{\text{average low-quarter depth of water infiltrated} = \text{MAD}}{\text{average expected irrigation depth in the sprinkler irrigated area}} * 100$$

for MAD = 34.8 mm,

average expected irrigation depth applied during irrigation = average application rate of sprinklers * application duration

= 4.8 mm/h * 10 h = 48 mm.

$$\text{PELQ} = \frac{34.8}{4.8 * 10} * 100$$

$$= 73 \text{ percent}$$

$$\text{sprinkler application efficiency} = \frac{\text{average measured rate in catch cans}}{\text{average application rate of sprinklers}} * 10$$

application efficiency of therefore,

$$= \frac{3.5}{4.8} * 100$$

$$= 73 \text{ percent}$$

The irrigation depth of 34.8 mm for sprinkler with a precipitation rate of 4.8 mm/h would be achieved at an application duration of 7.3 hours.
With the average sprinkler precipitation rate of 5.3 mm/h for the sprinklers used in this study, the irrigation depth of 34.8 mm would be achieved with an application duration of 6.6 hours.

Appendix VI: Agro-meteorological Data

Meteorological data recorded at Kibirigwi irrigation scheme meteorological station,(Altitude 1347 m a.s.l., Longitude 37^0 10 E and Latitude 0^0 32′ S) for the period 1980-1988

	mean monthly			
month	pan evaporation mm/month	total rainfall mm/month	daily wind speed, km/day	daily air temp. deg./c
January	140	17	67.9	22.7
February	151	17	76.4	22.3
March	190	105	72.8	22.1
April	129	300	55.1	22.4
May	118	274	47.2	22.2
June	93	68	38.7	20.3
July	76	48	40.4	18.9
August	84	49	41.2	20.7
September	117	40	53.6	20.3
October	117	122	59.9	21.5
November	129	224	56.8	21.2
December	131	67	58.8	20.7

Kibirigwi Meteorological Station is not a Kenya Meteorological Department Station.

Appendix VII: Crop Roots Distribution with Depth in the Soil

A. Crop: Tomatoes Variety: Money maker growth stage: harvest (maturity)

	Replicate 1.			Replicate 2.		
	distance from the plant position, cm					
depth cm	20	40	60	20	40	60
0						
17	17	15	13	16	12	15
37	10	24	12	26	22	19
57	18	25	21	22	20	21
77	8	18	20	18	20	7
97	8	11	7	9	3	0

average root depth for tomatoes = 100 cm

B. Crop: Capsicum growth stage: Harvest

	Replicate 1.			Replicate 2.		
	distance from the plant position, cm					
depth cm	20	40	60	20	40	60
0						
20	34	25	28	20	22	19
40	18	10	16	19	14	15
60	8	5	6	9	7	8
80	0	0	0	0	0	0

average root depth = 70 cm

C. crop: Growth stage:
Onions Bulb formation

	Replicate 1.			Replicate 2.		
	distance from the plant position, cm					
depth cm	10	20	30	10	20	30
0						
10	18	17	15	15	19	13
20	12	14	8	9	11	10
30	4	6	1	3	5	0
40	0	0	0	0	0	0

average root depth for Onions = 30 cm

D. Crop: Growth stage:
Cabbage Harvest

	Replicate 1.				Replicate 2.		
	distance from the plant position, cm						
depth cm	15	30	45	60	15	30	45
15	49	53	22	45	56	46	60
30	30	26	20	27	12	9	10
45	0	0	0	0	0	0	0

average root depth for cabbage = 40 cm

Appendix VIII: River Discarge Data

Discharge of Ragati river at R.G.S. 4BB1 in m^3 /s.
The flow record is for the period 1970-1987.

	Month											
Year	Jan	Feb	Mar	Apr	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1970	3.4	3.2	2.5	7.3	12.3	5.5	3.0	2.4	1.9	1.6	1.6	1.4
1971	0.8	0.6	0.6	1.7	4.6	2.9	2.3	1.9	1.5	1.2	1.1	1.2
1972	2.3	1.4	1.3	1.2	5.3	5.2	2.7	1.8	1.7	4.3	10.6	1.8
1973	4.6	2.8	1.9	4.0	7.3	5.6	3.4	2.5	1.7	1.8	4.0	2.4
1974	1.6	1.1	0.8	4.7	2.8	2.0	3.0	2.3	2.0	1.0	1.7	1.5
1975	0.8	0.4	0.4	2.6	6.0	4.5	3.1	2.5	1.9	1.4	1.5	1.3
1976	1.1	1.3	0.8	1.8	4.0	2.6	1.6	1.3	1.1	1.1	1.3	2.2
1977	2.6	1.5	1.6	4.1	7.6	2.8	2.5	2.0	1.5	2.2	6.7	5.5
1978	4.1	2.6	5.0	9.4	12.7	5.8	3.3	2.6	1.9	2.1	2.9	2.8
1979	2.8	4.7	3.9	8.2	17.8	18.2	7.5	4.2	2.5	2.9	3.8	2.6
1980	2.1	1.9	2.2	3.2	5.8	2.6	1.8	1.9	1.3	1.2	4.2	2.4
1981	1.4	1.1	3.6	8.4	14.8	7.7	4.0	2.8	2.3	1.7	1.4	4.2
1982	1.3	1.3	1.5	11.7	19.4	8.1	9.6	2.4	2.1	1.8	5.3	5.9
1983	5.4	2.2	0.7	17.0	14.8	9.2	7.1	1.9	1.2	2.3	3.8	2.2
1984	1.5	0.9	0.9	0.9	1.3	0.8	0.7	0.9	0.8	2.4	4.3	4.2
1985	2.7	1.6	1.3	3.8	9.4	8.2	4.2	2.3	2.7	1.4	3.5	3.3
1986	1.3	0.6	0.7	2.6	9.2	19.5	5.9	1.9	1.8	1.3	2.2	4.1
1987	1.3	0.9	0.7	3.4	7.3	17.4	2.2	1.9	1.0	0.7	3.8	4.8
Avg.	2.3	1.7	1.7	5.3	9.0	7.2	3.8	2.2	1.7	1.8	3.6	3.0