EVALUATION OF DRIP IRRIGATION SYSTEM ON COFFEE (*Coffea Arabica*): A CASE STUDY OF KILIMANJARO PLANTATION IN MOSHI DISTRICT KILIMANJARO REGION TANZANIA

BY

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ABSTRACT

This study was conducted at one of the estates in Kilimanjaro Plantation to assess the performance of the drip irrigation system on coffee yield. Climatic, plant and soil factors were used for the calculation of monthly crop water and irrigation requirements and results compared with actual performance of the irrigation system. Further evaluation of the system performance was carried out using catch cans. The experiment was carried out on a 3-year-old coffee cultivar N39 at 3m spacing between lines of plants and 1.5 m between plants. The experiment was laid out in a randomized complete block design with five treatments replicated four times. The treatments included five irrigation application levels: T1, T2, T3, T4 and T5 corresponding to flow rates of 0, 0.6, 1.2, 1.8 and 2.4 lph/emitter respectively. The results from calculations showed that the daily irrigation requirement is 18 litres per tree, or applying 90 litres at an irrigation interval of 5 days at peak demand. The EU in the selected block was found to be 94%, which is within the acceptable standards. The wetted area ranged from 0.12 to 0.21 m^2. The relative water supply ranged from 0.45 to 0.98 indicating that the crop demand was not met by both rainfall and irrigation. Coffee yield and water productivity was also investigated. The best treatment towards the yield of coffee was T5 which produced mean yield of 2945 kg/ha while treatment T1 produced the least yield of 2045 kg/ha. The best WP was 1.56 kg/m^3 found in T1 and lowest was 0.95 $kg.m^3$ in T5. There were significant differences in yield and irrigation water productivity between treatments. T1 and T2 were not significantly different. It is recommended that further research covering other parts of the plantation should be conducted to confirm the results from this study.

DECLARATION

I, ROBERT EDWARD CLEMENS, do hereby declare to the Senate of the Sokoine University of Agriculture that this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

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DEDICATION

To my late parents (Mr and Mrs Edward Clemens). Dedicated also to my son Andrew and daughter Gisela through whose love and affection I got encouragement to continue with the study.

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LIST OF ABBREVIATIONS AND SYMBOLS

ANOVA	Analysis of variance
CR	Capillary rise
CRI	Coffee research institute
CWP	Crop water productivity
DP	Deep percolation
Ea	Application efficiency
ECe	Electrical conductivity of saturated soil extract
ECw	Electrical conductivity of irrigation water
ET	Evapotranspiration
ETa	Actual Evapotranspiration
ETc	Crop water requirement
ETo	Reference evapotranspiration
EU	Emission uniformity
FAO	Food and Agriculture Organisation of the United Nations
FC	Field capacity
GC	Ground cover
ICO	International Coffee Organisation
IDA	International Development Association
IF	Irrigation Frequency
IRn	Net irrigation requirement
IRg	Gross irrigation requirement
IWMI	International Water Management Institute
KPL	Kilimanjaro Plantation Ltd
Kc	Crop coefficient
Kr	Reduction factor

LR	Leaching requirement
MAD	Management allowable depletion
Pe	Effective precipitation
Pw	Percentage wetted area.
PWP	Permanent wilting point
R	Rainfall
RAW	Readily available water
RH	Relative Humidity
RIS	Relative irrigation supply
RO	Runoff
RWS	Relative water supply
SAS	Statistical analysis for scientists
SWD	Soil water deficit
SWMRG	Soil Water Management Research Group
TACRI	Tanzania Coffee Research Institute
WD	Wetting Diameter
WUE	Water use efficiency
WP	Soil wetted portion
Zr	Effective rooting depth

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

The role of agriculture in the economic and social life of human beings cannot be overemphasized particularly due to income earned from agriculture by individuals and governments. Government earns income from agriculture through exports and this makes the sub-sector key to the economy (Sanusi *et al*., 2006). Agriculture is a key element of the Tanzanian economy and is highly dependent on water resources. After liberalization of the economy in 1986, increased food production and traditional and non traditional exports created greater demand for water (IDA, 2007).

Agricultural production is dependent on the weather, which in many parts of Tanzania is either unreliable or consistently dry (Rajabu, 1997). Rainfed agriculture remains susceptible to droughts. Due to this uncertainty of rainfall, irrigation is considered to be a viable solution for stabilizing and boosting agricultural production in Tanzania (Shagude, 2006). It is a means of poverty alleviation as more and more people go into cultivation of high value irrigated crops such as vegetables and fruits (Tanzania National Water Policy, 2002).

An irrigation system allows water to be available to the plant in sufficient quantities and quality to ensure that water is not a limiting factor in crop production. Irrigation is a highly water user technology and makes greatest impact on net water resources (Tanzania National Water Policy, 2002). Irrigation systems are designed to maximise the rate of increase in agricultural output and income by increasing the quality and quantity of production, increasing the efficiency in the use of water and reducing the overall costs of system operation (Zazueta, 2009).

In some areas, extensive use of water for irrigation and increasing need for municipal and industrial water is depleting available resources (Conway *et al.*, 2003). Cropland irrigation is a major consumer of water in semiarid and arid regions (Teixeira, 2006). Limited availability of irrigation water requires fundamental changes in irrigation management or urges the application of water saving methods (Dagdelen *et al*., 2005). In recent decades, revolutionary developments have taken place in irrigation technology. A more comprehensive understanding has evolved regarding the soil-crop-water relations as affected by climatic and soil factors. These conceptual developments have led to technical innovations in water control that have made possible the maintenance of near optimal moisture throughout the growing season, (Hillel, 1997).

One of these innovations is the drip irrigation system. Drip irrigation, also known as trickle irrigation or microirrigation, is an irrigation method which saves water and fertilizer by allowing water to drip slowly to the roots of plants, either onto the soil surface or directly into the root zone, through a network of valves, pipes, tubing, and emitters. Drip irrigation is gaining importance in the world, especially in areas with limited and expensive water supplies, since it allows limited resources to be fully utilized (Hezarjaribi *et al*., 2008). Interest in drip irrigation has also increased primarily due to undulating terrain, and social pressure to conserve water resources (Qassim, 2003).

The average global water availability reveals declining trends, with a 37% decline per capita availability of fresh water since the 1970s as population growth and degradation of water supplies outstrips the capacity to develop new sources (Shagude, 2006). The world population is currently growing at an average rate of 1.5 percent annually. It is predicted that by the year 2025 about 35% of the world population may face water shortage (Mofoke *et al.*, 2004). Efficient use of water by irrigation is becoming increasingly important and alternative water application methods such as drip may contribute substantially towards making the best use of water for agriculture and improving irrigation efficiency (Sezen *et al*., 2004).

In Tanzania, drip irrigation technology has been promoted since 2003 (SWMRG, 2005). In recent years drip irrigation system has been employed in large scale coffee estates along with other systems such as surface irrigation and sprinkler (Turpie *et al*., 2005).

The genus coffea comprises about ninety species, but only a few are cultivated and just two are commercially important (Amend, 2002). The two main species of coffee are '*Coffea arabica'* known as arabica coffee which accounts for 70% of the world production and *'Coffea canephora'* known as robusta coffee which accounts for 30% (Njoroge, 1997). Coffee is remarkable for being produced in almost all non-arid areas in the tropics. Over 50 countries produce coffee in significant amounts (ICO, 2009). An estimated 25,000,000 coffee farming families around the world depend on coffee. It is the second largest traded commodity in the world market after petroleum (Jayaraj, 2004).

Production of arabica coffee in Africa has doubled since the 1960's due to emergence of new producers in Southern Africa such as Malawi, Zimbabwe and Zambia and expansion of hectarage under coffee by the traditional producers of arabica coffee such as Burundi, Kenya and Rwanda during the same period (Opile, 1995). Increased production from the Asian countries such as Vietnam, Papua New Guinea has also been realised (Njoroge, 1997).

In Tanzania coffee accounts for about 20% of foreign exchange earnings and has been the mainstay of the country's agriculture based economy since its introduction as cash crop around 100 years ago (TACRI, 2005). A total of 235 000 ha are under coffee production in Tanzania. About 55 015 tons are produced per annum, of which smallholder farmers produce 95%. The remainder being grown on 12 200 ha of coffee estates (Baffes, 2003). Annual production in coffee estates ranges from 1.5-2.5 tons of dry beans per hectare while small scale dry land production is around 1.2 tons per hectare (Turpie *et al*., 2005).

The Tanzanian coffee industry experienced a decline from the early seventies following nationalization of large estates. The nationalized estates, which were owned and managed by primary societies, face major managerial difficulties and many were practically abandoned (Baffes, 2003). Some of the factors that contributed to the decline were; age of the trees which were up to 70 years resulting in low yields, lack of disease – resistant varieties, removal of subsidies, poor quality coffee and global price fluctuations. One of the reforms taken by the government to revitalise Tanzanian coffee industry was privatization of a number of estates which were previously nationalized (Masumbuko *et al*., 2003).

Among the privatized estates were eight neighbouring estates namely Kichoni, Gomberi, Chombo, Tchibo, Kaity, Kifumbu, Kilimanjaro and Mawingo. These were merged to form Kilimanjaro Plantation Limited (KPL). Between 1999 and 2003 KPL approached four village cooperatives in order to sign long term lease agreement (KPL, 2004). In the past the estates were irrigated using surface and sprinkler irrigation methods. Due to water scarcity problem KPL introduced the drip irrigation technology in 2004.

Carr (2001) detailed the following research needs among others to interpret the role that water plays in the growth and development of the coffee plant so that growers can plan and use water effectively for the production of reliable high quality crops:

- Well designed and managed field experiments should be conducted, over a range of typical sites, to quantify the yield response of coffee to water;
- Adequate supporting measurements (crop, soil and prevailing weather conditions) must be taken to allow the results to be interpreted sensibly, and apply with confidence to other locations where climate and soil may be different;
- The design and operating criteria for drip irrigation systems need to be specified with precision in order to optimise crop yield and water use efficiencies.

In view of the above and considering no such evaluation has been done since the installation of the system it is essential that an assessment of drip irrigation for the coffee estate be carried out in order to ascertain the optimum level of water application. By understanding, the optimum amount of water application substantial amount of water savings can be realized. The results of this study can therefore, assist the management to plan and use water effectively for coffee production. This study is also considered timely as it is in line with Government strategies of encouraging the use of drip irrigation due to its advantage of economy of water use (Omari, J.M. personal communication, 2006).

1.2 Objectives of the Study

1.2.1 Main objective

The overall objective of the study is to evaluate the drip irrigation system on coffee crop production at Kilimanjaro Plantation in Moshi District, Kilimanjaro Region in Tanzania.

1.2.2 Specific objectives

The specific objectives included:

(i) To assess performance of the drip irrigation system.

(ii) To determine optimum water requirements for coffee crop.

(iii) To assess the yield response of coffee to drip irrigation

1.3 Hypothesis of the Study

Coffee yield is significantly influenced by different application levels under drip irrigation.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Drip Irrigation

Many authors (Jahns, 2008; Shock, 2006; Tekinel and Kanber, 2005; McConnell and Czemerda, 2003; Qassim, 2003; Haman *et al*., 2003; Savva and Frenken, 2002;) have described drip irrigation as the slow, frequent application of water (usually every 1- 3 days), in small flow rates (2- 20 litres/hr), on or below the soil surface. Ideally, the volume of water should be applied directly to the root zone in quantities that approach the consumptive use of the plants.

Drip irrigation relies on the concepts of irrigating and maintaining the water content of the root zone at near optimum level. Irrigating only a portion of the land surface limits evaporation, reduces weed growth and minimizes interruption of cultural operations (Tekinel and Kanber, 2005). It can be regarded not only as a method of water application, but as a system for conveying fertilizer to the desired location at the proper time (Goldberg *et.al*., 1976) and also a means of conveying insecticides for controlling pests (Souza *et al.*,2006). Drip irrigation is especially appropriate for the production of capital intensive and row crops such as vegetables, fruits, and ornamentals (Valenzuela, 1994).

Considerable evidence supported the concept that water availability to plants enhanced plant growth, yield and quality improvement to some crops (Howel *et al.*, 1983). Drip irrigation is adaptable to any terrain and most soils. On clay soils, water must be applied slowly to avoid surface water ponding and runoff. On sandy soils, higher emitter discharge rates will be needed to ensure adequate lateral wetting of the soil.

Drip irrigation is particularly suitable for water of poor quality. Trickle irrigation system was first put into practice in the arid zones of Israel with hot, dry climate and high salt concentrations in the water (Gornat and Goldberg, 1973). Its use produced large yields. By comparison, the yields obtained by sprinkling were lower than those of drip by 50% or more. Successful systems require clean and reliable water supply, availability of spare components and accessories for replacements, skilled manpower and high level of interest and participation of the owner (Kahlown and Kemper, 2007). Foliar disease incidence is reduced compared to overhead sprinkler systems (Gathaara and Kingori, 1999).

The main limitation with drip irrigation system is blockage of the emitters. All emitters have very small waterways ranging from 0.2 – 2.0 mm in diameter (Haman *et al*., 2003a) that can be blocked if irrigation water is not clean. Blockage may also occur if the water contains biological contaminants i.e. algae, fertilizer deposits and dissolved chemicals creating significant problems in everyday maintenance. Effective and reliable water treatment is mandatory for successful operation of trickle irrigation system (Haman *et al*., 2003a). It also requires a high initial capital investment as well as greater management skills than for more conventional irrigation systems (Valenzuela, 1994).

Generally, groundwater requires less treatment and causes fewer clogging problems for trickle irrigation system than surface water. Water from other sources such as rivers, canal, streams or irrigation ditch have the greatest potential for clogging problems, due to organic contaminants (Haman *et al*., 2003b).

2.1.1 Drip irrigation scheduling

Moisture management throughout the growing season is a critical factor for production of high quality crops. Even relatively short periods of inadequate soil moisture can adversely affect many crops. Central to that management is appropriate irrigation scheduling (Hartz, 1999). Irrigation scheduling is a management practice used to determine how often to irrigate, how much to apply and where to apply the water with each irrigation. Proper scheduling is essential for efficient use of water, energy and other production inputs such as fertilizer. It allows irrigations to be coordinated with other activities including cultivation and chemical applications (Kihupi, 2000).

Efficient irrigation can be described as applying the crop's water needs as required to sustain optimum growth and production at the lowest capital and operating costs possible. Efficient irrigation is obtained by correctly designing and operating the irrigation system to match, crop and soil management limitations (Tam, 2005). Without an appropriate management and operation system a nicely developed irrigation scheme has no meaning (Haque, 2005).

To schedule your irrigation with confidence you need to understand how much water your soil can hold that is available to the crop. The soil surrounding plant's roots stores the water it needs to live, grow and produce a crop. This water is held by the soil with increasing strength as the soil dries out (Ramsey, 2007). Sandy soils are well known for their inability to hold water. Precise irrigation scheduling is required in these soil types to avoid unnecessary loss of water and nutrients while providing a sufficient amount of water for optimum plant growth and production. In sandy soils very little water is stored in the root zone, and excessive water applications result in the loss of mobile nutrients such as nitrogen due to deep percolation (Haman and Smajstrla, 2005).

There are two basic approaches to scheduling drip irrigation. These are soil based scheduling (Hartz, 1999) and evapotranspiration data based approach (Van der Gulik, 2004). Evapotranspiration data can be used to schedule trickle irrigation systems using a plant water requirement or water budget method. The plant water requirement method adjusts the trickle system operating time by comparing the actual ET data to the theoretical Peak ET used in the design. This method can be used in situations where the system is designed to irrigate each individual plant with one or more emitters. The water budget method can be used for row crops such as vegetables, strawberries or any crop that is spaced close enough together so that the system is irrigating the entire field (Van der Gulik, 2004).

Using a water budget to schedule trickle irrigation systems is similar to balancing a chequebook. The plant's water storage reservoir can be considered as a bank. This reservoir can hold a limited amount of water that is useful for the crop. Daily evapotranspiration amounts are withdrawn from the storage in the soil profile. Any rainfall or irrigation are added to the storage (Broner, 2005).

2.1.2 Crop yield under drip irrigation

A research was carried out to evaluate the economic feasibility of growing cabbage crop under drip irrigation and mulches in lateritic sandy soils of Khargpur West Bengal, India. The study revealed that there exist variation in yield with different treatments with yields of 111.72, 108.87 and 107.94 t ha^{-1} for the drip with plastic mulch, drip with rice husk mulch and drip with paddy straw treatments respectively. The yield in drip irrigation was significantly higher over furrow irrigation by 65% (Tiwan *et al*., 2002).

Kigalu *et al*. (2008) conducted a research to determine the effects of drip irrigation on the yield and crop water productivity responses of four tea clones in four consecutive years (2003/2004 – 2006/2007) at Kibena Tea Company limited in Njombe District in southern Tanzania. The results showed that yield in drip irrigated plots exceeded those obtained from overhead sprinkler system. Yields from drip irrigated plots ranged from 4954 to 6072 kg dried tea ha^{-1} while those obtained from sprinkler system averaged around 4200 kg dried tea ha^{-1}. Drip irrigation gave water saving of up to 50% and labour saving of 85%.

Narayanamoorthy (2004), evaluated the impact of drip irrigation in India with the case of sugarcane. The study was conducted using farm level data from Mararashtra. Using a discounted cash flow technique it was found that productivity was 23% higher than that under flood method of irrigation with water saving of about 44% per hectare and electricity savings of about 1059 kWh/ha.

In order to determine the effect of drip irrigation management on yield and quality of field grown green beans, Sezen *et al*. (2005) conducted a detailed research on irrigated field grown green beans in the Mediterranean region of Turkey. The results demonstrated that irrigation water amount and irrigation frequency had significant effect on yields of field-grown green beans. The results also indicated that water use efficiency (WUE) values decreased with increased irrigation interval. In the study significant linear relationship between yield and seasonal water consumption was found for each irrigation frequency.

Mofoke *et al*. (2006) evaluated an affordable continuous flow drip irrigation system that applies the exact peak water requirements continuously throughout the 24h period of a day and so maintains the crop root zone near the field capacity throughout the growing season in Bauchi State, Nigeria. The study used tomato as a test crop. The results showed that the continuous-flow drip irrigation system offered water savings of 42.3% and 15.7% at 0.03 and 0.05l/h respectively over furrow irrigation system. The yields obtained under four continuous flow rates of 0.03, 0.05, 0.06, 0.07l/h and bi-daily application as control were 42.9, 42.6, 44.4, 44.4 and 22.3t/ha respectively. The associated water use efficiencies were 0.155, 0.107, 0.085 and 0.064 t/ha/mm in the same order of the four discharges while that of control was 0.101 t/ha mm.

2.2 Coffee Agronomy

2.2.1 Coffee plant overview

Coffee plant is a woody perennial evergreen dicotyledon that belongs to the *Rubiaceae* family (Masumbuko *et al*., 2003). Because it grows to a relatively large height it is more accurately described as coffee tree. A well known feature of arabica coffee is the existence of two types of branches: Orthogeotropic, commonly called suckers which grow vertically and plagiogeotropic branches commonly called primaries which have different orientation angles in relation to the main stem. Primary branches give rise to secondary branches which in turn split to tertiary branches and that also branch to form quaternary branches (Obso, 2006).

Coffee leaves are elliptical, shiny, dark green and waxy and grow in opposite pairs. Young leaves are pale green becoming dark and shiny as they mature. Coffee is evergreen with the leaves remaining on the tree for nine to ten months and leaves remain active throughout the dry season. Coffee leaves are sensitive to direct sunlight and both high and low temperatures. Shaded leaves are much more photosynthetically efficient than unshaded leaves (Amend, 2002). The coffee leaf area index is between 7 and 8 for high yielding coffee (CRI, 2006).

There are six buds in each leaf axil. Given good conditions for flowering, four of these buds will normally produce inflorescences. Coffee flowers are small, white and aromatic. They are born in clusters of up to twenty (Amend, 2002). Flower buds start to wither after two days and all component parts drop except the ovaries. The fruits are oval, red when ripe, normally containing two seeds, each flat on one side and convex on the other (Amend, 2002).

2.2.2 Coffee root system and rooting depth

Effective rooting depth generally is estimated as half of the maximum rooting depth. It is where the majority of crop roots active in water and nutrient uptake will be. Maximum rooting depth is defined as the deepest depth attained by a crop for any specific soil situation (Johnson, 2007). The maximum rooting depth for coffee ranges from 0.9-1.5 m depth (Allen *et al*.,1998). Root concentration is in the 30-60 cm depth (CRI, 2006).

Garcia *et al*. (2006) conducted a study to evaluate the effect of the drip fertirrigation system over the root distribution of 3 year old coffee tree in Sao Paulo Brazil. They used emitters spaced 0.5 or 0.8 m and depth of installation 0.1 and 0.2 m below the ground. They concluded that the effective rooting depth was smaller (mean of 0.63 m) than that observed for plants irrigated by emitters spaced every 0.8 m (mean of 0.7 m).

2.2.3 Climate

Arabica coffee is grown in relatively cool climates in the region between the tropics of Cancer and Capricorn. Arabica can withstand fluctuations in temperatures provided that they are not too extreme (Obso, 2006). Average annual temperatures between 15ºC and 25ºC can support coffee growth with 20ºC as the ideal. Coffee trees can survive temperatures outside this range, but even short periods of high or low temperatures can reduce production. Above 25ºC no photosynthesis occurs in coffee leaves, and if temperatures are above 30ºC for an extended period the leaves will be damaged (Amend, 2002). High temperatures also affect superficial roots preventing a better plant root system distribution (Carmago and Marcelo, 2008).

Arabica coffee requires 1000 to 1150 mm of rainfall and maximum dry period should not exceed 4 months. Altitude influences rainfall and temperature. Arabica coffee grows well at an altitude between 1400 and 2100 m above sea level (Njoka and Mochoge, 1997).

Amend, (2002) described clouds and humidity to be important in making coffee cultivation possible in marginal areas. High humidity reduces the rate of evapotranspiration and therefore the amount of precipitation needed. Cloud cover can raise humidity and influence the temperature. Strong winds can physically damage coffee trees, but in general the most important effect of wind is increased evapotranspiration. A period of moisture stress helps cause a homogeneous flowering and therefore defined harvesting season (CRI, 2006).

2.2.4 Coffee soils

According to Njoka and Mochoge (1997) the best coffee soils are humic nitosols which are red clay loams of volcanic origin. They are deep, friable and free draining. Arabica coffee requires soils with pH range of 5.4 to 6.5. These humic soils are highly leached at higher altitude zones leading to low contents of plant nutrients. Coffee plants require high levels of nutrients (Cai, *et al*., 2006). To obtain high yields and quality coffee, these nutrients must be supplied from organic or inorganic sources. Constant monitoring of soil properties is essential as coffee plants remove a lot of minerals and other nutrients from the soil (D'Souza and Jayarama, 2006).

Oosterom *et al.* (1998) reported that Arabica coffee in Tanzania prefers higher altitudes, volcanic areas of natural fertility and gneiss areas of moderate fertility. They categorized the coffee soils as *Oruhama* acid clay soils, *Kikungu* reddish loamy to clayey soils and shallow soils all of moderate to low fertility. Others include *Orusenga* reddish sandy soils, *Orusenyi* bleached sandy soils and *Ipwishi* sandy groundwater soils, all of low to very low fertility and high fertility soils (Mbuga vertisols, Kitifu andosols and organic soils). Maro *et al*. (2005) suggested some optimal values for soil fertility parameters as shown in Table 1.

Table 1: Optimal fertility parameters for Tanzania coffee soils

Parameter	Unit	Value
pH		5
N	ppm	2.5
P	ppm	40
K	cmol/kg	1.25
Ca	cmol/kg	6.7
Mg	cmol/kg	2.5
OC	%	3

Source: Maro *et al*. (2005)

The field soil must be well aerated as the roots require abundant amount of oxygen (Rsbombard, 2008). Soils with high percentage of organic materials are best suited for coffee as they are more fertile, assist the assimilation of applied fertilizers, less prone to erosion and offer better water and nutrient retention. In summary, ideal soils for coffee should be deep, permeable, slightly acidic and porous (D'Souza and Jayarama, 2006).

2.2.5 Growth cycle

After planting, it takes five years to get full crop of beans that continues for another fifteen years (Rsbombard, 2008). Obso (2006) reported that it takes approximately 3 years to develop from germination to first flowering and fruit production depending on the climatic conditions in the area.

Flowers grow in clusters in the axils of the coffee leaves. Flower buds develop for several months, then growth stops and flowers become dormant. Dormancy is gradually reduced as the buds experience a period of water stress. After several weeks of water stress, dormancy is broken, and removal of water stress reinitiates flower development. When this happens, the buds develop quickly, and the flowers bloom within a few days (Amend, 2002).

It takes 7 to 9 months for the coffee fruits to mature, depending on the climatic conditions and coffee cultivars (Obso, 2006). About 4-5 weeks after each coffee flower is fertilized, cell division occurs and the coffee fruit is formed (pin head stage). Fruit expansion takes place from 6-16 weeks and bean filling takes place from 17-24 weeks The coffee cherry will change colour from green to red about 25 - 35 weeks after flowering (Agwanda, 1997).

2.2.6 Water requirement for coffee

To live and grow, plants need soil, sunlight, air and water. Water is a vital input in coffee production and plays a very important role in nutrient uptake and hence subsequent yields and quality. Adequate availability of water at the right time has to be assured (Mburu, 2004). Water is required for the manufacture of carbohydrates to maintain hydration of the protoplasm and as a vehicle for the translocation of carbohydrates and nutrients (Obso, 2006). Water is an essential component of all plant tissues. Tekinel and Kanber (2005) described three primary functions that are fulfilled by water as:

- Keeping plants erect by filling the plant tissues;

- Acting as a cooling agent in evaporating from the leaves, preventing overheating under hot conditions; and
- Carrying nutrients in solution from the soil into the plants through their roots.

Coffee plants cannot tolerate water logging and extended drought conditions (Obso, 2006).

Water use by coffee and other crops is mostly usefully expressed as a ratio of crop evapotranspiration to the reference crop evapotranspiration (ETc/ETo) also known as crop coefficient (Kc) (Gutierrez and Meinzer, 1994). Crop evapotranspiration (also called crop water requirements) is a loss through evapotranspiration (ETc) of a disease free crop growing in large fields under non restricting soil conditions including soil water, fertility and achieving full production potential under the growing environment (Allen *et al.,*1998). Quantifying ETc is essential for many applications in agriculture, such as crop zoning, yield forecast and irrigation management (Flumignan and Faria, 2008). Reference crop evapotranspiration is the rate of evapotranspiration from extensive surface 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water (Doorenbos and Pruitt, 1977).

Several methods are used to estimate reference crop evapotranspiation from different climatic variables (Allen *et al.,* 1998). These are Blaney-Criddle method, Hargreaves method, Pan evaporation method, modified Penman equation and modified Penman-Monteith equation (Kihupi, 2000). The analysis of the performance of the various calculation methods reveals the need for formulating a standard method for the computation of ETo. The FAO modified Penman-Monteith method is recommended as the standard method (Allen *et al.,* 1998). Marin *et al.* (2003) used the modified Penman-Monteith model to estimate maximum transpiration of coffee plants.

Gutierrez and Meinzer (1994) carried out an experiment to assess water use by drip irrigated coffee (*Coffea arabica L*. Yellow Catuai) growing in Hawaii using direct approaches. Irrigation requirements were determined by comparing the ETc values obtained against reference ETo values derived from modified Penman equation and expressed as the ETc/ETo ratio, or crop coefficient (Kc). The average Kc values were 0.75 to 0.79 for fields containing 2 to 4 year old plantings. The ratio was 0.58 for a field containing a 1-year-old planting.

An average Kc value of 1.1, was obtained by Silva *et al*. (2008) in a study of soil water extraction by roots and Kc for 3 to 5 years old coffee crop in Piracicaba, SP, Brazil. Luiz *et al*. (2005) obtained a Kc value of 1.0 in an experiment to measure evapotranspiration and irrigation requirements of a coffee plantation with 5-year-old trees in southern Brazil. For mature coffee grown without shade and where cultural practices involve clean cultivation with heavy cut grass mulching, Doorenbos and Pruitt (1977) recommended crop coefficients of about 0.9 throughout the year. If significant weed growth is allowed, coefficients close to 1.05 – 1.1 would be more appropriate.

Carr (2001) in his study of water relations and irrigation requirements of coffee found that for mature crops well supplied with water, the crop coefficient (Kc) appears to have a value in the range 0.7-0.8 times the evaporation from a US Weather Bureau Class A pan. There is evidence that Kc values are less than this on days when evaporation rates are high (>7mm/day).

Sato *et al*. (2007) monitored water and climatic regime from April to September 2004 of an adult coffee crop of the cultivar Catuai to estimate crop evapotranspiration and Kc applying the water balance method. The experiment was conducted in Lavras region – MG, Brazil. They found that coffee crop presented ETc values between 1.23 and 4.39 mm day^{-1} and Kc values from 0.59 to 1.16. A similar research was done on 16-year and 3-year old coffee plants in Muquem-FAEPE/UFLA, Lavras, Minas Gerais Brazil. The 16-year old coffee plants presented 2.91 mm day^{-1} average evapotranspiration, varying from 2.52 to 3.50 mm day^{-1} and 0.96 average crop coefficient varying from 0.72 to 1.50. The 3-year old plant which was in the same crop field after pruning process presented 1.72 mm day^{-1} average evapotranspiration varying from 1.55 to 2.01 and 0.57 average crop coefficient varying from 0.44 to 0.87. (Oliveira *et al*., 2003).

It was found that lack of plant available water can directly lead to water stress or indirectly to nutrient deficiencies limiting crop development. As a result, coffee development is reported to be limited when about half of the available soil moisture is depleted. Enden and Hombunaka (1999) reported this in a research work in Kenya which examined the influence of water deficiency on coffee growth. A period of water stress, induced by either dry soil or dry air, is needed to prepare flower buds for blossoming that is then stimulated by rainfall or irrigation. On the other hand, high amounts of water and nutrients are needed during the period of rapid fruit expansion to ensure large, high-quality seeds. Depending on the time and uniformity of flowering, this can occur at times when rainfall is unreliable, particularly in equatorial area (Carr, 2001).

2.2.7 Irrigation of coffee

Irrigation of coffee is mainly required in countries with a definite rainfall pattern spread over a period of 4 to 6 months. This type of rainfall is commonly referred to as Single Rainfall Regime (SRR). Under the SRR, the coffee bush is subjected to a drought period of 4 to 5 months. Countries like Vietnam, Africa and India depend on artificial irrigation to boost productivity (Titus and Pereira, 2002). In some coffee growing areas, supplemental irrigation is required as the annual rainfall is less than the seasonal crop water requirement and its distribution is usually erratic (Tesfaye *et al.*, 2008). The sustainability of irrigated coffee system production should be supported by three factors: high yield, high grain quality and yield costs reduction (Guerra *et al*., 2008a).

Irrigation aims to replace the water used by the crops or lost by evaporation or drainage through the soil with objects of producing the optimum yield and to apply water efficiently (Luke, 2006). In an effort to sustain high coffee yield, quality and environment in Kenya, irrigation along with other soil nutrient maintenance and protection schemes such as judicious use of fertilizers, green and farm yard manures, shade trees, intercropping, mulches etc were recommended (Njoka and Mochoge, 1997).

Mulching is the covering of the soil with a layer of dry vegetative materials. Its benefits include preservation of soil moisture, control of soil erosion, improvement of soil structure, supply of mineral nutrients in cases of decomposition, regulation of soil temperature, suppression of weeds and reduction of losses of nutrients applied in fertilizers. Mulch also protects the soil from raindrop impact and reduces velocity of runoff and wind. Due to these benefits mulch contributes to increased coffee yields and quality (Opile, 1995). Cai *et al*. (2006) reported that in many parts of China supplementary drip irrigation and rice straw mulching on the soil surface have been employed for centuries to preserve soil moisture in the coffee fields. Mechanical method to conserve water generated from runoff is another option. Mburu, (2004) recommended construction of terraces in form of earth embankments across the slope to intercept the surface runoff and convey it to the outlet at a non erosive velocity.

In countries like South America and Central America irrigation is not required because the rainfall is distributed throughout the year with no specific wet or dry season (Titus and Pereira, 2002).

Mitchell (1988) noted the advantages of irrigating coffee as follows as:

- Reduces drought period in coffee;
- Enhances the vegetative woods;
- Provides a reliable insurance cover against crop failure for the coming year;
- Increases the beneficial microbial content of the soil;
- Increases the organic matter decomposition in soil insitu because of the prevailing high temperatures;
- Provides the much needed micro climate, enabling the root zone to function effectively;
- Enables uniform fruit set and uniform berry size; and
- Improves the nutrient uptake.

Santana *et al*. (2004) reported that there were significant differences in all growth variables of two types of Arabica coffee at five irrigation levels in an experiment to determine the initial growth of two high-density coffee tree cultivars influenced by drip irrigation levels. In an experiment to evaluate the productivity and quality of coffee under drip irrigation in Uberaba MG, Brazil, Fernandes *et al*. (2008) observed that the productivities of non irrigated plantations were low compared to irrigated plantations. Areas irrigated with drip irrigation, showed productivity that was 95% higher than that without irrigation. The final quality of the beverage was seen to be better in irrigated sections than those without irrigation.

Gathaara *et al*. (1999) found that there was no significant yield increase above 50 mm of irrigation water application. This was concluded from field trial carried out on Arabica coffee Cultivar Ruiru 11 which was drip irrigated with five levels (0, 25, 50, 75 and 100 mm) and three irrigation intervals (21, 28 and 42 days). Results also showed that yield and quality were more responsive to the quantities of irrigation water than to the frequency of its application.

2.2.8 Deficit irrigation (DI)

Deficit irrigation is applying water below irrigation requirements to achieve economically acceptable reductions. Deficit irrigation is accomplished by allowing planned plant stress during one or more periods of the growing season. Deficit irrigation is also used when the water supply or the irrigation system limit water availability. In such situations the level of irrigation and the amount of land to be irrigated must be determined (Kihupi, 2000). Bakhsh *et al.* (2008) described drip irrigation as the most efficient irrigation method which can be used to apply deficit irrigation efficiently.

Irrigation is generally associated with minimising moisture stress. Under such conditions trees grow quickly and are very vigorous. Until a tree has reached its desired size it should not be stressed for water. Once the tree has grown to its desired size, however, vigorous growth not only increases the need for pruning but can reduce yield. Irrigation can be managed in such a way as to control the growth of shoots. Such management is known as regulated deficit irrigation (Goodwin, 2000). Irrigation supply under DI is reduced relative to that needed to meet maximum ETc (Fereres and Soriano, 2007).

Deficit irrigation is a common practice to mitigate drastic reductions in growth and yield of crop plants in areas of recurrent water scarcity and long dry spells (Tesfaye *et al.*, 2008). The resulting yield reduction may be small compared to benefits gained through diverting the saved water to irrigate other crops for which water will be normally insufficient under conventional irrigation practices (Chartzoulakis and Bertaki, 2001). Coffee plants are often intentionally water stressed to reduce vegetation growth and to encourage development of berries (Allen *et al.*, 1998). Alvim (1960) described water stress as a condition to break the dormancy of coffee flower buds.

2.2.9 Coffee yield response to water

With increasing water stress the yield starts to decrease. For many crops ETc shows a direct relationship with dry matter production or yield. When actual evapotranspiration (ETa) = ETc water supply is optimum; no stress exists and crop produces an optimum yield. On the other hand when ETa is reduced by stress, the yield will be less than optimum (Kihupi, 2000). The yield response of crops to drought and water deficits during the growing season is usually quantified by yield response factor Ky, based on the relationship described by Doorenbos and Kassam (1979).

Coffee yield response to available water is a major factor on yield prediction and irrigation feasibility. Results of irrigated and non irrigated yields on a 16 year field experiment with coffee plants carried out in Campinas, State of Sao Paulo, Brazil were analyzed as relative differences correlated to the relative differences of actual evapotranspiration. The annual yield response factor (Ky) showed a linear relationship to the plant age indicating an increase of plant sensitivity to water stress along the years (Arruda and Grande, 2003).

EARS (2008) reported that yield response factor is not known and surprisingly little has been reported on yield responses to drought. For that reason it established the relationship between drought and coffee yield using historical satellite data and historical data on coffee production. A relationship between the satellite-based agroclimatological data and reported coffee yields is built and used to provide future estimates. The relationship shows a strong correlation with a regression coefficient of 0.9. Coffee yield increases by 39 kg/ha with 1% increase in relative evapotranspiration and an offset of 1806 kg/ha. Relative evapotranspiration is defined as the ratio of actual to potential evapotranspiration.

2.3 Performance Evaluation of Drip Irrigation System

The evaluation of operating irrigation systems aims at understanding the system's adequacy and the determination of the necessary procedures for improving the system's performance. It is recommended that the evaluation should be carried out soon after system's establishment in the field, and periodically repeated, especially when considering drip irrigation systems, due to their sensitivity to operational conditions over time (Soccol *et al*., 2002).

An evaluation of an irrigation system will provide the necessary information for scientific irrigation scheduling. It will also show the existence of excessive application losses or whether the irrigation system needs service or improvement to increase application uniformity. The goal of system evaluation is to determine how much water is being applied and where it is going (Ley, 2003).

Meriam *et al*. (1980) identified four purposes for the work of performance evaluation as (a) To determine the efficiency of the system as it is being operated. (b) To determine how effectively the system can be operated and whether it can be improved. (c) To obtain information that will assist engineers in designing other systems. (d) To obtain information to enable comparing various methods, systems and operating procedures as a basis of economic decisions. Various criteria have been developed and used for evaluating irrigation system performance. They include mainly socio-economic and technical indicators of performance of irrigation systems. These are known as performance criteria of the system (Kanber *et al*., 2005). Several parameters are used in the evaluation of drip irrigation systems namely: efficiency, uniformity, wetted area and crop water productivity.

2.3.1 Adequacy of irrigation supply

When considering adequacy of irrigation supply two performance indicators are widely used namely relative water supply (RWS) and relative irrigation supply (RIS) (Knox *et al*., 2007). Relative water supply is the ratio of total water supply which includes Rainfall (P) and irrigation (I) to crop demand which is defined as crop evapotranspiration (ETc). Relative irrigation supply (RIS) is the ratio of irrigation supply to irrigation demand. Irrigation demand is defined as ETc less effective rainfall.

In interpreting RWS values, it is important to establish the critical RWS value below which water supply becomes inadequate. The value of one for RWS is the theoretical minimum requirement at the field level to ensure proper crop growth. If RWS is equal to or greater than one, then water supply is adequate to meet the theoretical optimum irrigation requirement (Sakthivadivel *et al*., 1993).

2.3.2 Uniformity

This is a measure which gives an indication of the evenness with which the irrigation was applied in the field (Karmeli *et al*., 1985). High uniformity of water distribution is required in drip irrigation system to minimize irrigation losses. After the system is installed, flow variation due to pressure differences, emitter plugging, temperature variation and aging have an adverse effect on uniformity (Hezarjaribi *et al.*, 2008). As higher uniformity of application is achieved, variation in the depths applied at different points in the field differs less from the average depth. This can be an important factor, particularly for high value crops, where small variations in irrigation uniformity can cause declines in crop quality. An irrigation system with good uniformity of application saves water, because it allows you to avoid over irrigating parts of the field while concentrating on putting adequate water on dry or other problem areas. (Ley, 2003).

Two indices of uniformity are used namely Christiansen's coefficient of uniformity (CU) (Christiansen, 1942) and Merriam and Keller's Emission Uniformity (EU) (Merriam and Keller, 1978).

The Christiansen's coefficient of uniformity is expressed as:

$$CU = \left(1 - \frac{D}{M}\right)100 \qquad (1)$$

Where: CU = coefficient of uniformity

D = average of the absolute values of the deviation from the mean discharge

M = average of discharge values

On the other hand, the emission uniformity is expressed as:

$$EU = \left(\frac{q_{LQ}}{q_a}\right)100 \qquad (2)$$

Where: EU = emission uniformity (%)

q_{LQ} = average of the lowest quarter of the observed discharge values

q_a = average of discharge values

The coefficient of uniformity and the emission uniformity generally increase with increasing heads and decrease with increasing slope (Ella *et al*., 2008).

2.3.3 Percentage of wetted area (PWA)

This is the proportion of the wetted area as compared to the whole irrigated area. A reasonable value for arid regions is to wet a minimum of 30%. For supplementary irrigation a value of PWA of 15-20% can be used (Vermeiren and Jobling, 1984). The wetting pattern is a function of only the dripper discharge and soil type. Karmeli *et al*. (1985) suggested empirically derived equations relating the wetted diameter (WD), to the emitter discharge for different soils. Once the wetted diameter is known, area wetted (AW) and wetted perimeter (WP) can be calculated. The percentage of wetted area under drip irrigation is dependent on the soil type and spacing of the emitters. When there is no overlap between wetting zones of adjacent sprayers or emitters, only the wetted area is considered. Equations 3 to 5 show some empirically determined relationships for WD determination under various textural classes (Karmeli *et al*., 1985).

$$WD = 1.2 + 0.1q_e \quad (\text{Fine soils}) \tag{3}$$

$$WD = 0.7 + 0.11q_e (\text{Medium soils}) \tag{4}$$

$$WD = 0.3 + 0.12q_e (\text{Coarse soils}) \tag{5}$$

Where: q_e = Emitter flow discharge in l/hr.

WD = Wetted diameter in m

In a study to determine the effect of different discharge values on the wetting patterns of a loamy sand soil under trickle soil in south Tunisia Thabet and Zayani (2008) found that low application rate (1.5 lh^{-1}) leads to water distribution in the horizontal direction while higher application rates (4 lh^{-1}) favoured the vertical direction of water for a given applied volume.

2.3.4 Crop water productivity

Crop water productivity (CWP) is defined as the relationship between the amount of crop produced or the economic value of the produce and the volume of water associated with crop production (Playan and Mateos, 2005). There are three dimensions of water productivity: physical productivity, expressed in kg per unit of water consumed; combined physical and economic productivity expressed in terms of net income returns from unit of water consumed, and economic productivity expressed in terms of net income returns from a given amount of water consumed against the opportunity cost of using the same amount of water (Kumar *et al*., 2005). The CWP considered in this study is physical productivity defined as: Mass of produce (kg) per volume of water supplied (m^3) expressed as (Playan and Mateos, 2005):

$$CWP = \frac{crop\ yield}{Ws} \tag{6}$$

Where: Ws = water supply

The crop water productivity definition is similar to crop water use efficiency (WUE) (Igbadun, 2006).

Kumar *et al*. (2005) defined two major ways of improving the physical productivity of water use in irrigated agriculture. First: the water consumption or depletion for producing a certain quantum of biomass for the same amount of land is reduced. Second: the yield generated for a particular crop is enhanced without changing the amount of water consumed or depleted per unit of land. Often these two improvements can happen together with an intervention either on the agronomic side or on the water control side.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location and size

The study was carried out at Kilimanjaro Plantation in Kibosho and Uru Divisions, Moshi District in Kilimanjaro Region. It is located between latitudes 3^{o}16’ South and longitudes 37^{o}19’ East. The altitude varies from 1050-1400 m.a.s.l. The plantation has a net area of 621 ha. Location map is shown on Fig. 1.

3.2 Climate

3.2.1 Temperature

Temperatures in the study area are at the highest in February/March and lowest in June/July. The minimum daily temperatures varies between 12.8^{o}C in August and 16.2^{o}C in April and the maximum between 21.1^{o}C in July and 28.6^{o}C in February (Appendix 1).

3.2.2 Rainfall

Kilimanjaro Plantation experiences a bimodal type of rainfall, characterized by what is known as long rains at the beginning of the year and short rains towards the end the year. The long rains fall between mid March right up to June while the short rains begin mid October to mid December. There are eight rainfall measuring stations at Kilimanjaro Plantation. That is each estate has one station. Records have been maintained since 2001 (Appendix 2). The mean annual rainfall over the 8-year period is 1408 mm. Annual rainfall ranged from low of 879 mm in 2003 to high of 2175 mm in 2006.

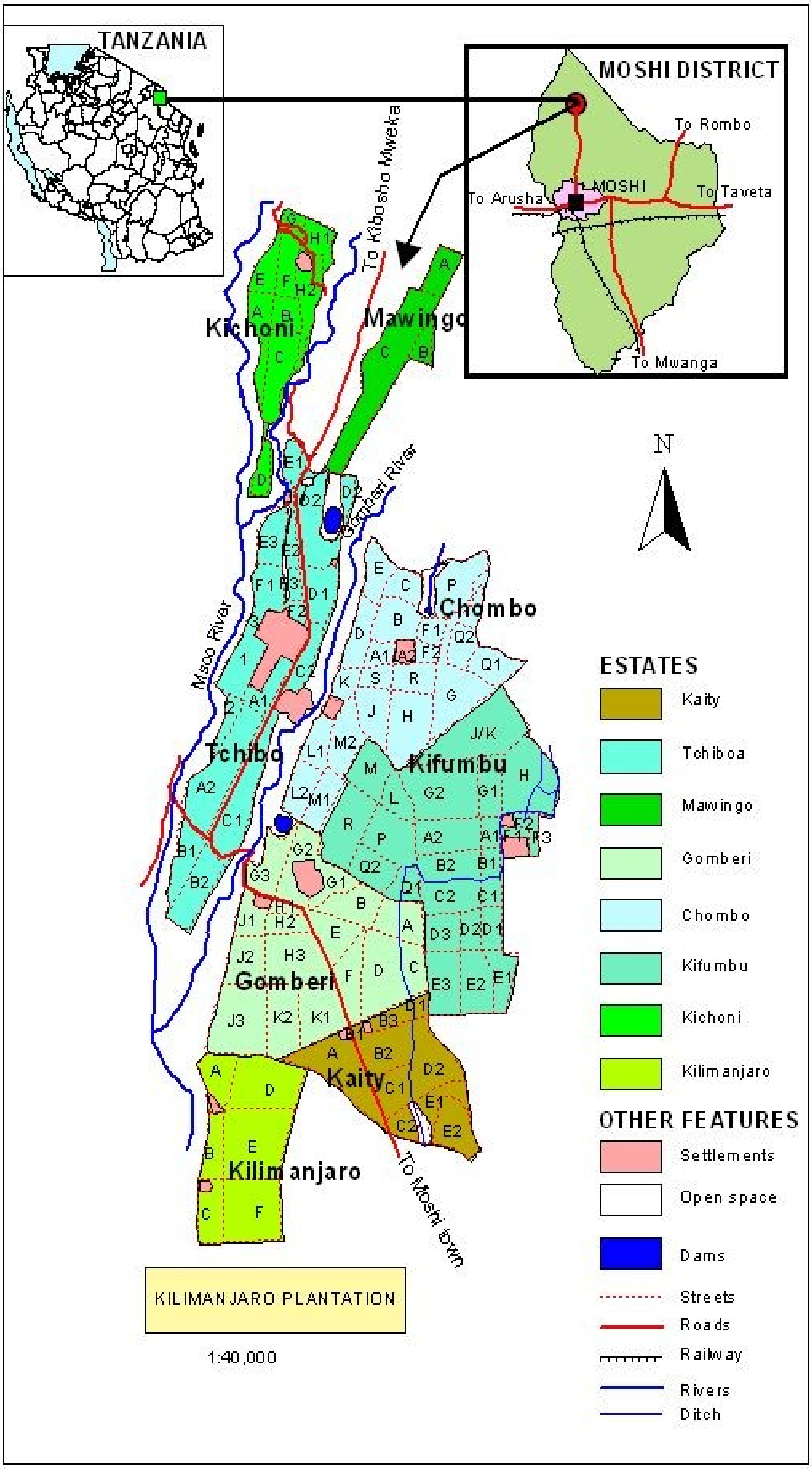

Figure 1: Location map of Kilimanjaro plantation in Moshi District, Kilimanjaro Region

3.2.3 Hydrology

The main water sources are Msoo, Lumbanga, Gomberi, Rau and Kyarongo rivers with a total capacity of 410 m^3/hr. The capacity of each river is indicated in Table 2. These were dry flows based on available measured quantities in February 2004 when the design of the drip irrigation system was done (KPL,2004). Table 4 also shows the area of each estate and its source of water.

Table 2: KPL River water sources and capacity

ESTATE	AREA Ha	RIVER SOURCE	CAPACITY m^3/hr
Kichoni	37.3	Msoo	30
Tchibo	90.55	Lumbanga	40
Chombo	100.15	Gomberi	40
Kifumbu & Kaity	198.01	Rau	150
Gomberi	111.31	Gomberi	0
Mawingo	27.66	Kyarongo	70
Kilimanjaro	55.58	Gomberi/Msoo confluence	80

Source: KPL, (2004)

3.3 Description of the Irrigation System

3.3.1 Layout of the irrigation system

Each irrigation section is served by independent pumping station from which a network of mains and sub mains convey water to section fields. Each pumping station is served by an open supply channel coming from river diversion weirs. Concrete diversion weirs were constructed across the river sources. The water is delivered to the reservoirs via canals. Part of the canals are lined with stone masonry. A number of spillways are installed along the canals over which possible surplus water can leave the irrigation system without causing harm to the system. The shape of all the reservoirs are rectangular with a provision of spillway. When water flows over the spillway it enters a drainage system. The earth reservoirs are covered with plastic membrane. From the reservoirs water is delivered into settling basins of capacity 525 m^3 ($30 \times 5 \times 3.5$ m) serving each estate.

From the settling basin the water is transported through a control head to a mainline of 200 mm pipe. The control head consists of pump, a series of disk filters, 1 valve, 2 pressure gauges, flow meter, fertigation equipment and automatic control unit. The mainline is connected to a sub main 75 mm diameter with a control unit at the head of each sub main. The control unit consists of 1 valve, 2 pressure gauges, air release valve and Inlet valve for fertigation. The control unit is protected by brickwork chamber of dimensions $1 \times 1.5 \times 2$ m with sliding steel door on top.

3.3.2 Underground system, lateral lines and field layout

The drip irrigation system used is Eurodrip irrigation systems from Greece. The underground pipe system is subdivided into the mainlines and sub main lines made of polyethylene (PE) pipes. They are buried 300 mm below the ground surface to allow other field operations. The submains are perpendicular to the direction of lateral lines. In some fields they run at the upstream edge of the field while in other fields they run in the middle of the field.

The laterals are made of polyethylene pipes. The size of the laterals varies from 16-20 mm diameter with emitter spacing of 0.75 m. The lateral lines are laid along the coffee rows one per row. The type of emitters are point source inline emitters. The flow rate is 2.4 l/hr at a pressure of 2.0 bars.

3.3.3 Operation of the system

The design was done under assumption that coffee under full production required an average of 100 mm per month during berry swell when overhead sprinklers were used. Due to efficiency of application in drip irrigation the amount was estimated to be half at 50 mm monthly. This is equivalent to 1.7 mm per day. (KPL, 2004).

1.7 mm of water per day per ha	=	17m^3/ha/day
Total coffee area	=	621 ha
Total water requirement therefore per day (24 hrs)	=	621 x 17m^3
	=	10,557m^3

The irrigation design was based on applying water in shifts so that total water application of 10,557m^3 (equivalent to 587m^3 per hr in 18 hrs) could be achieved. A 6 hr reserve per day was left for unexpected breakdowns or interruptions. This reserve also allows additional water application in selected blocks should the need arise (KPL, 2004).

3.3.4 Filtration system

Settling basins are provided at the end of each canal (Plate 1.). They serve as primary filtration unit increasing the efficiency of the secondary filters. Suspended particles that are heavier than water are removed by sedimentation process.

Plate 1: Settling basin

Filters are placed at the head of each main line. The types of filters used are disk filters (Plate 2). The filtration element consists of stack of grooved metal disks coated with epoxy and placed in a telescopic shaft inside a housing. Water flows through the disks from the outside inwards along the radii of the disks. Particles suspended in the water are trapped in the grooves of the disks, and clean water is collected in the center of the disks.

Plate 2: Disk filters

The disk filters are cleaned manually and automatically. During manual cleaning the housing is removed the telescopic shaft is expanded and the compressed disks separated for easy cleaning. They are normally cleaned by rinsing with water hose. The telescopic shaft prevents the individual disks from falling off the shaft during rinsing. Automatic back-flushing is triggered by preset pressure differential. The pressure differential opens the exhaust valve and water flows backwards through the disks, removing trapped particles from the grooves.

3.3.5 Fertigation

Fertigation is a system of applying fertilizer through the irrigation system. The method used to introduce fertilizer solution into the irrigation system is by means of pumps attached to fertilizer tanks hauled by a tractor. The fertilizer solution is introduced into the system under pressure in the control unit at head of the submain.

3.4 Data Collection

3.4.1 Sampling of the field

Convenience sampling technique was used to select the experimental plot. As the name implies, it is a non-probability sampling technique employed at the convenience of the researcher to reduce time and cost of collecting information. However, the drawback of the method is that it may not be representative of the entire population (Castillo, 2009). The plot was within Kifumbu estate block A1 (Fig. 1). The selected plot consisted of coffee plants which were 3 years old from which commercial yield is expected (Peasly and Rolfe, 2003). The irrigation of the field was reliable as it is under gravity system with available pressure of 2 bars. The coffee trees are N39 variety planted in March 2006. Coffee trees were spaced 3 m between the lines and 1.5 m between plants which provides a plant density of 2222 trees/ha.

3.4.2 Experimental design and treatments

The experimental design was randomized complete block design with five treatments replicated four times. Each block (R1-R4) had all the five treatments. The treatments included irrigation application levels: T1, T2, T3, T4 and T5 corresponding to flow rate 0, 0.6, 1.2, 1.8 and 2.4 lph/emitter respectively. Application volume of Treatment T5 was the normal volume adopted by the plantation. The size of the experimental blocks was 150 m x 12 m separated by a 9 m buffer area. The treatments were laid out as shown in

Fig. 2. Valves were installed at the head of each lateral in the experimental plot. The specified volume was attained by adjusting the valve and taking several measurements from an emitter using graduated cylinders until the desired volume is attained. The measurements were taken at four positions in the selected laterals i.e. at the beginning of the lateral, one third of the length, two thirds of the length and at the end of the lateral. The exercise was repeated during each irrigation event.

The experiment commenced on 1/1/2009. Prior to this irrigation was applied in the months of September to December 2008. This means all treatments including non irrigated treatment had received equal volume of 0.5904 m^3 per plant (Appendix 3).

3.4.3 Meteorological data

To find out to what extent irrigation can support the coffee crop and add to the production at Kilimanjaro plantation, historical meteorological data were collected from Lyamungo weather station. The station is located at Tanzania Coffee Research Institute (TACRI) at an altitude of 1268 m.a.s.l, 25 km west of the experimental site. Daily average values of rainfall, temperature, relative humidity, wind speed and sunshine hours (31 years of records ie 1977 to 2007) were obtained from this station. Appendix 4 and 5 give the summary of daily meteorological records and monthly long term rainfall records respectively.

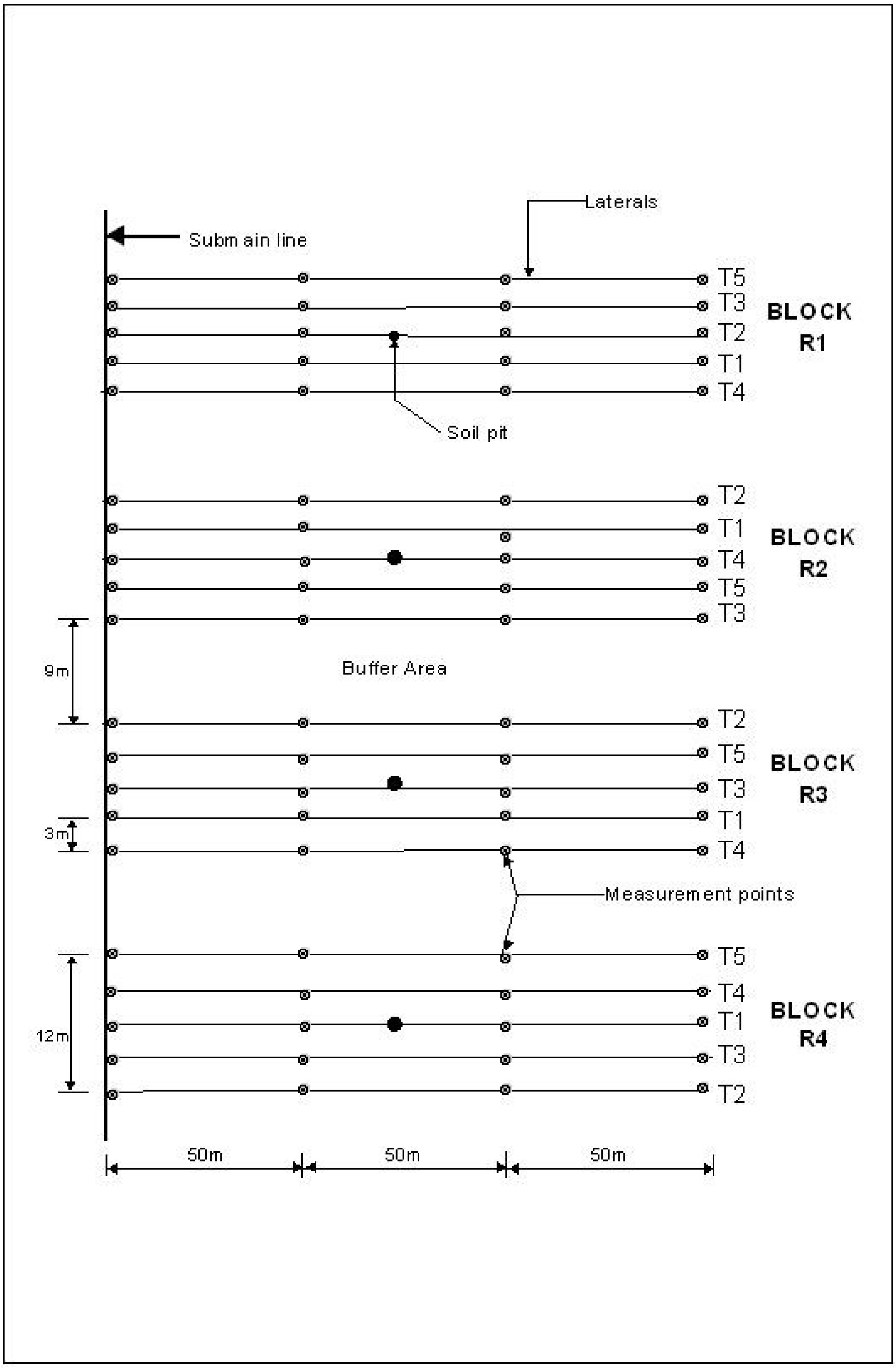

Figure 2: Sketch showing treatment layout within and between blocks

3.4.4 Measurements of system performance parameters

(i) Uniformity

The simplest approach to evaluate the performance of drip irrigation systems involves undertaking physical measurements of application rates using ‘catch cans’ as shown in Plate 3. Catch cans are small containers, which can be used to measure the volume of water emitted from a dripper over a given period of time. The volume of water is determined using a graduated container (Hornbuckle *et al*., 2007). By dividing the volume of water by the measurement time period, the drip system application can be determined.

Sixteen control points were selected in representative subunits with four laterals that is four control points per lateral (Keller and Karmeli, 1975). The four laterals were located at the beginning of the subunit, one third of the length of the subunit, two thirds of the length and at the end. Measurement points in the lateral were selected at the beginning of the lateral, one third of the length of the lateral, two thirds of the length and at the end .

(ii) Adequacy

The discharge computed in section 3.4.4 (i) was multiplied by irrigation duration to get the daily amount of water applied which was summed up for every month to obtain monthly irrigation amounts (Appendix 3). These along with mean monthly rainfall data (Appendix 2) were used to compute the RWS and RIS.

(iii) Percentage wetted area

The wetting pattern was determined by excavation using a shovel down to a depth of 30 cm. The diameter of excavation was roughly 80 cm. The wetted area was traced on a tracing paper 60 x 60 cm. Sixteen positions used for measuring uniformity (section i) were selected. The area was measured using a planimeter at a scale 1:1.

3.4.5 Soil physical properties

In order to gain information on the physical properties of the soils of the study area the following measurements were undertaken. The tests were done at Mlingano Research Institute laboratory in Tanga region.

Plate 3: Measuring application rate using catch cans

(i) Field capacity and bulk density

Soil samples for field capacity and bulk density were taken from pits 0.6 m deep dug at the centre of each experimental block as shown in Fig 4. The samples were taken using core samplers of known volume (98.2 cm^3) from depths 0-20 cm, 20-40 cm and 40-60 cm. Two samples were taken per depth thus giving six samples per pit. The samples were then sealed in containers to avoid moisture loss before being sent to the laboratory for analysis. Bulk density was calculated by dividing the oven-dry weight of the sample by the volume of the core sampler. Field capacity was determined as the moisture content at pF 2.4 (0.3 bar) using pressure plate apparatus.

(ii) Permanent wilting point

Soil samples for field capacity determination were also used to determine the permanent wilting point of the soil. Measurements of permanent wilting point were made from disturbed soil samples on a pressure plate apparatus in the laboratory. Wilting point was determined as the moisture content at pF 4.2 (15 bar).

3.4.6 Coffee yield

The method used in harvesting was selective picking. In this process ripe cherries were harvested by hand leaving behind the unripe cherries. Forty trees were selected that is 2 trees per treatment. There were 6 picks in the season which commenced on May up to August 2009.

3.5 Data Analysis

3.5.1 Calculation of crop water and irrigation requirements

Average monthly weather data derived from 31 years of record (1977-2007) were used to determine reference crop evapotranspiration (ETo) using FAO CROPWAT computer program. After determining ETo, ETcrop can be estimated using appropriate crop coefficients (Doorenbos and Pruitt, 1977).

For coffee crop Kc values range from 0.9 to 1.1(Allen *et al* ., 1998). In this study a crop coefficient of 0.9 was adopted (Doorenbos and Pruitt, 1977).

Crop water requirements under drip irrigation are lower than the conventional crop water requirements by a crop ground cover factor K_r. Since under drip irrigation only a portion of soil is wetted the evapotranspiration will be reduced (Goldberg *et al*., 1976; Keller and Karmeli, 1975). Table 3 shows values of K_r as recommended by different authors. According to Savva and Frenken (2002), Freeman and Garzoli (1994) recommended Kr values are the most conservative in terms of water application followed closely by Keller and Karmeli (1975). However, the difference between the three methods is negligible.

Table 3: Values of K_r recommended by different authors

Ground cover (GC) (%)	Crop factor K_r according to		
	Keller & Karmeli	**Freeman & Garzoli**	**Decroix**
10	0.12	0.10	0.20
20	0.24	0.20	0.30
30	0.35	0.30	0.40
40	0.47	0.40	0.50
50	0.59	0.75	0.60
60	0.70	0.80	0.70
70	0.82	0.85	0.80
80	0.94	0.90	0.90
90	1.00	0.95	1.00
100	1.00	1.00	1.00

Source: Savva and Frenken (2002)

In this study, since the coffee trees were matured a ground cover of 80 % was adopted (Savva and Frenken, 2002). Thus, K_r based on Keller and Karmeli (1975) value equal to 0.94 was adopted in determining the irrigation water requirement for evaluation purposes.

In order to estimate rainfall deficit a statistical analysis was made from long term rainfall records (32 years) to determine probabilities of rainfall or the amount of rainfall that is considered dependable.

Rainfall is a major climatic factor, which influences the crop growth. For management and planning purposes the information on the amount of rainfall which can be expected in a specific period under dry, normal and wet conditions (dependable rainfall) is important (Haque, 2005). Rainfall in wet, normal and dry years has been defined by Smith (1992) as the rainfall with respective 20, 50 and 80% probabilities of exceedance respectively. Frequency analysis for the monthly dependable rainfall was done using RAINBOW programme (Raes *et al*., 1990).

Similar frequency analysis was done for ETc. Monthly ETc is the amount calculated in section 3.5.1 times the number of days in a month. Effective rainfall was in this study estimated using the CROPWAT version 8.0 computer program USDA S C method (Kihupi, 2000).

The net and gross irrigation requirement per month was calculated using equations 8 and 9 respectively (Savva and Frenken, 2002).

$$IR_n = ET_c - Pe + LR \qquad (8)$$

$$IR_g = \frac{ETc}{E_a} - Pe + LR \qquad (9)$$

Where: IR_n = Net irrigation requirement (mm)

IR_g = Gross irrigation requirement (mm)

Pe = Effective precipitation (mm)

LR = Leaching requirement (mm)

E_a = Application efficiency (%)

= 90% for moderate climate (Savva and Frenken, 2002)

$$LR = LR_t \times \frac{IR_n}{E_a}. \qquad (10)$$

$$LR_t = \frac{EC_w}{2(max\,EC_e)} \qquad (11)$$

Where: LR_t = Leaching requirement ratio under drip irrigation

EC_w = Electrical conductivity of irrigation water (mmhos/cm)

max EC_e = Electrical conductivity of saturated soil extract that will reduce the crop yield to zero (mmhos/cm)

3.5.2 Irrigation scheduling

The maximum net amount that can be applied per irrigation was calculated by using Equation 12 (Vermeiren and Jobling, 1984).

$$IR_n = (\theta_{fc} - \theta_{pwp}) \times p \times Z_r \times P_w \qquad (12)$$

Where: IR_n = Max amount of water that can be applied (mm)

Θ_{fc} = Volumetric moisture content at field capacity (mm/m)

Θ_{pwp} = Volumetric moisture content at permanent wilting point (mm/m)

p = Maximum allowable depletion (%) (Appendix 14)

Z_r = Root zone depth (m)

P_w = Percentage wetted area (%)

Irrigation interval was calculated using equation 13

$$IF = \frac{IR_n}{ET_c} \qquad (13)$$

Irrigation duration was calculated using equation 14

$$I_t = \frac{IR_g / tree}{qr \times N} \qquad (14)$$

Where: qr = emitter flow rate l/hr

N = Number of emitters per plant.

3.5.3 Calculation of performance parameters

(i) Emission uniformity

Emission uniformity also termed Distribution uniformity is determined as a function of the relation between average flow emitted by the 25% of the emitters with lowest flow and the mean flow emitted by all control emitters as shown by Equation 2. The evaluated system is classified according to the EU values, following Merriam and Keller (1978) criterion as shown in Table 4.

Table 4: Systems classifications according to Emission Uniformity values (EU)

EU%	Classification
<70	Poor
70-80	Acceptable
80-90	Good
>90	Excellent

Source: Merriam and Keller (1978)

(ii) Adequacy of irrigation supply

Cumulative amounts of rainfall, ET_c and irrigation supply were computed during the whole period of the study. These were used to calculate the two performance indicators widely used, namely Relative Water Supply (RWS) and Relative Irrigation Supply (RIS). These were determined by the following equations (Knox, *et.al.*,2007):

$$\text{Re}\,lative\ water\ \text{sup}ply \;=\; \frac{Total\ water\ \text{sup}ply}{crop\ demand} \qquad (15)$$

$$Re\,lative\ irrigation\ supply \;=\; \frac{Irrigation\ supply}{Irrigation\ demand} \qquad (16)$$

Total water supply is defined as amount of rainfall (P) and irrigation (I) and crop demand is defined as the crop evapotranspiration or ETc. Irrigation supply is defined as contributions from irrigation (I) and irrigation demand is defined as ETc less effective rainfall (P). Effective rainfall was estimated using the CROPWAT version 8.0 computer program USDA S.C. method.

(iii) Percentage wetted area

Equation 3. by Karmelli *et al*. (1985) under Section 2.3.3 was used to calculate the wetted diameter from an estimate of soil type.

(iv) Crop water productivity (CWP)

The weight of the clean coffee was obtained by dividing the weight of cherry by 6 (Gathaara, 1999). CWP was calculated as units of coffee yield per unit of irrigation water applied.

3.5.4 Soil moisture deficit

The daily water balance, expressed in terms of depletion at the end of the day is estimated from Equation 17 (Allen *et al*., 1998).

$$SWD_i \;=\; SWD_{i-1} - \left(R_i - RO_i\right) - I_i - CR_i + ET_{c,i} + DP_i \qquad (17)$$

Where: $SWD_{,i}$ = Root zone depletion at the end of day (mm)

$SWD_{,i-1}$= Root zone depletion at the end of the preceding day (mm)

R_i = Precipitation on day i (mm)

RO_i = Runoff from the soil surface on day i (mm)

I_i = Net irrigation depth on day i (mm)

CR_i = Capillary rise from the groundwater table on day i (mm)

$ET_{c,\,i}$ = Crop evapotranspiration measured on day i (mm)

DP_i = Water loss out of the root zone by deep percolation on day i (mm)

Under drip irrigation CR_i, DP_i and RO_i don't apply . Therefore the SWD is expressed as:

$$SWD_i = SWD_{i-1} - R_i - I_i + ET_{c,i} \qquad (18)$$

Irrigation was done on 29 & 31/12/2008 (Appendix 3). It was assumed that the moisture content was at FC. To initiate the water balance for the root zone, the initial depletion $SWD_{r,i-1}$ was estimated to 0 mm on day 1.

3.5.5 Coffee yield response to water

Coffee yield obtained in Section 3.4.6. was divided by 2 to obtain yield per tree.

3.5.6 Statistical analysis

The statistical analysis model adopted in conformity with the experimental design described in section 3.4.2. was randomized complete block design having 1 factor irrigation application at 5 levels The statistical equation for the model is as given below (Montgomery,1984).

$$Y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij}. \quad (19)$$

Where: i = the level of factor which is 5

j = the number of replicate in each level which is 4.

Y_{ij} = the response variable due to (ij)th observation.

μ = the overall mean

α_i = the block effect

β_j = treatment or level effect

ε_{ij} = the experimental error.

SAS program was used to analyse yield data and water productivity i.e. the response variables. Treatment means were separated using Duncan's Multiple Range Test. The test of significance was based on p-value of 0.05.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Introduction

Performance evaluation of an irrigation system is done for various reasons among which could be to improve system operations, to assess progress against set objectives, to assess in general the status of the system, to identify constraints, and to understand the determinants of performance (Merriam and Keller, 1978). The results and discussions are confined to Kifumbu Estate where the experiment was conducted.

4.2 Rainfall Distribution and Irrigation Water Requirement

Results on dependable effective rainfall distribution and dependable ET_c are shown in Table 5.

Table 5: Dependable monthly dry, normal and wet year rainfall and ET_c (mm)

Month	Dependable monthly ET_c (mm)			Dependable effective monthly rainfall (mm)		
	Dry	Normal	Wet	Dry	Normal	Wet
January	113.8	106.8	98.0	8.0	36.0	123.3
February	107.7	100.4	91.5	6.7	38.5	66.3
March	107.1	100.8	91.5	36.7	86.5	155.3
April	87.5	77.3	74.0	263.3	502.0	721.3
May	79.4	74.2	69.9	269.7	397.0	549.7
June	76.1	70.7	66.1	45.3	87.0	159.3
July	83.5	77.0	69.2	30.7	62.0	91.3
August	84.3	79.1	70.8	15.3	35.0	62.5
September	93.8	89.5	83.3	6.3	12.0	24.3
October	109.0	99.7	91.5	5.3	22.0	77.5
November	98.7	95.2	85.7	24.0	62.5	111.3
December	105.7	100.1	87.4	32.3	85.0	169.3
Total	**1146.5**	**1070.8**	**978.9**	**743.6**	**1425.5**	**2311.4**

Dependable values for ET_c are compared to dependable effective rainfall for the dry year to calculate the net and gross irrigation requirement as shown in Table 6. and Fig. 3.

From Table 6 the following can be deduced:

(1) The average dependable yearly effective rainfall is 743.6 mm for dry years.

(2) The average annual ETc in the dry year is 1146.5 mm.

(3) The maximum gross irrigation requirement is 879.2 mm.

(4) Irrigation is required from June to March for the dry years.

(5) Actual application depth did not satisfy irrigation requirement in the all months.

Table 6: Rainfall distribution and irrigation water requirement

Month	**ET_c dry year mm/month**	**Rainfall, net and gross irrigation requirement in dry year (mm)**			**Id (mm)**
		Pe	**IR_n**	**IR_g**	
January	113.8	8.0	105.9	118.6	78
February	107.7	6.7	101.1	113.1	45
March	107.1	36.7	70.5	82.4	45
April	87.5	263.3	0	0	0
May	79.4	269.7	0	0	0
June	76.1	45.3	30.9	39.4	0
July	83.5	30.7	52.9	62.2	0
August	84.3	15.3	69.1	78.5	0
September	93.8	6.3	87.6	98.0	6
October	109.0	5.3	103.8	115.9	13
November	98.7	24.0	74.7	85.8	54
December	105.7	32.3	73.4	85.3	58
Total	**1146.5**	**743.6**	**769.9**	**879.2**	**299**

Id - Actual irrigation application depth (Appendix 6)

-

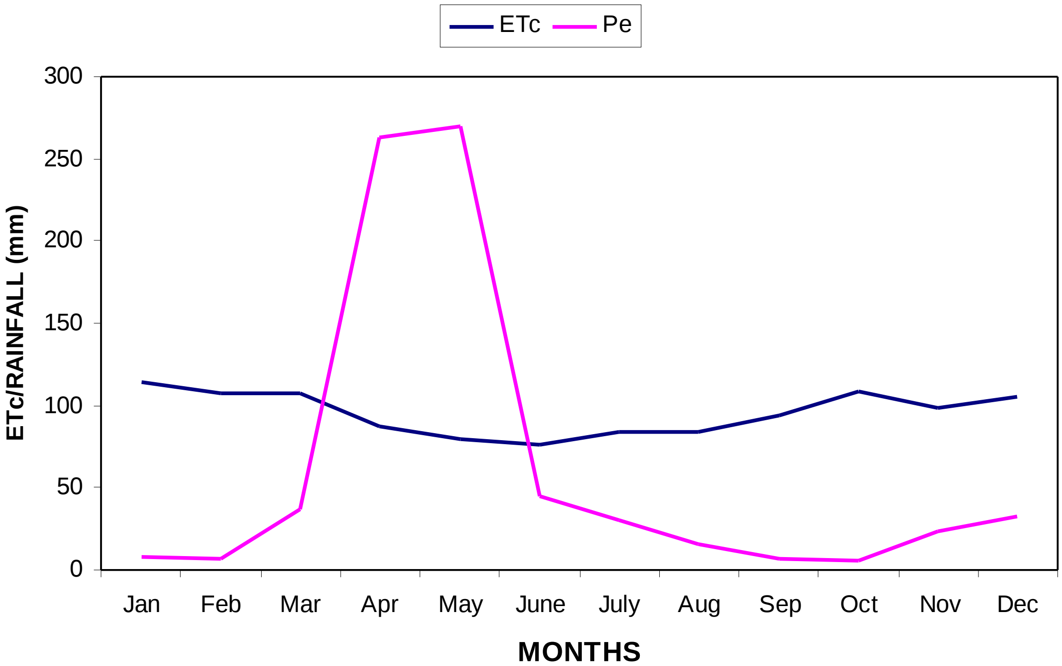

Figure 3: ET_c and expected rainfall amounts for each month at KPL with 20%and 80% probability of exceedance respectively

From the rainfall analysis irrigation is supposed to start in June and end in March for the dry year. However the practise in the plantation is to commence irrigation in October and end in March. This period is acceptable as the period of June to August is within the harvesting period. The period from August to October is the period of buds development (Kirenga, personal communication, 2009) when water stress is required in this period. According to Guerra *et al*. (2008b) a period of water stress of around 70 days is required for coffee buds synchronization resulting in high flowering and grain maturation uniformity.

Crisosto *et al*. (1992) recommended frequent irrigation to prevent flowering followed by a controlled water deficit and re-irrigation to stimulate flowering as a practical method to synchronize flowering and shorten the harvest period in leeward coffee production areas in Hawaii. Masarirambi *et al*. (2009) concluded that high soil moisture depletion followed with increased irrigation levels resulted in increased number of flowers and subsequent number of berries per bunch.

4.3 Irrigation Scheduling

The irrigation design was based on applying water in shifts so that total application objective of 10,557m^3 could be achieved (equivalent to 587 m^3 per hr in 18 hrs). A 6-hour reserve per day was left for unexpected breakdown or interruptions. The reserve also allows additional water application in selected blocks should need arise (KPL, 2004).

As shown in Appendix 3 the irrigation scheduling practised in the plantation was based on variable frequency and variable amount. The frequency varied from 1 - 8 days and irrigation duration varied from 4 - 14 hrs. This was because the person in charge with irrigation was engaged in other workshop activities hence he was unable to coordinate irrigation activities. The activity was left to estate managers who lacked the knowledge of irrigation water management.

Based on soil and plant parameters maximum application was calculated to be 90 l/tree. Irrigation interval was 5 days in the month of February and duration of application 19 hrs (Appendix 7).

Savva and Frenken (2002) recommended that drip irrigation system should be designed to operate as long as possible but not exceeding 90% of the available time nor more than 22 hrs per day to allow a safety margin for repairs.

The calculations for irrigation frequency were based on the peak demand in the month of February. Similar calculations were done for other months. Results are presented in Table 7 for the months which irrigation is required (section 4.2).

Table 7: Monthly irrigation frequency

Month	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
IF	6	6	6	6	5	6

4.4 System Performance Parameters

4.4.1 Emission Uniformity

The Emission Uniformity was determined to be 94% (Appendix 8). The values are above those recommended (Table 2) indicating that the EU in the representative block was excellent.

4.4.2 Percentage wetted area

The wetted area measured is as shown in table in Table 8. It ranged from 0.12 to 0.21 m^2. The measurement was taken on laterals with average discharge rate of 2.5 l/hr per emitter (Table 9). Irrigation was done for 6 hours the previous day.

Table 8: Measured wetted area in m^2

LATERAL	**POSITION**			
	0	**1/3**	**2/3**	**end**
I	0.18	0.15	0.14	0.14
II	0.21	0.14	0.15	0.18
III	0.16	0.20	0.14	0.12
IV	0.17	0.13	0.12	0.14

Table 9: Measured emitter flow rate in lph

LATERAL	**POSITION**			
	0	**1/3**	**2/3**	**end**
I	2.6	2.5	2.4	2.5
II	2.7	2.4	2.3	2.5
III	2.4	2.6	2.2	2.4
IV	2.7	2.4	2.4	2.6

Table 8 shows wetted area decreasing towards the end for the majority of the laterals tested. This corresponds to the emitter flow rates shown in Table 9 which are higher at the beginning of the laterals. The number of emitters per lateral is 200. The wetted area at position 1/3 of the lateral is higher because the emitter flow rate at that position was high. The measured values are very small compared to calculated values using Equation 3 which is 1.63 m^2 for fine soils. It is generally recommended that a sufficiently large fraction of the root zone be wetted by irrigation to ensure adequate water and nutrient supply to the plant (Sepulveda and Zazueta, 2004). This suggests that irrigation application duration should be increased.

Acar *et al*. (2009) found that higher emitter discharges increased both vertical and lateral wetting advances and wetted volume in loam or clay soil from irrigated source in Turkey.

4.4.3 Adequacy of irrigation supply

Adequacy of irrigation is determined by evaluating two indicators namely RWS and RIS. RWS relates the water made available to the crop including irrigation and rainfall to the crop demand. It provides information on the relative excess or scarcity of water supplied. RIS indicates how well the irrigation supply and crop demand is matched. Results are as shown in Table 10.

Table 10: Irrigation performance indicators (RWS and RIS) for each month

Month	P_e (mm)	I_d (mm)	ET_c (mm)	Total Water Supply (mm)	Irrigation Demand (mm)	RWS	RIS
Oct	32.2	12.8	99.7	45.0	67.5	0.45	0.19
Nov	39.2	54.4	95.2	93.6	56.0	0.98	0.97
Dec	13.7	57.6	100.1	71.3	86.4	0.71	0.67
Jan	26.7	77.9	106.8	104.6	80.1	0.98	0.97
Feb	35.3	44.8	100.4	80.1	65.1	0.80	0.69
Mar	29.6	44.8	100.8	74.4	71.2	0.74	0.63

The RWS ranged from 0.45 in the month of October to 0.98 in the month of November and January. The values are below the critical value (1.0) confirming that the amount supplied both by rainfall and irrigation did not match the crop demand.

The RIS ranged from 0.19 to 0.97. The values are below 1 indicating that the crop was not getting enough water (IWMI, 2000). A value greater than 1 implies that too much water has been supplied possibly causing water logging and negatively impacting yields (Knox, *et al.*, 2007).

4.5 Irrigation Water Quality

The characteristics of the water samples are presented in Table 11. The pH value is less than 7.0 indicating that the water is acidic. This characteristic prevents the possibility of calcium precipitation which may form a scale that sticks tightly inside walls of pipes which eventually blocks the water line and clogs emitters (Lamont, 2005; Schultheis, 2005).

The levels of electrical conductivity (EC_w) of less than 0.75 mmhos/cm indicate that the water used for irrigation cannot cause salinity problems (Ayers and Westcot, 1976). This value is also less than electrical conductivity of the saturated soil extract that will not decrease the crop yield (min EC_e which ranges from 1.7 – 4.0 mmhos/cm for fruit and nut crops)(Appendix 9). This indicates that no yield reduction can be expected from this water.

Table 11: Irrigation water quality characteristics

Parameter	Units	Values
pH		6.20
Ca	mg/L	5.00
Mg	mg/L	19.00
K	mg/L	2.15
Na	mg/L	4.33

EC_w	mmhos/cm	0.5

4.6 Soil Physical and Chemical Properties

A summary of physical properties of soil is presented in Table 12. The textural analysis showed composition of soil as clay for a profile of 60 cm of the top soil. The average bulk density values ranged from 1.04 to 1.15 g/cm^3 for the same. Porosity ranged from 35.8 – 58.0%. Obso (2006) reported that optimum soil moisture levels and low to medium soil bulk densities are necessary to enhance healthy roots and shoot growth of coffee seedlings. Soil porosity is also important and soils with porosity 50-60%, are best suited for coffee plant growth (D'Souza and Jayarama, 2006). This indicates that the soils in the study area are suited for coffee production.

Soil chemical properties are shown in Table 13. The N value varies from 0.02 to 0.19% and P value varies from 6.83 to 17.42 ppm. All these values are below the recommended values in Table 1. This may affect coffee yield. Bornemisza (1982) described N as the most important among the soil nutrients taken by the coffee plant. The pH values ranges from 4.8 to 5.6. The values are within that recommended in Table 1.

Table 12: Soil physical properties

Block	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Bulk density (g/cm^3)	FC (% vol)	PWP (% vol)	Porosity (%)	Textural class
I	0-20	54	28	18	1.04	23.7	17.1	47.2	C
	20-40	56	44	20	1.04	24.0	18.1	45.5	SC
	40-60	54	26	20	1.07	25.6	12.8	43.9	C
II	0-20	48	24	28	1.09	15.5	13.0	35.8	C
	20-40	58	20	22	1.06	31.0	11.3	50.5	C
	40-60	60	20	20	1.07	31.4	11.2	50.2	C
III	0-20	52	22	26	1.07	38.5	11.3	58.0	C
	20-40	58	20	22	1.07	30.7	11.0	51.1	C
	40-60	60	20	20	1.09	40.1	10.6	56.5	C
IV	0-20	48	24	28	1.08	39.7	11.7	53.4	C
	20-40	56	22	22	1.08	26.4	11.6	39.4	C

	40-60	70	8	22	1.15	44.7	10.5	47.2	C

C: Clay, SC: Silty clay

D'Souza and Jayarama (2006) and Goldberg, *et al*. (1976) recommended regular soil analysis as coffee plants remove a lot of minerals and other nutrients from the soil. This will indicate the lower nutrient levels which have to be replaced with adequate external application to maintain soil fertility balance. Conversely if the analysis shows too high levels of nutrients it may be necessary to leach the soil and then refertilize with the necessary elements.

Soil salinity values range from 0.6 – 1.2 dS/m (Table 13). These are below the minimum values reported by Keller and Bliesner (1990) for fruit and nut crops which range from 1.7 – 4.0 dS/m (Appendix 9) indicating that salinity in the soils will not reduce coffee yield.

Table 13: Soil chemical properties

Soil depth (cm)	Organic matter (%)	pH	Soil salinity (dS/m)	N (%)	P ppm
0 - 20	2.67	4.8	1.2	0.19	17.42
20 – 40	1.65	5.4	0.6	0.02	12.78
40 -60	1.20	5.6	0.6	0.02	6.83

4.7 Maintenance of Irrigation System and Equipment

Maintenance of canals consisted of grass cutting, desilting of the canals and repairing of the lined portion. Canals were regularly cleaned and desilted which included removal of all vegetation in the unlined portions. Such vegetation is useful in protecting the canal banks. The effect of this is that it does not only cause erosion of the canal banks but also increases the volume of sediments in the canals which is harmful to the drip irrigation system. Severe leakages were also observed along the canals during the study period worsening the situation of water scarcity problem. The diversion weir across the Rau river did not have sufficient protection putting it in danger of collapsing in case of severe floods.

Tensiometers which were used to monitor the soil moisture content were all out of order. These instruments are used to measure the energy status (or potential) of soil water. The measurement is a very useful one because it is directly related to the ability of plants to extract water from soil (Smajstrla and Harrison, 2002). Tensiometer readings indicate when irrigation should begin. In general the tensiometers prevent overirrigation and waste of water and soil nutrients (Tekinel and Kanber, 2005). The range of tensiometer operation is limited to 0 to about 85 cb. Above 85 cb the column of water in the glass tube will form water bubbles and the instrument will cease to function (Smajstrla and Harrison, 2002). From the data presented on irrigation interval and duration this might be the reason the tensiometers ceased to function.

For that reason it is important to replace the instruments. Clause (2005) recommended placement of two tensiometers per station one in the rootzone and one below the root zone. The shallow instrument tells when to start irrigation while the deep instrument evaluates the penetration of the moisture. Placement should be at the edge of the wetted area under tree canopy. Table 14 gives recommended depths of tensiometer installation.

Table 14: Recommended depth for tensiometers

Root system (cm)	**Shallow instrument (cm)**	**Deep instrument (cm)**
<45	15 – 30	-
<60	15 – 20	45
<90	20 - 40	60
<120	30 - 45	90

Source: Tekinel and Kanber (2005)

In the study area two instrument were installed at each measurement site. One was installed at a depth of 30 cm and the other at a depth of 60 cm. The maximum rooting depth for coffee ranges from 0.9 – 1.5m (Appendix 10). The installation depth are within the recommended range in Table 15.

4.8 Tree Health

Coffee trees were in good health when the study commenced. The cherries were in the pin-head stage. In the course of the study the trees which were not irrigated (T_1) and those in T_2 treatments showed signs of wilting as shown in Plate 4. However they recovered after the showers which occurred in early April 2009. Maturity of the cherry was very much delayed in these treatments.

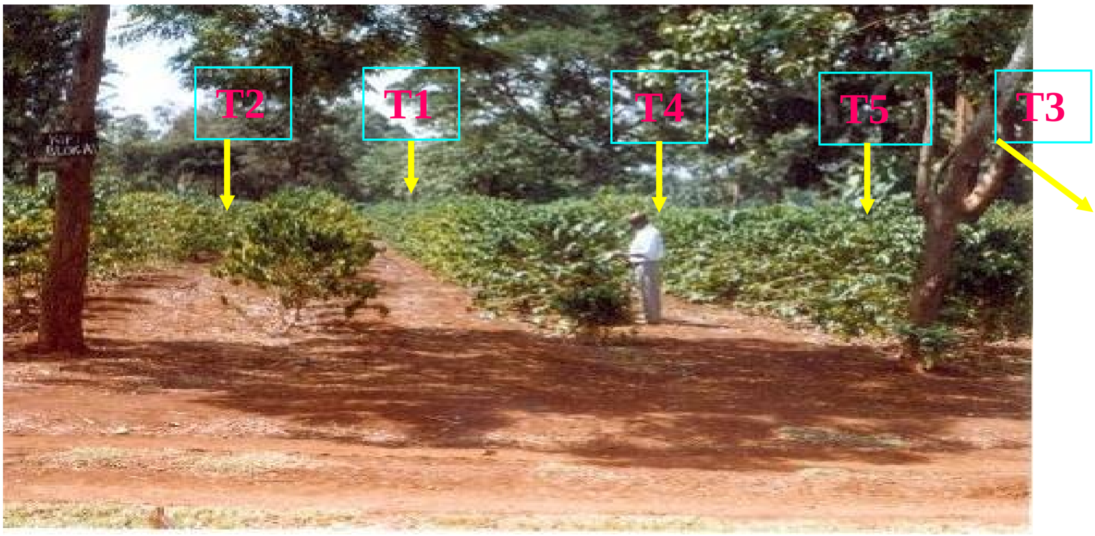

Plate 4: Coffee health status for different treatments in typical block during study period

4.9 Soil Moisture Deficit

The soil moisture depletion in the root zone was monitored using a soil water balance technique (Appendix 11). Fig. 4 shows graphically the estimated soil moisture depletion in the root zone for treatment T5 application level. The figure indicate that beyond 54^{th} day (23^{rd} February) the soil water deficit was greater than readily available water (RAW) indicating that there was under irrigation in that period. This was mainly due to diminishing water levels in the supply canal.

In irrigation, the aim is to replenish the root zone moisture to field capacity (FC). The criteria of when to irrigate is normally when the critical point i.e. maximum allowable deficit (MAD) is reached (Clause, 2005). In irrigation, water should remain above the MAD, which is usually taken to be equal to 50 % or the determined MAD level in order to optimise yield. The MAD level in this study was 45% (Appendix 7). Beyond the MAD ease of water uptake is reduced thereby stressing the plant. The stress caused may result in yield reduction. The severity of water stress beyond the MAD will vary with soil type. The problem with the irrigation schedule at KPL is that it did not take into account the level of moisture depletion in the root zone.

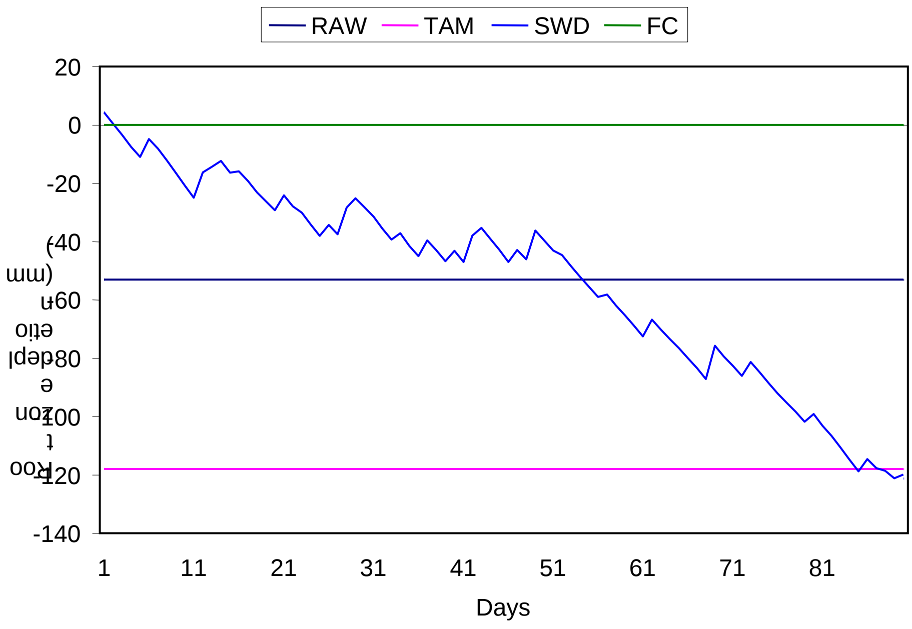

Figure 4: Soil moisture depletion in the root zone for irrigation treatment T5

4.10 Coffee Yield Response to Water/Crop Water Productivity

Table 15 present the summation of all 6 picks. The weight of the clean coffee was obtained by dividing the weight of cherry by 6 (Gathaara, 1999). Total yield per ha was obtained by multiplying by the number of coffee trees per ha which is 2222 trees.

Table 15: Coffee cherry yield data kg per tree

TREATMENT	REPLICATION				MEAN
	R1	R2	R3	R4	
T1	6.05	6.10	5.84	4.10	5.52
T2	5.60	6.72	5.65	4.45	5.61
T3	6.62	6.60	6.59	5.40	6.30
T4	6.99	8.82	7.94	6.60	7.59
T5	8.59	8.74	8.44	6.04	7.95

Coffee yield and CWP results are summarized in Table 16. Treatments affected coffee yield significantly at 5% significance level (Table 17). The best treatment with respect to yield of coffee was T5 which produced mean yield of 2945 kg/ha while treatment T1 produced the least yield of 2045 kg/ha. This difference in yield can be attributed to the different amounts of water applied to these treatments. Treatment T1 and Treatment T2 did not differ significantly.

Table 15: Coffee yield and water productivity

TRT	Clean coffee yield (kg/ha) Replications				Total	Mean (kg/ha)	Irrigation application (mm)	CWP kg/m³
	R1	R2	R3	R4				
T1	2 241	2 259	2 163	1 518	8 181	2 045[d]	131[e]	1.56[a]
T2	2 073	2 489	2 092	1 648	8 302	2 076[d]	176[d]	1.18[b]
T3	2 452	2 444	2 440	2 004	9 340	2 335[c]	221[c]	1.06[bc]
T4	2 589	3 266	2 940	2 444	11 239	2 810[a]	266[b]	1.05[bc]
T5	3 181	3 237	3 126	2 237	11 781	2 945[b]	311[a]	0.95[c]

Different letters within the column indicate significant difference at P<0.05;

Table 16: Analysis of variance for coffee yield among different treatments

Source	d.f.	Sum of Squares	Mean Square	F Value	Table F 0.05
Treatment	4	2 765 788	691 447	5.30	3.06
Error	15	1 959 597	130 640		
Corrected Total	**19**	**4 725 385**			

Other researchers have reported similar results. According to Gomes *et al*. (2007) the yield falls in the range of 1359 kg/ha without irrigation to 2707 kg/ha for application depth of 60% class A evaporation pan. Gathaara *et al*. (1993) found that the lower yield limit for unirrigated trees was 2080 kg/ha and maximum yield under drip irrigation was 3000 kg/ha for plant density of 2625 trees/ha. In an experiment to study the effect of drip irrigation on coffee with plant density 5290 trees/ha in Kenya, it was found that yield per hectare without irrigation was 3.92 t/ha, whereas with drip irrigation it increased to 4.46 t/ha (Chauhan, 2001). In Brazil in the second year after planting it was found that yield with no irrigation was 100 kg/ha, with sprinkler irrigation it was 1400 kg/ha whereas with drip irrigation it was 2800 kg/ha (Chauhan,2001).

There was significant differences (P<0.05%) in water productivity among treatments (Table 18). The best treatment with respect to the WP of coffee was T1 which produced WP of 1.56 kg/m^3 while T5 showed the least WP of 0.95 kg/m^3. T3 and T4 did not differ significantly. The results from this study are in close agreement with those of Peasley and Rolfe, (2003) who obtained WP of 0.68 and 2.1 kg/m^3 from use of 4.11 Megalitres(ML)/ha and 1.23 ML/ha respectively.

Table 17: Analysis of variance for CWP among different treatments

Source	**d.f.**	**Sum of Squares**	**Mean Square**	**F Value**	**Table F 0.05**
Treatment	4	0.898	0.225	6.62	3.06
Error	15	0.503	0.034		
Corrected Total	**19**	**1.401**			

The yield response to water for the 5 irrigation application levels is shown in Fig. 5. From Fig.5, the following can be deduced:

(i) There is a positive linear relationship between applied water and coffee yield.(R^2 = 0.9288)

(ii) The intercept means that there is still some yield of 1197.6 kg/ha even if no irrigation water is supplied.

(iii) The amount of irrigation water applied was limited to what was supplied by the plantation. Thus the optimum amount that could result in maximum yield was not attained.

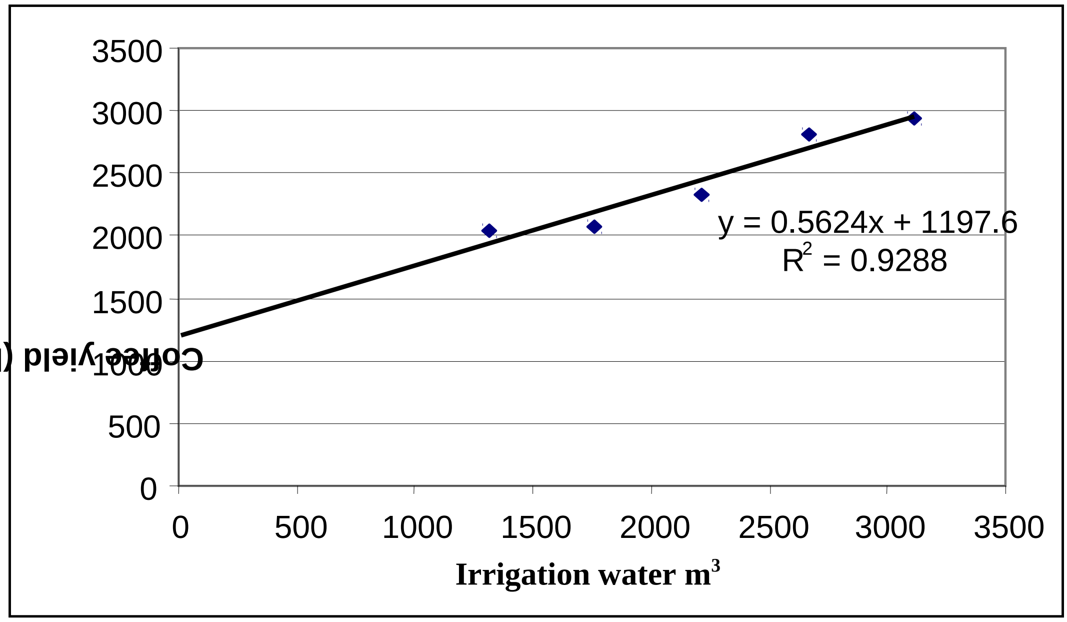

Figure 5: Relationship between amount of irrigation water and coffee yield

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

Due to limited resources (time and funds) the study was limited to Kifumbu Estate , one of the Estates of KPL. Most of the conclusions and recommendations drawn are confined to this estate. Hence they cannot be taken to represent the whole plantation.

5.1 Conclusions

(i) Lack of water management knowledge played a big role on the coffee estate's irrigation schedules. Given the issue of increasing costs and scarcity of water for irrigation purposes the research has supplied important information to the management as to the precise amount of irrigation water required for the plantation and appropriate irrigation scheduling required. That is daily application of 18 litres per tree or applying 90 litres/tree with irrigation frequency of 5 - 6 days.

(ii) The Emission Uniformity (EU) of the drip irrigation system was within recommended range of uniformity for drip irrigation systems. However the wetted area was not sufficient due to low application duration.

(iii) The RWS and RIS are below 1 indicating that supply from irrigation and rainfall did not meet the crop demand. This was mainly due to diminishing water level in the supply canals.

(iv) The best treatment was T5 which received cumulative amount of 3114m^3/ha to produce 2954 kg/ha. However this was limited to what was supplied by plantation.

5.2 Recommendations

(i) Further research covering other parts of the plantation should be conducted to corroborate results from this study.

(ii) To mitigate the water scarcity problem irrigation should be practised with mulches. Further deficit irrigation management should be adopted and mechanical methods should be employed to conserve water generated from runoff. Canal systems should be rehabilitated and if possible the whole length should be lined to minimize the losses due to leakages. It will also minimize the volume of sediments in the irrigation system. The number of storage reservoirs should be increased by sacrificing a certain portion of land to accommodate water during the period when irrigation is not required i.e. August – September.

(iv) Additional equipment should be added to the weather station for measuring wind speed and sunshine. Tanzania Meteorological Agency should be consulted for proper equipment and appropriate location to install them. Replacement of the tensiometers is also recommended.

(v) Short courses to irrigation staff on drip irrigation water management may improve water management strategies under conditions of water scarcity.

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APPENDICES

Appendix 1: Summary of monthly long term climatic records (31 Years)

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Max temp (ºC)	27.8	28.6	27.1	24.4	23.1	21.4	21.1	21.7	23.9	25.8	26.3	26.4
Min temp (ºC)	14.2	14.5	15.2	16.2	15.5	14.0	13.2	12.8	12.8	13.4	14.5	14.6
Mean temp (ºC)	21.0	21.6	21.2	20.3	19.3	17.7	17.2	17.3	18.4	19.6	20.4	20.5
Dewpoint (ºC)	17.4	17.2	18.0	18.3	16.9	15.2	13.9	14.4	14.7	15.9	16.9	17.8
Max RH (%)	79	76	81	90	93	90	90	90	87	83	84	82
Min RH (%)	56	54	60	70	74	70	67	64	60	56	60	60
Mean RH (%)	68	65	71	80	84	80	78	72	74	70	72	71
Wind (km/day)	75	79	75	66	69	70	71	73	80	89	80	69
Sunshine(h/day)	7.3	7.4	6.6	4.3	3.3	3.6	4.1	4.3	6.1	6.2	6.1	6.3
Epan (mm)	119.0	120.5	108.1	66.1	55.7	54.7	61.3	68.9	101.0	174.6	95.5	104.2

Appendix 2: Monthly rainfall for eight year and study period at KPL in mm.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	mean
2001	208	71	109	537	272	59	34	18	0	0	5	0	1313	109
2002	214	36	102	872	222	34	58	82	57	91	50	135	1953	163
2003	30	4	29	173	461	80	23	0	9	10	12	48	879	73
2004	62	53	39	364	122	45	17	11	5	141	25	53	937	78
2005	17	30	72	400	394	70	40	30	0	16	59	1	1129	94
2006	31	18	226	450	559	126	62	40	38	190	266	169	2175	181
2007	24	64	75	273	436	54	65	87	5	6	41	52	1182	99
2008	54	77	296	753	204	119	89	11	2	34	42	14	1695	141
2009	28	38	31	382	216	132								
Total	668	391	979	4204	2886	719	388	279	116	488	500	472	11263	
mean	74	43	109	467	321	80	49	35	15	61	63	59	1408	

Appendix 3: Irrigation application volume before and during the study period

DAY	Vol/plant	Irrigation duration	Vol/plant/day	Cumulative Vol
	l/hr	hrs	m^3	m^3
23/9/2008	4.8	6	0.0288	0.0288
21/10/2008	4.8	12	0.0576	0.0864
5/11/2008	4.8	6	0.0288	0.1152
7/11/2008	4.8	4	0.0192	0.1344
11/11/2008	4.8	6	0.0288	0.1632
13/11/2008	4.8	10	0.0480	0.2112
18/11/2008	4.8	7	0.0336	0.2448
22/11/2008	4.8	6	0.0288	0.2736
25/11/2008	4.8	6	0.0288	0.3024
28/11/2008	4.8	6	0.0288	0.3312
3/12/2008	4.8	6	0.0288	0.3600
10/12/2008	4.8	6	0.0288	0.3888
15/12/2008	4.8	6	0.0288	0.4176
16/12/2008	4.8	6	0.0288	0.4464
17/12/2008	4.8	4	0.0192	0.4656
21/12/2008	4.8	6	0.0288	0.4944
29/12/2008	4.8	12	0.0576	0.5520
31/12/2008	4.8	8	0.0384	0.5904

Irrigation treatment T2

DAY	Irrigation Interval (days)	Vol/plant l/hr	Irrigation duration hrs	Vol/plant/day m^3	Cumulative Vol m^3
31/12/08					0.5904
01/01/09		1.2	8	0.0096	0.6000
06/01/09	5	1.2	9	0.0108	0.6108
12/01/09	6	1.2	12	0.0144	0.6252
13/01/09	1	1.2	6	0.0072	0.6324
14/01/09	1	1.2	6	0.0072	0.6396
16/01/09	2	1.2	4	0.0048	0.6444
21/01/09	5	1.2	8	0.0096	0.6540
23/01/09	2	1.2	2	0.0024	0.6564
26/01/09	3	1.2	6	0.0072	0.6636
28/01/09	2	1.2	12	0.0144	0.6780
03/02/09	6	1.2	6	0.0072	0.6852
06/02/09	3	1.2	8	0.0096	0.6948
09/02/09	3	1.2	6	0.0072	0.7020
11/02/09	2	1.2	6	0.0072	0.7092
18/02/09	7	1.2	12	0.0144	0.7236
26/02/09	8	1.2	4	0.0048	0.7284
03/03/09	5	1.2	9	0.0108	0.7392
10/03/09	7	1.2	14	0.0168	0.7560
14/03/09	4	1.2	8	0.0096	0.7656
21/03/09	7	1.2	6	0.0072	0.7728
27/03/09	6	1.2	5	0.0060	0.7788
01/04/09	5	1.2	6	0.0072	0.7860
15/04/09	14	1.2	6	0.0072	0.7932

Irrigation treatment T3

DAY	Irrigation Interval (days)	Vol/plant l/hr	Irrigation duration hrs	Vol/plant/day m^3	Cumulative Vol m^3
31/12/08					0.5904
01/01/09		2.4	8	0.0192	0.6096
06/01/09	5	2.4	9	0.0216	0.6312
12/01/09	6	2.4	12	0.0288	0.6600
13/01/09	1	2.4	6	0.0144	0.6744
14/01/09	1	2.4	6	0.0144	0.6888
16/01/09	2	2.4	4	0.0096	0.6984
21/01/09	5	2.4	8	0.0192	0.7176
23/01/09	2	2.4	2	0.0048	0.7224
26/01/09	3	2.4	6	0.0144	0.7368
28/01/09	2	2.4	12	0.0288	0.7656
03/02/09	6	2.4	6	0.0144	0.7800
06/02/09	3	2.4	8	0.0192	0.7992
09/02/09	3	2.4	6	0.0144	0.8136
11/02/09	2	2.4	6	0.0144	0.8280
18/02/09	7	2.4	12	0.0288	0.8568
26/02/09	8	2.4	4	0.0096	0.8664
03/03/09	5	2.4	9	0.0216	0.8880
10/03/09	7	2.4	14	0.0336	0.9216
14/03/09	4	2.4	8	0.0192	0.9408
21/03/09	7	2.4	6	0.0144	0.9552
27/03/09	6	2.4	5	0.0120	0.9672
01/04/09	5	2.4	6	0.0144	0.9816
15/04/09	14	2.4	6	0.0144	0.9960

Irrigation treatment T4

DAY	Irrigation Interval (days)	Vol/plant l/hr	Irrigation duration hrs	Vol/plant/day m^3	Cumulative Vol m^3
31/12/08					0.5904
01/01/09		3.6	8	0.0288	0.6192
06/01/09	5	3.6	9	0.0324	0.6516
12/01/09	6	3.6	12	0.0432	0.6948
13/01/09	1	3.6	6	0.0216	0.7164
14/01/09	1	3.6	6	0.0216	0.7380
16/01/09	2	3.6	4	0.0144	0.7524
21/01/09	5	3.6	8	0.0288	0.7812
23/01/09	2	3.6	2	0.0072	0.7884
26/01/09	3	3.6	6	0.0216	0.8100
28/01/09	2	3.6	12	0.0432	0.8532
03/02/09	6	3.6	6	0.0216	0.8748
06/02/09	3	3.6	8	0.0288	0.9036
09/02/09	3	3.6	6	0.0216	0.9252
11/02/09	2	3.6	6	0.0216	0.9468
18/02/09	7	3.6	12	0.0432	0.9900
26/02/09	8	3.6	4	0.0144	1.0044
03/03/09	5	3.6	9	0.0324	1.0368
10/03/09	7	3.6	14	0.0504	1.0872
14/03/09	4	3.6	8	0.0288	1.1160
21/03/09	7	3.6	6	0.0216	1.1376
27/03/09	6	3.6	5	0.0180	1.1556
01/04/09	5	3.6	6	0.0216	1.1772
15/04/09	14	3.6	6	0.0216	1.1988

Irrigation treatment T5

DAY	**Irrigation Interval (days)**	**Vol/plant l/hr**	**Irrigation duration hrs**	**Vol/plant/day m^3**	**Cumulative Vol m^3**
31/12/08					0.5904
01/01/09		4.8	8	0.0384	0.6288
06/01/09	5	4.8	9	0.0432	0.6720
12/01/09	6	4.8	12	0.0576	0.7296
13/01/09	1	4.8	6	0.0288	0.7584
14/01/09	1	4.8	6	0.0288	0.7872
16/01/09	2	4.8	4	0.0192	0.8064
21/01/09	5	4.8	8	0.0384	0.8448
23/01/09	2	4.8	2	0.0096	0.8544
26/01/09	3	4.8	6	0.0288	0.8832
28/01/09	2	4.8	12	0.0576	0.9408
03/02/09	6	4.8	6	0.0288	0.9696
06/02/09	3	4.8	8	0.0384	1.0080
09/02/09	3	4.8	6	0.0288	1.0368
11/02/09	2	4.8	6	0.0288	1.0656
18/02/09	7	4.8	12	0.0576	1.1232
26/02/09	8	4.8	4	0.0192	1.1424
03/03/09	5	4.8	9	0.0432	1.1856
10/03/09	7	4.8	14	0.0672	1.2528
14/03/09	4	4.8	8	0.0384	1.2912
21/03/09	7	4.8	6	0.0288	1.3200
27/03/09	6	4.8	5	0.0240	1.3440
01/04/09	5	4.8	6	0.0288	1.3728
15/04/09	14	4.8	6	0.0288	1.4016

Appendix 4: Daily long-term climatic data (1977 – 2007)

Daily Dew Point Temperature (ºC)

Day	Month											
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
1	17.8	16.4	17.2	18.1	17.7	16.5	14.3	14.0	15.7	15.4	16.3	16.8
2	17.8	16.6	22.3	17.8	17.4	16.1	14.6	14.0	14.2	15.6	16.6	17.4
3	17.3	17.1	17.8	18.2	17.4	16.0	14.1	14.5	14.8	15.8	16.7	17.5
4	17.9	16.9	16.9	18.3	17.2	16.2	14.1	14.4	14.6	15.3	16.8	16.8
5	17.2	16.6	17.7	18.5	17.8	15.9	14.0	14.0	14.8	15.9	17.0	17.7
6	17.6	17.6	17.7	18.3	17.7	15.8	14.3	14.0	14.7	16.0	17.0	17.4
7	17.9	16.7	17.2	18.5	17.2	15.7	14.4	13.9	14.7	15.9	17.3	17.8
8	17.9	17.1	17.4	18.4	17.4	15.5	14.1	14.2	14.9	15.9	16.6	17.3
9	17.6	17.7	17.7	18.5	17.4	15.3	14.1	14.5	14.8	15.7	16.8	17.9
10	17.7	17.8	17.5	18.4	17.1	15.4	14.1	14.4	14.6	15.6	17.0	17.2
11	18.0	17.3	17.9	18.5	17.0	14.9	14.1	14.4	14.6	15.2	17.2	18.1
12	17.4	17.3	17.6	18.3	17.2	14.7	13.9	14.9	14.6	15.2	17.7	18.0
13	17.7	17.9	18.1	18.6	17.1	14.5	14.2	13.7	14.6	15.3	16.9	17.8
14	18.0	17.3	18.2	18.5	17.2	14.8	13.3	14.3	14.6	15.6	17.0	17.7
15	17.3	17.5	17.3	18.6	16.9	15.1	14.0	14.5	14.3	15.3	17.0	17.9
16	17.8	17.2	18.0	18.3	16.8	15.0	13.8	14.7	14.2	15.9	16.6	18.1
17	18.3	17.2	17.4	18.3	16.6	14.5	13.1	14.7	15.0	15.5	16.9	17.7
18	17.6	17.2	17.8	18.3	16.1	14.8	13.8	14.8	14.8	16.2	17.0	18.1
19	17.3	17.5	17.7	18.8	16.9	15.1	13.7	14.8	14.7	16.6	17.1	18.1
20	17.1	16.8	17.9	18.4	16.6	14.9	14.0	14.7	14.4	15.9	16.8	18.2
21	17.1	17.4	18.0	18.0	16.8	14.8	14.1	14.3	14.7	16.2	16.5	18.2
22	17.1	16.8	17.9	18.2	16.9	14.9	13.7	14.4	14.6	16.5	16.5	17.7
23	17.3	17.7	17.9	18.4	16.8	15.2	14.0	14.7	14.2	15.8	17.1	18.4
24	17.2	17.1	18.0	18.3	16.4	15.2	14.1	14.7	14.5	16.6	16.9	18.1
25	17.1	17.4	18.5	18.2	16.5	15.1	14.0	14.6	14.9	16.1	17.5	17.7
26	17.4	17.3	18.0	18.2	16.7	14.8	14.2	14.5	14.3	16.4	16.8	17.8
27	17.3	16.8	18.4	18.2	16.4	14.9	14.0	14.1	14.3	16.4	17.1	17.9
28	16.4	17.0	18.4	18.1	16.4	14.9	13.6	14.0	14.8	16.0	17.5	17.8
29	17.4	17.8	18.2	17.8	16.3	15.0	13.6	14.2	14.7	16.2	16.8	18.0
30	16.9		18.4	17.9	16.1	13.7	13.5	14.5	15.0	16.3	17.1	17.7
31	16.3		18.2		16.2		13.5	14.7		16.1		17.3
Total	540.7	498.9	557.3	548.9	524.3	455.2	432.2	445.9	439.7	492.3	508.3	550.3
mean	17.4	17.2	18.0	18.3	16.9	15.2	13.9	14.4	14.7	15.9	16.9	17.8

Daily Maximum Temperature (ºC)

Day	Month											
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
1	27.6	28.5	26.4	24.8	29.8	21.6	20.9	20.5	23.4	25.2	26.5	26.4
2	27.5	28.1	27.3	25.5	22.7	21.9	20.8	21.1	22.7	25.2	25.6	26.0

3	27.4	28.4	28.0	25.3	23.2	21.5	20.4	21.2	22.1	24.2	25.9	26.2
4	27.8	28.4	27.8	25.5	23.5	22.7	20.9	22.2	22.5	25.2	25.9	26.1
5	27.6	28.7	27.9	25.5	23.6	22.1	20.8	21.8	22.7	25.0	25.8	26.2
6	27.5	28.9	28.0	25.8	23.1	21.8	21.2	21.6	22.9	25.2	26.4	26.3
7	27.4	28.6	28.0	24.9	23.3	21.7	20.9	21.7	23.2	25.5	26.4	26.0
8	26.6	28.6	28.1	24.7	23.5	22.0	21.0	21.2	23.0	25.2	26.1	26.0
9	26.8	28.7	27.7	24.8	23.0	21.6	20.4	21.1	23.0	25.1	26.3	26.2
10	27.9	28.7	27.9	24.7	23.4	21.9	20.8	21.4	23.1	25.5	26.4	26.2
11	28.0	28.9	27.1	24.8	23.1	21.6	20.4	21.7	22.8	25.4	26.4	26.0
12	27.7	28.4	27.6	24.6	23.0	21.3	21.1	22.0	23.5	25.4	26.4	26.8
13	28.0	28.1	27.3	24.8	23.0	21.8	20.7	21.5	24.0	25.9	26.6	26.8
14	27.7	28.1	27.4	24.4	22.5	22.0	21.2	21.4	23.4	25.8	26.7	26.3
15	27.7	28.2	27.3	24.5	26.4	21.3	20.2	20.9	30.3	25.7	26.5	26.1
16	27.3	28.4	26.6	24.3	23.2	21.5	20.4	20.9	23.8	26.6	26.3	26.5
17	27.2	28.7	27.3	24.4	22.7	21.5	20.6	21.4	23.4	26.2	26.5	26.7
18	27.2	28.7	26.9	24.2	22.7	21.5	20.9	21.6	23.6	26.2	26.5	26.3
19	28.2	28.3	27.1	24.0	22.8	21.4	21.3	22.5	24.0	25.8	26.3	26.9
20	27.6	28.2	27.1	24.3	22.7	21.1	21.2	21.9	24.2	26.1	26.7	26.5
21	28.3	29.1	27.1	23.9	22.6	21.0	20.9	21.4	23.3	26.1	25.3	26.6
22	28.9	29.3	26.5	24.0	22.1	20.4	20.9	22.4	23.7	26.2	26.4	26.3
23	28.1	28.9	27.1	23.8	22.2	20.6	20.6	22.2	24.3	26.1	26.4	26.2
24	28.2	29.2	27.1	24.5	22.7	21.3	21.3	22.1	24.6	26.4	26.6	26.3
25	27.9	28.5	26.4	23.9	22.6	20.7	20.8	22.4	24.7	26.7	26.4	26.5
26	28.2	28.5	26.4	23.2	22.4	20.7	21.1	22.3	24.5	26.8	26.2	26.7
27	28.1	29.1	26.7	23.7	22.6	21.2	21.0	21.8	25.0	26.5	26.4	26.8
28	28.3	29.1	26.6	23.7	22.0	21.0	21.4	22.4	24.6	26.7	26.3	26.7
29	28.4	28.5	26.4	23.2	22.5	21.3	21.1	22.3	25.0	26.2	25.7	26.1
30	28.6		26.1	23.2	22.1	20.8	21.3	22.8	24.9	26.1	26.3	27.1
31	28.6		26.3		22.1		27.7	22.2		26.3		26.9
Total	862.4	829.9	841.3	733.1	717.0	642.5	654.2	673.6	716.0	800.5	788.4	818.5
mean	27.8	28.6	27.1	24.4	23.1	21.4	21.1	21.7	23.9	25.8	26.3	26.4

Daily Minimum Temperature (^oC)

Day	Month											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1	14.5	14.6	14.4	15.4	15.9	14.4	13.2	12.5	12.4	12.5	14.3	14.5
2	13.7	14.3	14.3	15.1	16.1	14.7	13.2	12.8	12.6	13.2	14.2	14.6
3	14.1	14.3	14.4	15.4	16.0	14.3	13.5	12.9	13.5	12.4	14.1	14.4
4	14.1	14.4	14.3	15.9	16.0	14.7	13.4	12.5	12.9	13.4	14.6	14.3
5	14.0	14.3	14.3	16.1	16.3	14.7	13.3	12.7	12.8	13.4	14.6	14.1
6	14.1	14.0	14.8	16.3	16.1	14.4	13.3	13.1	12.7	13.9	14.1	14.3
7	14.1	14.5	14.7	16.1	15.8	14.4	13.5	12.4	13.0	13.9	14.8	14.8
8	14.1	14.3	14.4	15.7	16.1	14.2	13.3	12.8	13.2	14.0	13.8	14.2
9	14.1	14.7	14.3	16.3	16.1	14.5	13.3	12.5	13.2	13.7	14.6	14.9
10	14.3	14.4	14.0	16.2	16.3	14.0	13.1	13.2	13.1	13.3	14.5	14.6

11	14.4	14.6	14.7	16.2	15.6	14.2	13.2	12.7	13.0	13.4	14.7	14.8
12	14.6	14.4	14.9	16.1	15.6	13.6	13.0	12.8	12.9	13.1	14.4	15.1
13	14.1	14.5	15.0	16.1	16.0	13.3	13.6	12.8	13.1	13.4	14.4	14.9
14	14.1	14.6	18.6	16.1	15.8	13.8	13.4	13.1	13.0	13.4	14.8	14.8
15	14.1	14.9	15.5	16.3	15.8	14.0	13.2	13.2	12.5	13.5	14.8	15.4
16	14.1	14.7	15.0	19.8	15.8	14.1	12.8	13.0	12.9	13.4	14.7	15.4
17	14.4	14.5	15.3	16.0	15.4	13.9	13.0	13.3	12.4	13.2	14.8	15.0
18	14.3	14.5	15.0	16.1	15.5	14.1	12.8	12.9	13.0	13.1	14.6	14.7
19	14.1	14.7	15.4	16.2	15.3	13.9	13.4	12.9	12.8	13.3	14.7	15.0
20	14.1	14.5	15.5	15.9	15.2	13.9	13.8	12.9	13.2	13.3	14.2	14.8
21	14.1	14.5	15.4	16.0	15.3	13.6	13.1	12.5	13.0	13.5	14.2	14.7
22	14.0	14.8	15.4	16.3	15.2	13.4	13.2	12.5	12.5	14.1	14.3	15.0
23	14.1	14.1	15.6	16.3	15.2	13.6	13.6	12.5	12.7	13.6	13.7	14.8
24	14.6	14.7	15.7	16.4	15.1	13.7	13.3	12.9	12.0	13.7	14.8	14.5
25	14.4	15.2	15.2	16.1	15.3	13.9	13.0	12.4	12.4	13.5	14.8	14.7
26	14.4	14.6	15.6	16.3	15.1	13.5	12.9	12.5	12.1	13.5	15.0	14.8
27	14.3	14.8	15.7	16.4	14.8	13.5	12.6	13.0	12.2	13.3	14.7	14.6
28	14.0	15.0	15.4	16.2	14.9	13.4	12.9	12.4	12.4	13.4	15.2	14.6
29	14.2	14.4	15.6	16.2	14.8	13.4	13.1	12.7	12.3	13.6	14.9	13.9
30	14.4		16.0	15.7	14.8	13.6	12.9	13.0	12.7	13.8	14.9	13.8
31	14.8		15.5		14.8		12.7	13.1		13.3		13.7
Total	440.5	421.8	470.2	484.9	482.0	418.8	408.5	396.4	382.6	416.0	436.4	453.4
mean	14.2	14.5	15.2	16.2	15.5	14.0	13.2	12.8	12.8	13.4	14.5	14.6

Daily Evaporation (mm/day)

Day	**Month**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1	3.5	4.1	4.0	2.9	1.5	1.6	1.7	1.8	2.6	5.4	3.5	3.5
2	3.5	4.1	4.1	2.8	1.6	1.7	1.9	1.9	3.0	5.5	3.5	3.4
3	3.8	4.2	4.1	2.5	3.5	1.7	1.7	2.1	2.8	5.7	3.2	3.4
4	3.5	4.2	4.2	2.5	1.6	1.8	2.4	2.4	2.6	6.2	3.3	3.2
5	3.5	4.4	4.0	3.1	3.8	1.8	1.8	2.0	2.9	5.9	3.3	3.3
6	3.4	4.1	4.0	2.5	1.5	1.8	1.8	2.1	3.0	5.7	3.1	3.1
7	3.3	4.0	4.1	3.0	1.7	1.8	2.0	2.2	3.1	6.1	3.0	3.4
8	3.7	4.4	4.1	2.6	1.6	1.7	1.8	1.7	3.1	5.8	3.0	3.1
9	3.7	4.1	3.5	2.3	1.6	1.6	1.6	2.4	3.1	5.7	3.4	3.3
10	4.1	4.2	3.9	2.6	1.7	2.0	1.7	1.9	2.6	5.2	3.0	2.9
11	3.9	4.2	3.5	2.4	2.0	2.0	1.5	2.2	3.0	5.5	3.1	3.4
12	3.7	4.2	3.7	2.2	1.6	2.2	1.7	2.1	3.5	5.4	3.3	3.8
13	3.8	4.0	3.4	2.1	1.6	2.1	1.9	2.0	3.1	6.2	3.3	3.2
14	3.5	3.8	3.5	2.3	1.5	2.3	2.0	2.3	3.4	5.2	3.4	3.2
15	3.6	3.9	3.5	1.8	1.7	2.0	2.0	3.3	3.5	6.6	3.2	3.4
16	3.9	4.1	3.4	1.7	1.8	1.9	1.8	1.9	3.5	6.4	3.2	3.0
17	3.6	4.3	3.5	2.2	1.9	1.6	1.9	2.2	3.6	5.6	3.1	3.3
18	3.8	4.0	3.6	1.9	1.8	1.8	1.7	2.0	3.1	5.1	3.6	3.3

19	4.2	4.0	3.3	2.0	1.6	1.9	2.1	2.3	3.6	5.4	3.1	3.8
20	3.7	4.2	3.7	2.0	1.4	2.2	2.1	2.3	3.5	5.5	3.1	3.5
21	4.3	4.3	2.8	1.8	1.6	1.6	1.8	2.1	3.5	5.1	2.8	3.6
22	4.0	4.4	3.0	1.9	1.5	1.7	1.5	2.3	3.6	5.6	3.4	3.2
23	4.3	4.1	3.3	1.9	1.6	1.5	1.9	2.2	3.9	5.9	2.7	3.4
24	4.0	4.2	3.1	2.0	1.7	1.7	2.0	2.6	3.8	5.8	3.0	3.1
25	3.7	3.8	3.1	1.8	1.8	1.7	1.9	2.5	3.7	6.1	3.2	3.4
26	4.1	4.2	2.8	1.9	1.6	1.6	2.3	2.0	4.2	5.5	3.2	3.6
27	4.4	4.2	3.0	1.8	1.7	2.0	2.3	2.6	3.9	6.0	3.1	3.7
28	4.0	4.5	3.2	2.0	1.9	1.7	2.0	2.2	4.1	5.7	3.3	3.4
29	4.5	4.5	3.1	1.6	1.7	2.0	1.8	2.6	4.0	5.7	3.1	3.8
30	3.9		2.8	1.8	1.8	1.8	2.0	2.7	3.6	5.6	3.0	3.5
31	4.2		3.1		1.9		4.7	1.9		3.3		3.5
Total	119.0	120.5	108.1	66.1	55.7	54.7	61.3	68.9	101.0	174.6	95.5	104.2
mean	3.8	4.2	3.5	2.2	1.8	1.8	2.0	2.2	3.4	5.6	3.2	3.4

Daily Sunshine(h/day)

Day	**Month**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1	6.9	7.7	7.6	6.1	2.6	3.8	3.8	4.7	5.3	5.7	6.8	6.1
2	7.1	7.5	7.4	5.8	2.6	2.7	4.4	3.7	5.2	5.4	6.5	6.9
3	7.7	7.5	7.4	5.9	3.8	4.1	4.1	5.1	4.3	4.9	6.1	6.5
4	7.3	7.7	6.9	5.4	2.9	4.3	3.8	5.4	4.7	6.0	5.6	6.8
5	6.8	7.8	7.6	5.2	3.3	3.7	3.8	4.1	5.5	5.9	6.7	7.1
6	7.3	7.9	7.5	4.8	3.0	4.6	3.8	4.4	5.5	6.1	6.7	6.4
7	7.2	7.5	7.6	4.8	3.3	4.1	4.1	3.8	4.5	5.2	5.7	6.4
8	7.5	7.7	7.4	4.3	2.8	2.7	4.6	4.0	4.8	5.2	6.6	6.4
9	8.2	7.9	7.3	4.5	3.8	3.9	3.4	4.2	5.3	6.2	6.3	6.0
10	7.1	7.7	7.1	4.5	3.8	3.5	3.3	4.4	5.5	6.4	5.6	6.4
11	7.4	7.7	6.6	5.1	3.7	3.8	3.7	5.2	6.2	6.7	5.9	6.4
12	7.1	6.9	6.6	4.3	3.3	4.3	3.4	3.9	6.5	6.2	6.3	6.3
13	6.7	7.3	6.6	4.0	2.4	4.7	4.1	4.7	5.9	6.2	6.7	6.6
14	7.2	7.1	6.5	4.5	2.7	3.7	3.5	3.6	6.2	6.1	6.7	5.7
15	6.9	7.9	6.1	4.7	3.5	3.2	3.4	3.1	6.7	6.5	5.6	5.8
16	7.2	7.8	6.6	4.6	3.0	3.3	3.0	3.5	6.4	5.9	6.4	6.0
17	7.0	8.0	5.7	4.4	4.2	3.3	3.9	3.4	6.1	6.6	5.9	5.6
18	7.9	7.7	5.8	4.1	3.1	3.3	5.0	4.6	6.2	6.4	6.0	6.3
19	7.2	7.4	6.7	4.5	2.4	3.0	4.6	5.1	5.8	5.9	6.5	6.5
20	7.9	8.4	8.0	3.9	3.2	3.6	3.8	4.3	5.8	6.4	5.8	6.4
21	8.1	7.8	5.8	4.1	2.4	2.9	3.5	5.4	5.9	6.3	6.5	5.1
22	7.4	7.8	6.0	4.5	3.3	3.5	3.5	5.2	7.1	6.5	6.4	5.2
23	7.3	7.5	6.2	4.9	3.4	3.3	4.2	4.4	7.2	6.6	6.3	5.2
24	7.5	7.4	5.6	4.2	4.3	2.7	3.7	4.4	6.5	6.7	5.9	6.2
25	7.5	7.8	5.7	3.4	3.8	2.8	4.2	4.6	6.4	7.3	5.6	6.1

26	7.5	7.7	5.8	4.0	3.4	3.9	4.8	4.1	7.5	7.1	4.9	6.3
27	7.6	7.5	6.4	3.4	3.2	3.9	4.0	3.8	7.2	7.0	5.1	6.3
28	7.4	7.6	5.6	3.2	3.2	3.7	3.8	4.5	7.7	6.8	5.4	6.7
29	7.6		5.6	3.7	2.9	2.9	7.1	5.2	6.9	6.7	5.8	7.3
30	7.8		5.4	3.8	4.7	3.6	4.4	3.7	6.5	6.3	5.9	7.7
31	5.9		6.4		3.7		5.6	3.9		6.4		8.0
Total	227.1	214.2	203.4	134.5	101.8	106.8	126.5	134.2	181.9	193.5	182.3	196.5
mean	7.3	7.4	6.6	4.3	3.3	3.6	4.1	4.3	6.1	6.2	6.1	6.3

Daily Wind Run (km/day)

Day	**Month**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1	76	73	77	72	69	71	78	74	71	83	87	79
2	76	84	78	69	63	68	77	69	75	85	84	75
3	70	81	81	71	62	67	76	71	74	87	89	76
4	74	85	83	66	62	68	75	71	72	83	81	67
5	71	80	75	65	59	67	69	66	77	81	111	77
6	72	81	80	69	65	66	70	76	69	88	75	67
7	75	75	75	63	71	73	74	71	75	83	83	75
8	68	84	79	63	62	67	69	75	73	87	87	69
9	73	83	76	65	66	70	70	80	72	91	85	65
10	80	82	78	62	80	72	67	74	94	89	85	69
11	74	79	77	63	70	73	66	74	76	89	82	68
12	68	79	79	66	70	72	70	76	81	89	79	71
13	73	77	76	63	67	72	63	72	76	92	80	71
14	72	75	75	66	64	72	76	71	82	87	80	67
15	70	77	70	65	68	78	70	70	81	90	78	66
16	71	75	75	62	64	72	67	69	79	102	82	62
17	75	79	75	67	72	72	71	70	75	93	80	73
18	82	79	72	70	71	72	67	61	80	86	77	71
19	74	76	79	61	82	68	78	74	86	88	77	62
20	78	76	78	67	72	70	67	79	86	87	75	66
21	80	80	66	65	80	69	67	69	81	92	75	73
22	76	77	68	66	68	66	63	75	85	91	75	72
23	80	83	71	66	73	71	65	78	85	85	80	61
24	79	78	71	64	67	72	81	71	83	97	74	69
25	79	79	70	70	75	74	75	77	80	90	75	66
26	80	92	75	62	68	66	66	72	89	91	72	69
27	77	73	70	70	66	70	64	76	90	93	73	62
28	78	78	71	70	68	74	74	74	90	96	73	69
29	81	75	72	69	67	68	77	79	80	91	72	69
30	80		67	75	67	66	76	75	88	89	72	75
31	77		74		69		74	67		84		61
Total	2337	2298	2314	1994	2125	2107	2201	2255	2404	2759	2393	2144
mean	75	79	75	66	69	70	71	73	80	89	80	69

Daily Maximum Relative Humidity(%)

Day	Month											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1	76	83	75	87	94	93	88	91	90	81	81	82
2	79	77	76	85	94	93	90	92	89	81	85	82
3	77	78	73	88	93	88	88	92	89	85	84	81
4	77	75	71	90	93	93	91	88	90	85	84	80
5	75	71	75	88	96	93	91	91	89	86	81	79
6	79	76	78	89	94	89	92	88	88	83	83	83
7	83	76	78	93	94	89	92	90	87	84	85	82
8	75	78	80	88	91	91	89	92	90	87	87	80
9	77	75	78	89	94	91	90	91	90	83	85	81
10	80	74	79	90	94	90	91	87	90	81	84	80
11	80	72	84	89	94	91	89	91	89	83	83	84
12	81	77	81	89	89	91	91	94	88	83	82	83
13	80	79	81	85	92	89	91	90	89	85	82	83
14	78	74	82	92	95	90	93	89	87	85	82	72
15	82	74	81	88	95	89	90	91	87	81	85	82
16	81	76	82	92	93	87	91	91	89	78	81	83
17	79	78	83	92	90	85	90	90	86	84	84	82
18	79	75	84	92	91	89	87	90	88	82	86	79
19	74	78	82	93	91	89	88	89	86	83	85	82
20	82	77	78	89	93	92	90	90	84	80	83	86
21	76	80	86	89	91	87	91	91	85	84	86	85
22	79	80	84	94	92	92	91	88	84	83	82	85
23	79	77	83	95	93	89	90	92	82	79	85	82
24	78	76	83	93	93	90	90	93	84	84	83	82
25	80	75	86	90	94	89	89	86	85	79	84	85
26	81	77	83	92	96	91	89	87	85	82	86	85
27	77	72	82	89	93	89	95	91	80	79	83	81
28	79	77	84	95	91	88	90	89	85	84	85	80
29	75	82	85	93	89	89	91	91	85	81	82	80
30	77		88	95	93	87	89	86	81	82	84	79
31	84		85		91		84	91		84		80
Total	2438	2218	2511	2713	2875	2693	2788	2793	2600	2563	2510	2530
mean	79	76	81	90	93	90	90	90	87	83	84	82

Daily Minimum Relative Humidity(%)

Day	Month											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1	59	54	53	66	75	74	69	64	62	55	56	59
2	58	53	55	64	76	74	72	64	62	59	59	61
3	59	52	56	63	74	70	68	62	66	58	59	59
4	58	54	54	65	74	70	69	63	63	53	65	61
5	57	51	55	67	76	69	66	64	61	57	61	60
6	56	54	57	68	74	71	67	65	61	59	60	62
7	57	56	57	71	71	69	69	65	64	57	62	64
8	59	57	56	68	74	70	70	66	63	61	59	59
9	56	58	58	69	73	68	70	66	62	56	61	59
10	56	55	55	67	68	69	68	65	64	58	60	59
11	58	55	58	70	76	64	67	63	62	54	60	61
12	58	54	59	67	75	68	67	66	59	55	61	58
13	57	57	61	68	75	66	67	64	63	55	58	59
14	59	51	58	71	76	68	68	66	62	55	58	62
15	61	52	61	71	71	68	68	64	57	54	62	61
16	58	54	59	71	74	68	68	67	57	55	60	63
17	57	53	62	71	71	71	66	65	60	51	58	61
18	57	58	64	71	74	70	65	64	59	57	63	60
19	58	57	62	70	73	69	64	66	58	57	57	58
20	55	53	60	73	74	67	69	63	58	55	61	61
21	53	55	63	72	75	69	68	63	60	56	57	63
22	53	52	61	72	75	72	66	62	55	58	60	60
23	54	54	58	69	74	70	63	63	55	56	59	61
24	56	53	62	69	72	72	67	62	56	56	61	62
25	56	54	64	74	73	72	67	62	59	55	63	63
26	57	53	64	73	74	69	66	63	54	57	59	58
27	55	52	62	72	75	70	63	61	56	55	60	57
28	53	53	64	73	72	69	64	60	56	56	61	58
29	53	52	66	73	76	71	63	57	56	58	61	57
30	51		64	74	73	73	64	61	58	60	61	56
31	51		68		74		63	63		57		56
Total	1748	1568	1856	2095	2284	2091	2071	1969	1788	1743	1800	1860
mean	56	54	60	70	74	70	67	64	60	56	60	60

Appendix 5: Monthly long-term rainfall records (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Total
1977	49	50	116	844	243	36	17	102	8	175	100	107	1847
1978	106	56	183	383	292	213	114	32	10	0	201	259	1850
1979	123	106	71	625	550	172	82	61	70	14	36	127	2034
1980	42	35	75	514	546	24	75	78	10	80	115	173	1765
1981	37	17	89	318	555	87	29	44	24	87	12	60	1359
1982	9	45	34	995	701	-	108	38	23	167	180	35	2335
1983	1	-	53	336	418	260	80	15	28	11	22	63	1286
1984	23	37	64	816	275	222	94	20	38	61	118	162	1930
1985	2	244	97	-	-	32	55	-	16	-	30	208	685
1986	-	-	38	583	534	114	34	11	9	70	71	176	1640
1987	13	10	53	162	324	46	108	125	15	3	48	10	917
1988	66	7	111	663	203	146	14	8	23	3	64	85	1391
1989	127	25	19	289	811	135	62	63	22	44	33	33	1662
1990	41	-	303	725	511	87	21	-	-	-	-	-	1689
1991	73	0	140	174	549	48	10	70	9	7	89	109	1277
1992	0	67	25	516	425	45	76	35	4	2	59	50	1304
1993	178	57	29	151	298	77	104	19	2	29	17	79	1039
1994	13	46	119	258	382	36	71	21	7	42	50	241	1285
1995	10	39	118	369	574	53	41	44	10	19	5	51	1333
1996	29	169	147	811	458	103	38	19	14	20	33	5	1844
1997	4	34	147	624	397	115	65	9	2	297	149	274	2116
1998	175	167	84	744	267	101	65	24	14	27	21	32	1720
1999	12	11	223	502	314	254	108	47	25	12	90	17	1615
2000	6	0	174	274	227	82	60	16	15	1	61	123	1039
2001	145	49	49	643	325	76	34	44	6	5	55	5	1435
2002	151	38	122	714	256	37	38	74	58	57	75	117	1736
2003	124	10	25	199	438	166	-	19	10	10	18	113	1133
2004	45	68	23	367	66	56	15	8	-	21	-	106	774
2005	19	51	70	412	362	61	43	41	3	23	77	24	1185
2006	35	6	172	414	685	101	64	35	40	214	298	136	2200
2007	15	51	64	225	408	93	40	118	8	15	66	55	1158
2008	47	66	354	705	277	137	86	8	2	42	87	35	1846
Total	1717	1559	3387	15354	12670	3215	1851	1245	525	1555	2278	3071	48428
mean	55.5	53.8	106.0	495.3	408.7	103.7	59.7	41.6	17.5	51.9	76.0	99.0	1513.4
s.d.	55.9	55.2	79.1	233.0	164.5	65.8	31.3	32.3	16.1	71.2	63.6	75.7	
c.v	1.0	1.0	0.7	0.5	0.4	0.6	0.5	0.8	0.9	1.4	0.8	0.8	

Appendix 6: Sample calculation of monthly application depth

Measured Emitter discharge	=	40 ml/min (Treatment T5)
	=	2.4 l/hr
Spacing of coffee within rows	=	1.5m.
Emitter spacing	=	0.75 m

This means two emitters are serving one plant.

Volume applied to one plant	=	4.8l/hr.
Total volume applied in January	=	0.3504 m^3 /tree (Treatment T5)
Tree spacing is area (A)	=	3 x 1.5m
	=	4.5 m^2
Application depth	=	0.3504/4.5 = 0.0779 m
	=	77.86 mm

Appendix 7: Design calculations

(1) Crop water requirements

ETc = ETo x Kc x Kr

ETo = 4.39 mm/day Peak demand February (Appendix 5)

Kc = 0.9 (Doorenbos and Pruit, 1977)

Kr = 0.94 (Table 5)

ETc = 4.39 x 0.9 x 0.94

ETc = 3.71 mm/day

(2) Irrigation requirement

$IRn = (\theta_{fc} - \theta_{pwp}) \times p \times Z_r \times P_w$

Z_r = 0.6m

P_w = 0.4 (sect 5 below)

θ_{fc} = 30.9% (Table 16)

= 309 mm/m

θ_{pwp} = 12.5% (Table 16)

= 125mm/m

p = allowable depletion

p = p table + 0.04 (5 - ETc) (Appendix 10)

p = 0.4 + 0.04(5-3.71)

p = 0.45

IRn = (309 – 125) x 0.45 x 0.6 x 0.4

= 19.9 mm

(3) Irrigation frequency (IF) and duration (It)

$$IF = \frac{IRn}{ETc}$$

$$IF = \frac{19.9}{3.71} = 5.4 \text{ days} \approx 5\text{days}$$

$$It = \frac{IRn/tree}{qr \times N}$$

IRn/tree = 19.9 x1.5x3 = 89.55l/tree

qr = emitter flow rate l/hr = 2.4l/hr

N = Number of emitters per plant = 2

It = 18.66hr. ≈ 19hrs

$$IRn/tree/day = \frac{89.55}{5} = 17.91 \approx 18 litres$$

(4) leaching requirement

From equation 10 and 11

$LR_t = \frac{0.5}{2 \times 8} = 0.03$ assumption max EC_e = 8 for fruits (Keller and Bliesner ,1990)

LR = 0.03 x 4.12

LR = 0.12

(5) Percentage wetted area

GUIDE FOR DETERMINING VALUES OF P
(Percentage of soil wetted by various discharges and spacings for a single row of uniformly spaced emitters in a straight line)

Source: (Vermeiren and Jobling, 1984)

Appendix 8: Calculation of emission uniformity (EU)

$$EU(\%) = \left(\frac{q_{LQ}}{q_a}\right)100$$

$$q_{LQ} = \frac{40 + 40 + 39 + 37}{4} = 39$$

Effective spacing between laterals S_l m	Emission-point discharge														
	Less than 1.5 lph			2 lph			4 lph			8 lph			More than 12 lph		
	Recommended spacing of Emission Points along the Lateral for Coarse (C), Medium (M) and Fine (F) Textured Soils – S_e, m														
	C 0.2	M 0.5	F 0.9	C 0.3	M 0.7	F 1.0	C 0.6	M 1.0	F 1.3	C 1.0	M 1.3	F 1.7	C 1.3	M 1.6	F 2.0
	Percentage of Soil Wetted														
0.8	38	88	100	50	100	100	100	100	100	100	100	100	100	100	100
1.0	33	70	100	40	80	100	80	100	100	100	100	100	100	100	100
1.2	25	58	92	33	67	100	67	100	100	100	100	100	100	100	100
1.5	20	47	73	26	53	80	53	80	100	80	100	100	100	100	100
2.0	15	35	55	20	40	60	40	60	80	60	80	100	80	100	100
2.5	12	28	44	16	32	48	32	48	64	48	64	80	64	80	100
3.0	10	23	37	13	26	40	26	40	53	40	53	67	53	67	80
3.5	9	20	31	11	23	34	23	34	46	34	46	57	46	57	68
4.0	8	18	28	10	20	30	20	30	40	30	40	50	40	50	60
4.5	7	16	24	9	18	26	18	26	36	26	36	44	36	44	53
5.0	6	14	22	8	16	24	16	24	32	24	32	40	32	40	48
6.0	5	12	18	7	14	20	14	20	27	20	27	34	27	34	40

q_a = mean flow of all control points

$$q_a = \frac{661}{16} = 41.31$$

$$EU\% = \frac{39}{41.31} = 94.4\%.$$

Appendix 9: Minimun and maximum values of ECe for various crops

Crops	ECe (dS/m)	
	Min	Max
Field crops		
Cotton	7.7	27
Sugar beet	7.0	24
Sorghum	6.8	13
Soya bean	5.0	10
Sugar cane	1.7	19
Fruit and nut crops		
Date palm	4.0	32
Fig olive	2.7	14
Pomegranate	2.7	14
Grapefruit	1.8	8
Orange	1.7	8
Lemon	1.7	8
Apple, pear	1.7	8
Walnut	1.7	8
Peach	1.7	6.5
Vegetable Crops		
Zucchini squash	4.7	15
Beets	4.0	15
Broccoli	2.8	13.5
Tomato	2.5	12.5
Cucumber	2.5	10
Cantaloupe	2.2	16
Spinach	2.0	15
Cabbage	1.8	12
Potato	1.7	10

Note: Minimum ECe does not reduce yield

Maximum ECe reduces yield to zero

Source: (Keller and Bliesner,1990)

Appendix 10: Effective rooting depth and depletion fraction for some crops Ranges of maximum effective rooting depth (Zr), and soil water depletion fraction for no stress (p), for common crops

Crop	Maximum Root Depth (m)	Depletion Fraction (for ET =5 mm/day) p
a. Small Vegetables		
Broccoli	0.4-0.6	0.45
Brussel Sprouts	0.4-0.6	0.45
Cabbage	0.5-0.8	0.45
Carrots	0.5-1.0	0.35
Cauliflower	0.4-0.7	0.45
Celery	0.3-0.5	0.20
Garlic	0.3-0.5	0.30
Lettuce	0.3-0.5	0.30
Onions		
- dry	0.3-0.6	0.30
- green	0.3-0.6	0.30
- seed	0.3-0.6	0.35
Spinach	0.3-0.5	0.20
Radishes	0.3-0.5	0.30
b. Vegetables - Solarium Family (Solanaceae)		
Egg Plant	0.7-1.2	0.45
Sweet Peppers (bell)	0.5-1.0	0.30
Tomato	0.7-1.5	0.40
c. Vegetables - Cucumber Family (Cucurbitaceae)		
Cantaloupe	0.9-1.5	0.45
Cucumber		
- Fresh Market	0.7-1.2	0.50
- Machine harvest	0.7-1.2	0.50
Pumpkin, Winter Squash	1.0-1.5	0.35
Squash, Zucchini	0.6-1.0	0.50
Sweet Melons	0.8-1.5	0.40
Watermelon	0.8-1.5	0.40
d. Roots and Tubers		
Beets, table	0.6-1.0	0.50
Cassava		
- year 1	0.5-0.8	0.35
- year 2	0.7-1.0	0.40
Parsnip	0.5-1.0	0.40
Potato	0.4-0.6	0.35
Sweet Potato	1.0-1.5	0.65
Turnip (and Rutabaga)	0.5-1.0	0.50
Sugar Beet	0.7-1.2	0.553
e. Legumes (Leguminosae)		
Beans, green	0.5-0.7	0.45
Beans, dry and Pulses	0.6-0.9	0.45
Beans, lima, large vines	0.8-1.2	0.45
Chick pea	0.6-1.0	0.50
Fababean (broad bean)		
- Fresh	0.5-0.7	0.45
- Dry/Seed	0.5-0.7	0.45
Grabanzo	0.6-1.0	0.45
Green Gram and Cowpeas	0.6-1.0	0.45
Groundnut (Peanut)	0.5-1.0	0.50
Lentil	0.6-0.8	0.50

Crop	Maximum Root Depth (m)	Depletion Fraction (for ET =5 mm/day) p
Peas		
- Fresh	0.6-1.0	0.35
- Dry/Seed	0.6-1.0	0.40
Soybeans	0.6-1.3	0.50
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)		
Artichokes	0.6-0.9	0.45
Asparagus	1.2-1.8	0.45
Mint	0.4-0.8	0.40
Strawberries	0.2-0.3	0.20
g. Fibre Crops		
Cotton	1.0-1.7	0.65
Flax	1.0-1.5	0.50
Sisal	0.5-1.0	0.80
h. Oil Crops		
Castorbean (Ricinus)	1.0-2.0	0.50
Rapeseed, Canola	1.0-1.5	0.60
Safflower	1.0-2.0	0.60
Sesame	1.0-1.5	0.60
Sunflower	0.8-1.5	0.45
i. Cereals		
Barley	1.0-1.5	0.55
Oats	1.0-1.5	0.55
Spring Wheat	1.0-1.5	0.55
Winter Wheat	1.5-1.8	0.55
Maize, Field (grain) (field corn)	1.0-1.7	0.55
Maize, Sweet (sweet corn)	0.8-1.2	0.50
Millet	1.0-2.0	0.55
Sorghum		
- grain	1.0-2.0	0.55
- sweet	1.0-2.0	0.50
Rice	0.5-1.0	0.204
j. Forages		
Alfalfa		
- for hay	1.0-2.0	0.55
- for seed	1.0-3.0	0.60
Bermuda		
- for hay	1.0-1.5	0.55
- Spring crop for seed	1.0-1.5	0.60
Clover hay, Berseem	0.6-0.9	0.50
Rye Grass hay	0.6-1.0	0.60
Sudan Grass hay (annual)	1.0-1.5	0.55
Grazing Pasture		
- Rotated Grazing	0.5-1.5	0.60
- Extensive Grazing	0.5-1.5	0.60
Turf grass		
- cool season 5	0.5-1.0	0.40
- warm season 5	0.5-1.0	0.50
k. Sugar Cane	1.2-2.0	0.65
l. Tropical Fruits and Trees		
Banana		
- 1st year	0.5-0.9	0.35
- 2nd year	0.5-0.9	0.35
Cacao	0.7-1.0	0.30

Crop	**Maximum Root Depth (m)**	**Depletion Fraction (for ET =5 mm/day) p**
Coffee	0.9-1.5	0.40
Date Palms	1.5-2.5	0.50
Palm Trees	0.7-1.1	0.65
Pineapple	0.3-0.6	0.50
Rubber Trees	1.0-1.5	0.40
Tea		
- non-shaded	0.9-1.5	0.40
- shaded	0.9-1.5	0.45
m. Grapes and Berries		
Berries (bushes)	0.6-1.2	0.50
Grapes		
- Table or Raisin	1.0-2.0	0.35
- Wine	1.0-2.0	0.45
Hops	1.0-1.2	0.50
n. Fruit Trees		
Almonds	1.0-2.0	0.40
Apples, Cherries, Pears	1.0-2.0	0.50
Apricots, Peaches, Stone Fruit	1.0-2.0	0.50
Avocado	0.5-1.0	0.70
Citrus		
- 70% canopy	1.2-1.5	0.50
- 50% canopy	1.1-1.5	0.50
- 20% canopy	0.8-1.1	0.50
Conifer Trees	1.0-1.5	0.70
Kiwi	0.7-1.3	0.35
Olives (40 to 60% ground coverage by canopy)	1.2-1.7	0.65
Pistachios	1.0-1.5	0.40
Walnut Orchard	1.7-2.4	0.50

Source: Allen *et. al.*, (1998)

The values for p apply for ETc ≥ 5 mm/day. The value for p can be adjusted for different ETc according to

p = p table + 0.04 (5 - ETc)

Where: p is expressed as a fraction and ETc as mm/day (Allen *et al*., 1998).

Appendix 11: Soil moisture deficit
January 2009

Date	SWDi-1 (mm)	ETo (mm)	Kc	ETci (mm)	Ri (mm)	Ii (mm)	SWDi (mm)
1/1/2009	0.0	4.9	0.8	4.2	0.0	8.5	-4.4
1/2/2009	-4.4	4.8	0.8	4.0	0.0	0.0	-0.3
1/3/2009	-0.3	4.5	0.8	3.8	0.0	0.0	3.5
1/4/2009	3.5	4.8	0.8	4.0	0.0	0.0	7.5
1/5/2009	7.5	4.2	0.8	3.5	0.0	0.0	11.0
1/6/2009	11.0	4.2	0.8	3.5	0.0	9.6	4.9
1/7/2009	4.9	4.0	0.8	3.4	0.0	0.0	8.2
1/8/2009	8.2	4.9	0.8	4.1	0.0	0.0	12.3
1/9/2009	12.3	5.0	0.8	4.2	0.0	0.0	16.5
1/10/2009	16.5	5.2	0.8	4.4	0.0	0.0	20.9
1/11/2009	20.9	4.9	0.8	4.1	0.0	0.0	25.0
1/12/2009	25.0	4.9	0.8	4.1	0.0	12.8	16.3
1/13/2009	16.3	5.3	0.8	4.5	0.0	6.4	14.4
1/14/2009	14.4	5.2	0.8	4.4	0.0	6.4	12.4
1/15/2009	12.4	4.9	0.8	4.1	0.0	0.0	16.4
1/16/2009	16.4	4.5	0.8	3.8	0.0	4.3	15.9
1/17/2009	15.9	4.1	0.8	3.4	0.0	0.0	19.3
1/18/2009	19.3	4.5	0.8	3.8	0.0	0.0	23.1
1/19/2009	23.1	3.7	0.8	3.1	0.0	0.0	26.2
1/20/2009	26.2	4.0	0.8	3.3	0.2	0.0	29.3
1/21/2009	29.3	4.9	0.8	4.1	0.8	8.5	24.2
1/22/2009	24.2	4.5	0.8	3.8	0.0	0.0	27.9
1/23/2009	27.9	5.0	0.8	4.2	0.0	2.1	30.1
1/24/2009	30.1	4.8	0.8	4.0	0.0	0.0	34.1
1/25/2009	34.1	4.7	0.8	4.0	0.0	0.0	38.1
1/26/2009	38.1	3.1	0.8	2.6	0.0	6.4	34.3
1/27/2009	34.3	3.8	0.8	3.2	0.0	0.0	37.5
1/28/2009	37.5	4.4	0.8	3.7	0.0	12.8	28.4
1/29/2009	28.4	4.1	0.8	3.4	6.6	0.0	25.2
1/30/2009	25.2	3.7	0.8	3.1	0.0	0.0	28.3
1/31/2009	28.3	3.8	0.8	3.2	0.0	0.0	31.5

February 2009.

Date	SWDi-1 (mm)	ETo (mm)	Kc	ETci (mm)	Ri (mm)	Ii (mm)	SWDi (mm)
2/1/2009	31.5	4.9	0.8	4.1	0.0	0.0	35.6
2/2/2009	35.6	4.5	0.8	3.8	0.0	0.0	39.3
2/3/2009	39.3	5.1	0.8	4.3	0.0	6.4	37.2
2/4/2009	37.2	5.1	0.8	4.3	0.0	0.0	41.5
2/5/2009	41.5	4.2	0.8	3.5	0.0	0.0	45.0
2/6/2009	45.0	3.7	0.8	3.1	0.0	8.5	39.6
2/7/2009	39.6	4.0	0.8	3.3	0.0	0.0	43.0
2/8/2009	43.0	4.5	0.8	3.8	0.0	0.0	46.8
2/9/2009	46.8	4.7	0.8	3.9	1.1	6.4	43.2
2/10/2009	43.2	4.6	0.8	3.9	0.0	0.0	47.0
2/11/2009	47.0	5.1	0.8	4.3	0.0	13.3	38.0
2/12/2009	38.0	4.3	0.8	3.6	0.0	6.4	35.3
2/13/2009	35.3	4.5	0.8	3.8	0.0	0.0	39.1
2/14/2009	39.1	4.5	0.8	3.8	0.0	0.0	42.8
2/15/2009	42.8	4.9	0.8	4.1	0.0	0.0	47.0
2/16/2009	47.0	4.1	0.8	3.4	7.5	0.0	42.9
2/17/2009	42.9	3.8	0.8	3.2	0.0	0.0	46.1
2/18/2009	46.1	3.6	0.8	3.1	0.0	12.8	36.3
2/19/2009	36.3	3.9	0.8	3.3	0.0	0.0	39.6
2/20/2009	39.6	4.3	0.8	3.6	0.2	0.0	43.1
2/21/2009	43.1	4.5	0.8	3.7	2.3	0.0	44.6
2/22/2009	44.6	4.7	0.8	4.0	0.0	0.0	48.5
2/23/2009	48.5	4.2	0.8	3.5	0.0	0.0	52.1
2/24/2009	52.1	4.0	0.8	3.4	0.0	0.0	55.5
2/25/2009	55.5	4.2	0.8	3.5	0.0	0.0	59.0
2/26/2009	59.0	4.3	0.8	3.6	0.0	4.3	58.2
2/27/2009	58.2	4.3	0.8	3.6	0.0	0.0	61.9
2/28/2009	61.9	4.1	0.8	3.4	0.0	0.0	65.3

March 2009

Date	**SWDi-1 (mm)**	**ETo (mm)**	**Kc**	**ETci (mm)**	**Ri (mm)**	**Ii (mm)**	**SWDi (mm)**
3/1/2009	65.3	4.2	0.8	3.5	0.0	0.0	68.8
3/2/2009	68.8	4.3	0.8	3.6	0.0	0.0	72.5
3/3/2009	72.5	4.4	0.8	3.7	0.0	9.6	66.6
3/4/2009	66.6	4.3	0.8	3.6	0.0	0.0	70.1
3/5/2009	70.1	4.0	0.8	3.4	0.0	0.0	73.5
3/6/2009	73.5	3.6	0.8	3.0	0.0	0.0	76.5
3/7/2009	76.5	4.2	0.8	3.5	0.0	0.0	80.0
3/8/2009	80.0	4.0	0.8	3.4	0.0	0.0	83.4
3/9/2009	83.4	4.6	0.8	3.9	0.0	0.0	87.2
3/10/2009	87.2	4.1	0.8	3.4	0.0	14.9	75.7
3/11/2009	75.7	4.4	0.8	3.7	0.0	0.0	79.4
3/12/2009	79.4	3.7	0.8	3.1	0.0	0.0	82.6
3/13/2009	82.6	4.1	0.8	3.4	0.0	0.0	86.0
3/14/2009	86.0	4.5	0.8	3.8	0.0	8.5	81.3
3/15/2009	81.3	4.4	0.8	3.7	0.0	0.0	84.9
3/16/2009	84.9	4.4	0.8	3.7	0.0	0.0	88.6
3/17/2009	88.6	4.2	0.8	3.5	0.0	0.0	92.1
3/18/2009	92.1	3.7	0.8	3.1	0.0	0.0	95.2
3/19/2009	95.2	3.6	0.8	3.1	0.0	0.0	98.3
3/20/2009	98.3	4.3	0.8	3.6	0.2	0.0	101.7
3/21/2009	101.7	4.5	0.8	3.8	0.0	6.4	99.1
3/22/2009	99.1	4.8	0.8	4.0	0.0	0.0	103.1
3/23/2009	103.1	4.2	0.8	3.5	0.0	0.0	106.6
3/24/2009	106.6	4.7	0.8	3.9	0.0	0.0	110.5
3/25/2009	110.5	5.2	0.8	4.3	0.0	0.0	114.8
3/26/2009	114.8	4.6	0.8	3.9	0.0	0.0	118.7
3/27/2009	118.7	3.6	0.8	3.0	1.9	5.3	114.5
3/28/2009	114.5	3.8	0.8	3.2	0.0	0.0	117.7
3/29/2009	117.7	3.4	0.8	2.9	2.0	0.0	118.6
3/30/2009	118.6	3.1	0.8	2.6	0.0	0.0	121.2
3/31/2009	121.2	3.1	0.8	2.6	3.8	0.0	119.9