Comparison of Water Consumption between Greenhouse and Outdoor Cultivation

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by

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Disclaimer

Abstract

Crop water requirement for roses grown out-door and in greenhouse (commercial multi-span) were investigated in Naivasha, Kenya. The actual ET in the greenhouse was estimate by measurement of water balance in hydroponics. The difference between the water applied and drainage gave the actual ET ($mm.day^{-1}$). For outdoor conditions the Penman-Monteith equation was used to predict the potential ET for outdoor grown roses. Using previous studies that have computed actual ET outdoor using satellite remote sensing, the actual ET in the greenhouse was found to be 65% of actual ET outdoor.

The microclimate in a forced and a natural ventilated greenhouse is also investigated. The main results are then discussed with respect to quality of roses in the two greenhouses. It is shown that the high vapour pressure deficit >3kPa and high temperature>30^{o}C are the main causes of low quality roses (short and thin stems) produced in the forced ventilated greenhouse.

Calculated ET, vapour pressure deficit and Radiation follow the same trend and hence it is inferred that a simple empirical equation for prediction of ET need to incorporate radiation, vapour pressure deficit as well as LAI (leaf area index). Furthermore, a simplified empirical equation incorporating radiation vapour pressure deficit and leaf area index is developed and validated for predicting potential ET in greenhouse with climate control. Calculated greenhouse evapotranspiration rate in hourly and daily values agree fairly well with measured rates. From a practical point of view such a model could be easily implemented in algorithms for rose irrigation control as radiation and vapour pressure deficit are two variables currently being monitored in greenhouses.

The irrigated area both outdoor and greenhouse was reviewed. The area under greenhouse was found to have increased from 1191 ha to 1600 ha while outdoor area has reduced from 4142 ha to 3800 ha between year 2004 and 2005.

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1. INTRODUCTION

1.1. General Problem Description

Water use by crops is of increasing concern as demands for water are growing while supplies are not. The overgrowing population and recent droughts are putting water resources under pressure and calling for new approaches for water planning and management if escalating conflicts are to be avoided and environmental degradation is to be reversed.
Irrigation is the major consumer of diverted water from surface and groundwater in the world. Therefore, it must be carried with high efficiency. One prerequisite for efficient irrigation is knowledge of consumptive use of major crops or their evapotranspiration. Such information is required to minimize percolation losses, runoff and thus environmental pollution (Orgaz et al., 2005). The use of greenhouse in arid regions decreases crop water requirements by reducing evapotranspiration. The plastic cover utilised on these structures changes locally the radiation balance by entrapping long-wave radiation and creates a barrier to moisture losses.

For outdoor conditions, the approach using the product of reference ET (ET_0) and a crop coefficient (K_c) as proposed by FAO (Allen et al., 1998) is commonly used to calculate potential ET world wide. Of the many approaches used to calculate $ET_{o,}$ the Penman-Monteith equation, based on metrological data and a hypothetical reference crop, is now considered the standard reference (Allen et al., 1998). This enables the transfer of standard K_c values among locations and climates. This has been a primary reason for the global acceptance and usefulness of the crop coefficient approach and the K_c developed in the past studies (Allen et al., 1998). As in open field, accurate predictions of crop water requirements are necessary for an efficient use of irrigation water in greenhouse crop production. Furthermore, under closed spaces as greenhouses, the predominant role of crop transpiration in decreasing the heat load during warm periods is supplementary reason to develop irrigation scheduling that allow the maximization of the transpiration fluxes.

This study will investigate the amount of water consumed in a greenhouse environment and compare it with open field. The major crops grown in greenhouses at the study area are rose flowers. It is estimated that 95% of crops grown in greenhouses constitute rose flowers hence the study focuses on the crop.

Knowing how much water is required does not only aid farmers in determining their potential to save water, it does also give them facts needed when approached by legislators, conservators and regulators.

1.2. Objectives

Research objectives

- To compare water requirement in a greenhouse environment with outdoor irrigation system
- Compare microclimate of natural and a forced ventilated greenhouse
- Compare water allocated to irrigation by Ministry of Water and Irrigation with crop water requirement.
- Develop an empirical model for predicting potential evapotranspiration for roses in Naivasha, Kenya
- Review actual irrigated area

Research questions

- By how much is actual ET reduced in greenhouse cultivation compared to outdoor?
- What are the main factors that affect evapotranspiration in a greenhouse environment?
- Is water requirement for rose flower higher or lower compared to permitted abstraction?
- What is the trend of irrigated agriculture in Naivasha?

1.3. Research Approach

The research consisted of three phases: pre-fieldwork, fieldwork and post fieldwork. Downloading of satellite images (ASTER) was done in pre-fieldwork. At the same time, related literatures were collected (either from the library or the internet) and reviewed. During the fieldwork the microclimate inside and outside the greenhouse were recorded. In addition the water applied to different stages of rose cultivar and excess drainage was monitored either by water meters or measured using a diver and v-notch method. The analysis was done after the field work.

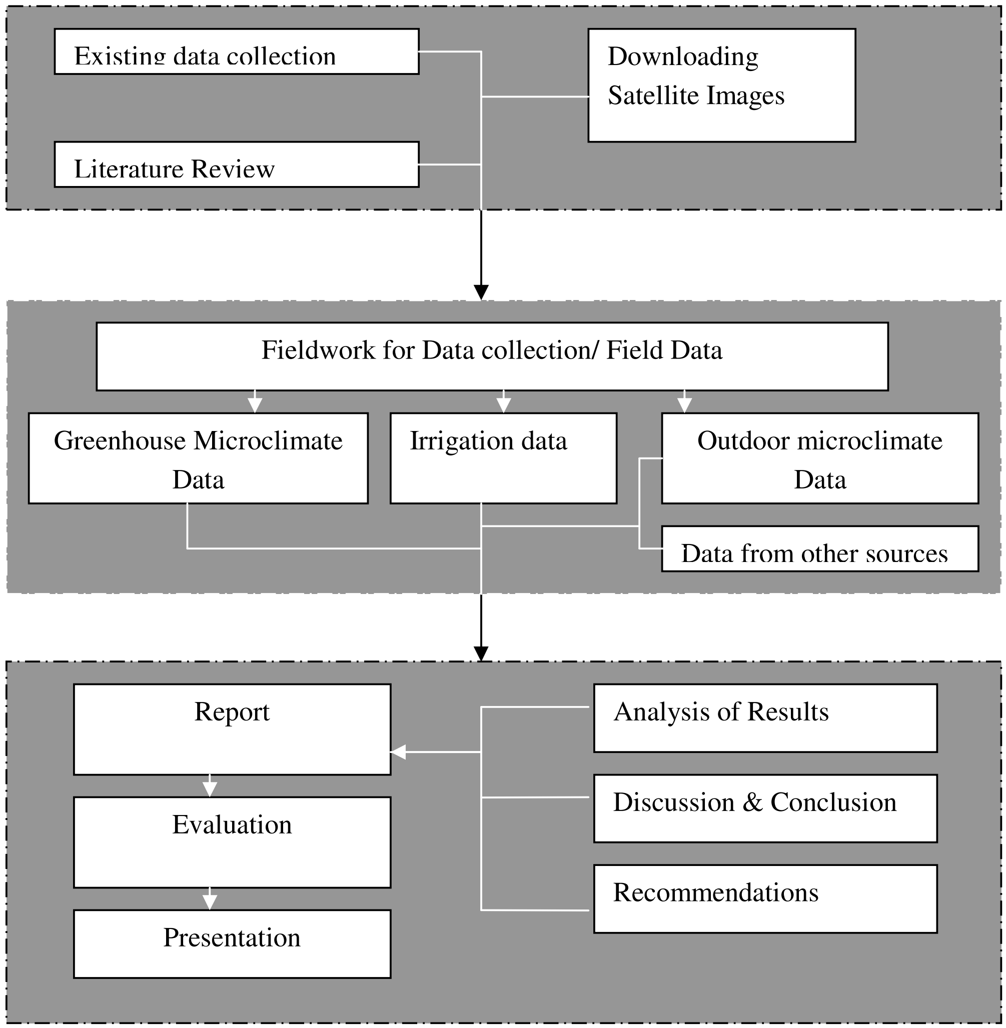


Figure 1-1: Simplified steps on study methodology

1.4. Outline of the Thesis

The aforesaid objectives are addressed through the following chapters

Chapter 2 highlights the general overview of the study area. In this chapter, brief information about geography, climate, geology and soils, land use and irrigation practice of the study area have been described.

Chapter 3 contains the brief description on existing literature review and general information on previous studies and findings on specific area of interest.

Chapter4 focuses on materials and methods used in the study. Information about the data available for outdoor conditions, indoor conditions as well as the assessment of integrity of the data has been given. The methodology of the techniques used in the study is also given in this chapter.

Chapter 5 discusses the results on water consumption between greenhouse and outdoor conditions. It also compares the microclimate data of a natural ventilated greenhouse and a forced ventilated one. Further, a simplified model is developed for computing water consumption in a greenhouse with a mature rose crop as well as reviewing the actual irrigated area in Naivasha basin.

Chapter 6 contains conclusions drawn in the study and recommendations made for the next study.

2. General Overview of the Study Area

2.1. Geography

Kenya is positioned on the equator on Africa's east coast. Its northernmost and southernmost points are approximately equidistant--a little over 40 north and south of the equator. Kenya shares borders with five other countries. The perimeter of Kenya's international land borders is 3,446 km., including borders with Sudan (306 km), Ethiopia (779 km), Somalia (682 km), Tanzania (769 km), and Uganda (772 km). Kenya's eastern and northern neighbours are Somalia and Ethiopia. To the northwest lies the Sudan. The total area of Kenya is 582,650 square kilometres; almost 13,400 sq. kilometres of this total takes the form of water, mainly in Lake Turkana.

Lake Naivasha (0. 45ºS, 36. 26ºE), altitude 1890, lies on the floor of Africa's Eastern Rift Valley and cover approximately 140 km^2. It is the second-largest freshwater lake in Kenya. It is one of a series of 23 major in the East Rift Valley – eight in central Ethiopia, further eight in Kenya and seven in Tanzania – spanning latitudes from approximately 7° N to 5° S. The overall climate of the Eastern Rift Valley is semi-arid.

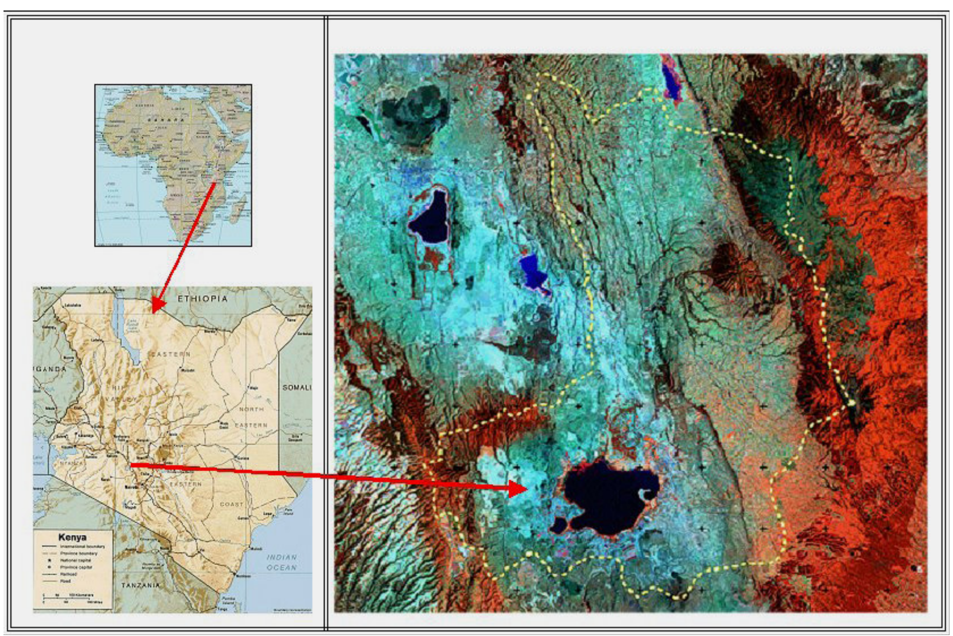


Figure 2-1: Location of the study area in international, national and regional contexts.

2.2. Climate

Given that Kenya straddles the equator; its terrain is highly diversified with climatic conditions ranging from moist to arid. In this part of Africa, seasons are distinguished by duration of rainfall rather than by changes in temperature. In the Western Plateau and the Highlands, rain falls in a single long season. East of the rift valley, there are two distinct seasons: a period of long rains from March to May and one of short rains from September to October. Rainfall is most plentiful in the Highlands and on the coast which receive an average of 1010 mm. The Western Plateau receives over 1780 mm annually. More than 70% of the country, however, is arid or semi-arid, receiving less than 510 mm per year. Rainfall is sporadic in the dry areas.

Variations in altitude are the major factor in temperature differences in the various parts of the country. The Highlands generally have a cool, bracing climate with a mean annual maximum of 26.10C and a mean annual minimum of 10C. Nairobi, at an elevation of 1,670 meters, has a mean annual temperature of 19^{o}C. The nation's highest temperatures are found in the Northern Plain, where the mean maximum is 34C and temperatures often reach 43.3^{o}C. Temperatures vary between 14^{o}C and 29^{o}C in the Eastern Plateau, and between 34^{o}C and 17.8^{o}C and 21.1^{o}C in the coastal areas. The hottest months fall between January and March; the coldest are June and July.

The study area has quite diverse climatic conditions due to considerable difference in altitude and landforms. The annual temperature range is approximately 7.9^{o}C TO 28.8^{o}C
The rainfall regime within the lake catchment is influenced by rain shadow from the surrounding highlands of Nyandarua range (Aberdares). Rainfall is well distributed throughout the year but at Naivasha there is a discernible peak in April. Naivasha experiences an average yearly rainfall of 660 mm approximately whereas the wettest slopes of the Nyandarua Mountains within the lake's catchment receive as much as 1025mm.
The evaporation experienced by Naivasha is between 1600 and 1800mm so runoff from the non-immediate catchment would seem to be broadly sufficient to maintain lake level. The mean monthly values of some meteorological state variables are shown in Figure 2-2 and table 2-3.

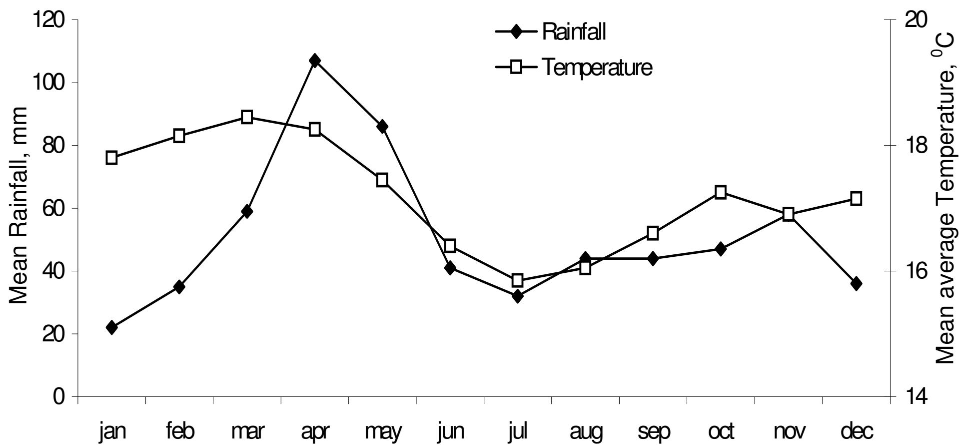


Figure 2-2: Mean monthly rainfall and temperature Source: FAO's CROPWAT database

Table 2-1: Mean monthly values of meteorological observations for Lake Naivasha (recorded in Naivasha Meteorological Station). Source: FAO's CROPWAT database

Mean Rainfall, mm	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	22	35	59	107	86	41	32	44	44	47	58	36
Maximum Temperature, ^{0}c	17.8	18.1	18.5	18.3	17.5	16.4	15.9	16.1	16.6	17.3	16.9	17.2
Minimum temperature, ^{0}C	8	8.1	9.7	11.5	11.2	9.8	9.2	9.3	8.7	9.0	9.2	8.6
Relative Humidity, %	62	61	65	75	80	79	77	76	74	72	77	72
Wind speed, km day^{-1}	104	104	104	104	121	121	121	130	130	130	104	104
Sunshine, hours	5.9	5.9	5.3	4.7	4.9	4.8	4.2	4.7	5.4	5.5	4.4	4.2
Solar Radiation, W m^{-2}	171	186	179	164	157	150	143	159	177	179	158	152

2.3. Geology and Soils

In general, the study area is covered by two types of quaternary deposits: lacustrine, and volcanic origin. The deposits contain largely clay, silt, and volcanic materials. The soils can also be grouped into two: soils developed on the lacustrine plain, and soils developed on the volcanic plain. Soils developed on the lacustrine plain are moderately to well drained, very deep, silty clay to clay loam. Soils developed on the volcanic plain are well drained, moderately deep to very deep, with noncalcareous to moderately calcareous topsoil.

2.4. Land Use

There are four major land-use/land-cover units in the area: agriculture, natural vegetation, settlements, and game sanctuaries. The agriculture sector, which includes cereal growing, horticulture, floriculture, and dairy farming, is mainly concentrated around the lake. Most of the floriculture takes place inside greenhouses. The natural vegetation cover surrounding the lake is mainly papyrus swamp vegetation while outside of the lake surrounding, shrub, acacia, and cactus trees are the main natural vegetation covers. Settlement is mainly concentrated in Naivasha town although scattered homes and villages can also be found within the study area. Game sanctuaries are mainly present in the west of the study area.

2.5. Irrigation Practice

Most of the irrigation schemes lie around the lake. Modern irrigation systems are employed: Centre pivot, sprinkler (mainly for open field) and drip (mainly for greenhouse). In either case, irrigation water is pumped from the lake and ground water, and stored temporarily in a reservoir until it is withdrawn for irrigation purpose. In the greenhouses, flowers (typically roses) are grown for export purpose. Whereas, vegetables (squash, chilli and others), cereals (maize and others), and flowers are grown in open fields. Irrigation scheduling is not properly practiced in the area. Some farmers irrigate when they feel the soil gets dry, while few farmers use tensiometer-based irrigation control, despite water scarcity. The vast majority of greenhouses in Naivasha consists of traditional, low-investment, non-heated, plastic-covered shelters. However, modern greenhouses equipped with computerised climate-controlled systems are currently replacing the traditional ones.

The size of individual farms varies in size from 20 to over 100 hectares, with workforces of between 250 and 6000 (Collinson, 2001).

3. Literature Review

3.1. Previous Study

Consumptive use of irrigated area around Lake Naivasha has been investigated in the past. Mekonen, (1999) derived K_c values for vegetable crops using metrological based approaches combined with satellite hydrology. Ahammad, (2001) linked remote sensed data and field data to estimate water use and water productivity, while (Oppong-Boateng, 2001) assessed the use of groundwater for irrigation in the southern part of Lake.
During these studies data on water applied by the farmers was scarce as most farms did not have measuring devices. Due to pressure from the Government and local stakeholder organizations notably the LNRA (Lake Naivasha Riparian Association) farmers have installed water measuring instruments. Few studies have been undertaken on water requirement in greenhouse at Naivasha. However, Measurements of micro-meteorological variables were conducted simultaneously inside and outside greenhouse in 1999. The incoming radiation short wave radiation inside one of the greenhouse was found to be about 36% less than outside (Mekonnen, 1999).

Huatuco, (1998) estimated the water demand in the catchment, which accounts for 77 M. m^3 $year^{-1}$, whereas the water abstraction directly from the lake was estimated to be 35 M m^3 $year^{-1}$.in general irrigation accounted for 84% of the total abstraction (i.e. 64.68 M.m3 $year^{-1}$).

The Ministry of Water and Irrigation issue permits for abstraction of water. For irrigation purposes farmers are allowed 22.5 m^3 ha^{-1} day^{-1} (Huatuco, 1998). Irrigation Engineers and irrigation managers have disputed the value arguing that the fixed figure is not based on crop water requirement for different crops nor does it take into account differences in climate between regions in the country. Part of this study will compare water requirements for rose flower grown outdoors and greenhouse with water permitted.

There was no documentation on greenhouse water consumption around Lake Naivasha Catchment. However, according to farmers, on average 5 mm day^{-1} is applied to crops in greenhouse (Huatuco, 1998).

3.2. Crop Water Requirement

3.2.1. Crop Water Requirement (Outdoor)

There exist a multitude of methods for estimation of reference evapotranspiration (ET_0). Overviews of many of these methods are found in review papers or books (e.g. ACSE 1990). One of the approaches normally used to quantify the potential ET of irrigated crops is the crop coefficient-reference evapotranspiration (K_cET_0) procedure. In this procedure, reference evapotranspiration (ET_0) is computed for grass or alfalfa reference crop and is then multiplied by an empirical crop coefficient (K_c) to produce an estimate of crop evapotranspiration (ET_c). The ET_0 represents the non-stressed ET based on weather data taken from a grassed weather surface. The K_cET_0 approach has been a preferred approach for estimating the ET for most irrigation projects because of difficulties in applying inflow-outflow water balances. Inflow-outflow balances require estimating deep percolation components before computing ET as a residual (Allen, 2000).

Compared to other production costs and considering the potential damage of water stress, the commercial rose grower has no strong incentives to save water. His/her main task is, rather, to enable uninterrupted transpiration in order to avoid any stress event, facilitate maximal photosynthesis and consequently to increase yields. In order to do so, it is essential to prevent sharp fluctuations in water availability (Raviv and Blom, 2001). On the other hand, it is the present author's opinion that roses grown outdoors consume water at potential evapotranspiration owing to the above mentioned conditions.

The Penman-Monteith equation is the most widely used method for reference evapotranspiration prediction, based on the relevant climatic data such as net radiation absorbed by leaves, temperature, vapour pressure deficit and wind speed.

3.2.2. Crop Water Requirement (Greenhouse)

The use of greenhouse in arid regions decreases crop water requirements by reducing evapotranspiration. The plastic cover utilised on these structures changes locally the radiation balance by entrapping long-wave radiation and creates a barrier to moisture losses. As a result ET_o is reduced by 60 to 85% compared to outside the greenhouse (Fernandes et al., 2003). This leads to clear reduction in water demand when compared to field agriculture. Thus, greenhouse agriculture provides a way of increasing crop water use efficiency.
This has been highlighted by Mears, (1990) who stated that:

"While a greenhouse is generally regarded as necessary to provide a warm environment in cold climates, it has also been shown that with properly designed cooling system. It is possible to improve plant growing conditions under extensively hot conditions. Adaptation of modern technologies to arid conditions will undoubtedly lead to increased opportunities for production of high value plants and materials in areas where the environment is extremely harsh. Protected cultivation also has the potential benefit of substantially increasing plant productivity per unit water consumption which is important in many areas where water sources are severely limited"

Greenhouse cultivation reduces evapotranspiration (ET) to about 70% of open field, therefore improving the water use, relative to unprotected cropping (Stanghellini, 1993). It obviously does not rain in the greenhouse, and water has to be provided by an irrigation system. In general, irrigation system is controlled to provide enough easily available water to plants, and thus transpiration is close to its potential value (Jolliet, 1999).

Baille, (2001) found that by applying a dense white paint to glass, a reduction of about 50% on solar radiation resulted. This drastic change in the greenhouse radiation load led to indirect modifications of other microclimatic variables such as air temperature and vapour pressure deficit, through the microclimate interactions. On the other hand (Orgaz et al., 2005) conducted an experiment to determine K_c for horticultural crops under greenhouse (melon and watermelon). The K_c values were found to be similar to those under field conditions.

Crop water requirement of drip irrigated tomatoes grown in greenhouse in tropical environment has been investigated in the past. Greenhouse farming system performed better than open farming systems in terms of crop yield, irrigation water productivity and fruit quality. The results revealed that the crop evapotranspiration inside the greenhouse matched 75-80% of the crop evapotranspiration computed with the climate parameters observed in the open environment. In other words, the greenhouse farming can save about 20-25% of water compared to the open drip irrigated farming system (Harmato et al., 2004). On the other hand Stanghellini, (1993) found that in intensive open-field cultivation of tomatoes, the water use per ton of fruit is about $50m^3$, under plastic-net roof $40m^3$, whereas the production in glass house would be $30m^3$. For regions with water shortages, the water use per unit yield might be reduced by as much as 50%, given the larger output from greenhouse cultivation.

It is worth noting that Penman-Monteith method at optimum level of 75-80% of ET_c was used for estimating crop water requirement under the greenhouse based on daily microclimate outside and beyond greenhouse environment where the temperature, relative humidity and wind speed were not very different between inside and outside the greenhouse. For other climates where these differences are very large the method could probably not work and hence the need for the present research on comparison of crop water requirement of greenhouse using the microclimate inside the greenhouse.

Contemporary greenhouse operations require control of irrigation and nutrient supply in order to optimize crop growth and minimise cost and pollution due to effluents.

3.2.2.1. Simplified Model for Predicting Water Requirement in a Greenhouse

Evapotranspiration rate is an important component of canopy energy and water balance. In greenhouses, its estimation is essential for climate and irrigation control. Irrigation control involves the determination of both timing and quantity of water application. The most common and simple method used until now for scheduling irrigation consists in estimating the crop evapotranspiration by means of the radiation-based method . Munoz et al, (1996) doubted the applicability of this method and the applicability of Penman-Monteith equation for irrigation control of roses in a greenhouse. The fact that roses, unlike most other crops, are being constantly harvested and thereby exhibiting large fluctuation of the transpiring area must be taken into consideration when attempting to formulate any climatic model. Inputs typical to greenhouse intensive cultivation such as supplementary lighting, heating pipes, air humidity and CO_2 concentration are not well predicted by classical, field-oriented models (Baille et al., 1996).

Optimal irrigation scheduling of greenhouse soil less crops is very important since it influences the root zone environment, media water potential, and salt accumulation, which in turn affects plant growth and photosynthesis, and consequently crop production and quality (Raviv and Blom, 2001)

Simplified versions of the Penman Monteith equation have been proposed by several authors, ((Jolliet and Bailey, 1992); Bailey et al., 1994b) for estimation of crop water requirement in a greenhouse. The model is of the form;

$$ET = A.R_i + B.VPD \qquad \textbf{(3-1)}$$

Where;
α and β are coefficients that depend on the species. The coefficient can be Identified in-situ if the measurements of water supply and drainage are available (Baille, 1994). The disadvantage of the method is that it requires sensors for measurements of Radiation and vapour pressure deficit. It also requires an estimation of leaf area index. However, modern greenhouses both in Mediterranean and arid regions have installed sensors to monitor temperature and relative humidity. Global radiation is also monitored not necessarily in each greenhouse but rather generally, outdoor.

In this thesis, an attempt has been made to study and derive the coefficients α and β for Naivasha, Kenya for a greenhouse with a mature crop and a greenhouse with climate control.

3.2.2.2. Microclimate of a Natural and Fan-ventilated Greenhouse

Cooling has always been an important problem for greenhouse operators in warm climates, potentially limiting production and constraining profits. Greenhouse cooling is typically accomplished by ventilation, either mechanically, via exhaust fans or naturally, via wind and buoyancy (Willits, 2003)Greenhouse cooling is quite difficult and complicated task, far more difficult than heating, since the cooling devices used in other kind of building demand huge investments and high energy consumption. The net solar radiation in the greenhouse, reaches 500-600 W m^{-2} during summer. In order to obtain greenhouse air temperatures close to outside ones, a total of about 200-250 W m^{-2} of sensible heat needs to be removed. Low cost methods such as forced ventilation, cooling pads, fog systems, screens, etc., or in most cases, a combination of the previous methods are used for the removal of redundant energy. The most common methods used for greenhouse cooling in Mediterranean areas are natural or forced ventilation (Kittas et al., 2005)Furthermore, in Mediterranean countries, high pressure deficit (VPD>3kPa) are currently observed in greenhouses during summer. These conditions are responsible for the decrease in yield and quality of greenhouse production (Katsoulas et al., 2001).

Rose flower stems adapt to high VPD by decreasing leaf area for maintaining high sap flow rate per unit area. Dayan, (2000) reported that rose flowers produced in greenhouses in Israel during summer had short thin stems carrying small buds with pale petioles, but cooling the air in the greenhouse improved flower quality. These studies suggest that leaf area and other morphological properties (such as ratio of leaf area to stem cross- section area) of rose flower stem may change during growth under different environmental conditions.
Stem length is the primary indicator for the economic value of cut-flower rose production. Shoots with length lower than 30cm could be considered unmarketable, shoots with length between 30 to 60 cm could be considered of mean economic value, and shoots longer than 60cm could be considered of relatively high quality (Katsoulas et al., 2005).

The prime aim of a greenhouse is to grow plants, and therefore high transmission of solar radiation in the wave band 400-700nm is essential to maximize photosynthesis rates. The amount of structural material and the properties of the cladding will influence the proportion of incident radiation transmitted to the plants. The photosythetically active radiation will be accompanied by radiation at other, mostly longer, wavelengths. All the radiation entering the greenhouse will contribute to the potential elevation of the greenhouse temperature above that of the external air. The greater the insulation properties of the house the greater will be the elevation, though as general rule those cladding materials that might be chosen for good thermal resistance will also tend to be less good at admitting radiation for plant growth (Day and Bailey, 1999). Elevated temperatures will only be desirable when outside temperature conditions are below the optimum for plant growth. To make full use of an expensive structure through as much of the year as possible generally requires methods of cooling the house to be available. The most common is by natural ventilation, exchanging hot and humid air inside the house with cooler, drier air from outside. Forced ventilation using fans is also used and sometimes increased cooling is obtained by passing very dry external air through a wet pad before it enters the house.

Forced ventilation is used to cool the greenhouse by replacing the air in the house, which has been heated by absorbing solar energy, with cooler external air. The fans extract air from the greenhouse, which is replaced by outside air entering an inlet on the opposite side of the house.

In this study two greenhouses one fan ventilated and a natural ventilated are compared to see if the ventilation is adequate [(65 %< RH<85%), (18^{o}C<temperature<25^{o}C)] for production of roses.

4. Materials and Methods

4.1. Outdoor Condition

Data for outdoor conditions were obtained from Oserian farm (see appendix I); the data include daily solar radiation, daily rainfall, maximum and minimum air temperature, class A pan evaporation and average daily relative humidity. In addition to the mentioned data, hourly data from an automatic weather station (Campbell) located west of Naivasha (Londia farm) were available for the period 1 May to 6 September, 2005. See table 4-1 and table 4-2 below for parameters

Table 4-1 : Parameters downloaded from Campbell automatic weather station at Loldia farm

Parameter	Units
1. Shortwave incoming Radiation	Wm^{-2}
2. Air temperature	^0C
3. Due point temperature	^0C
4. Wind speed	ms^{-1}
5. Wind direction	-
6. Relative humidity	%

Table 4-2: Parameters obtained from Oserian farm

Parameter	Units
Daily solar radiation	$MJm^{-2}day^{-1}$
Daily Minimum Air Temperature	^oC
Daily maximum Air temperature	^oC
Daily pan evaporation	mm
Daily rainfall	mm

4.1.1. Outdoor Evapotranspiration

The Penman-Monteith equation for predicting ET_0, where it is applied on 24-h calculation time-steps, has the form

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \textbf{(4-1)}$$

Where,
ET_0 is reference evapotranspiration {mm day-1],
R_n is net radiation at the crop surface [MJ m^{-2} day-1], G is soil heat flux density [MJ m^{-2} day^{-1}],
T is air temperature at 2 m height [^oC],
u_2 is wind speed at 2m height [ms^{-1}],
e_s is saturation vapour pressure [Kpa],
ea is actual vapour pressure [Kpa],
e_s-e_a is saturation vapour pressure deficit [Kpa],
Δ is the slope of the vapour pressure curve [kPa $^oC^{-1}$],
γ is the psychrometric constant [kPa $^oC^{-1}$].

The Penman-Monteith equation (modified by FAO) predicts the evapotranspiration from a hypothetical grass reference surface that is 0.12 m in height having a surface resistance of $70sm^{-1}$ and an albedo of 0.23. The equation provides a standard to which evapotranspiration in different periods of the year or in other regions can be compared and to which the evapotranspiration from other crops are related (Allen, 2000)
Standardized equations for computing all parameters in the above equations are given in (Allen et al., 1998).

For hourly time steps, the "900" value changes to "37" for ET_0 in [mm h^{-1}] R_n and G in [MJ m^{-2} h^{-1}], and where T is mean hourly air temperature [^oC] and e_s and e_a is computed using mean hourly air temperature. In hourly calculation time-steps, G for the grass reference surface is presumed to be $0.1R_n$ during daylight and $0.5R_n$ during night time hours.
The crop coefficient, K_c, is basically the ratio of ET_c to the reference ET_0, and it represents an integration of the effects of major characteristics that distinguish the crop from the reference ET_0. These characteristics are crop height (affecting roughness and aerodynamic resistance); crop soil surface resistance (affected by the fraction of ground covered by vegetation and by the soil surface wetness). In FAO-56, K_c, is defined for pristine conditions having no water or other ET reducing stresses (Allen, 2000).

Actual ET_c, is calculated in FAO-56 as:

$$ET_c = K_c ET_0 \quad \textbf{(4-2)}$$

Where ET_c is the ET realized from the vegetation and K_c is the actual crop coefficient.

4.2. Greenhouse

The experiments were conducted in two multi-span greenhouses E-W oriented, located at Panda and Bigot flower farms in Naivasha, Kenya (0°40’42’’S, 36°25’E) and (0° 40’ 41’’S, 36°26’E) respectively. Another greenhouse considered is located at Oserian flower farm southern part of Naivasha (0°51’20”S, 36°15’00”E)

4.2.1. Data

The parameters measured and their instrumentation is listed in table 4.3. Most instruments were connected to either, an in-build data logger or an external data logger with a sampling interval of 5 minutes. For manual measurements the sampling interval was 30 minutes.

Table 4-3: Instruments and Measurements

Parameter	Instrument/s	Manufacturer	Data Logger
Shortwave incoming radiation	Pyranometer	Kipp-Zonen	Skipper /van Essen Instrument
	Silicon pyranometer sensor	Onset (S-LIB-M003)	HOBO Weather Station Data Logger 15 channels
Air temperature	R/H-temperature sensor	Onset	HOBO Weather Station data Logger 15 channels
	R/H-temperature sensor	Onset	Internal logger
	Dry bulb	Assman pyschrometer No. 3011	manual
	Hobo pendant temperature/ light sensors (2No.)	Onset	Internal logger
Wet bulb temperature	Aspirated psychrometer	Assman pyschrometer No. 3011	Manual recordings
Air speed	-hot wire anemometer	Testo 425	Manual recordings
Soil moisture content	Soil moisture content sensor	Onset (S-SMA-	HOBO Weather Station
	Soil probes (3No.)	M003)	Data Logger 15 channels
	Tensiometers (3No.)		Manual record
Relative humidity	RH-sensor	Onset (S-THA-M0XX)	HOBO Weather Station Data Logger 15 channels
	RH-sensor	Onset	Internal logger
Leaf temperature	4 high precision thermistors	Onset	Internal logger
	IR Thermometer	Onset	Manual
Light intensity	2-Pendant temperature/light sensors	Onset (UA-002-xx)	HOBO Pendant Data Loggers
Water level	Water level sensor (3No.)	Onset(U20-001-01)	HOBO Water Level Logger

4.2.2. Greenhouse Evapotranspiration

Stanghellini, (1987) revised the Penman-Monteith equation to represent conditions in a greenhouse, where air velocities are typically low (<1.0 ms^{-1}). A multi-layer canopy is considered to estimate hourly ET_0, using a well-developed tomato crop (*lycopersicon esculentum Mill.*) grown in a single glass, Venlo-type greenhouse with hot water pipe heating. The Stanghellini model includes calculations of the solar radiation heat flux derived from empirical characteristics of short wave and long wave radiation absorption in a multi-layer canopy (Kirnak and Short, 2001; Prenger et al., 2002). The leaf area index (LAI, m^2m^{-2}) is used to account for energy exchange from multiple layers of leaves on greenhouse plants. The form of the equation is:

$$ET_0 = 2.LAI.\frac{1}{\lambda}\frac{\Delta(Rn - G) + K_t.\frac{VPD.\rho.C_P}{r_a}}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \qquad \textbf{(4-3)}$$

$$R_n = 0.07R_{ns} - \frac{252\rho C_P(T - T_0)}{r_R} \qquad \textbf{(4-4)}$$

Where

$$\gamma = \frac{C_P P}{\varepsilon\lambda} \qquad \textbf{(4-5)}$$

$$r_R = \frac{\rho.C_P}{4.\sigma(T + 273.15)^3}, \qquad \textbf{(4-6)}$$

LAI is the leaf area index in [m^2m^{-2}],
K_t is a time unit conversion factor (86,400 s day^{-1} for ET_0 in mm day^{-1}; 3600s day^{-1} for ET_0 in mm h^{-1}).
r_c is the canopy resistance [s m^{-1}],
Rns is the net short wave radiation [$MJm^{-2}day^{-1}$]
T_0 is the leaf temperature [^oC]
r_a is the aerodynamic resistance [s m^{-1}],
Cp is the specific of air [MJ kg^{-1} $^oC^{-1}$],
ρ is the mean air density [kg m^{-3}],
ϵ water to dry molecular weight ratio [-],
λ is the latent heat of vapourization [MJ kg^{-1}],
σ is Stefan-Boltzmann constant [$MJm^{-2}K^{-4}$ day^{-1}]
r_R is the radiative resistance [sm^{-1}],

P is atmospheric pressure [kPa].
VPD is the vapour pressure deficit [kPa]

For ET calculation, internal and external resistances r_c and r_a for the canopy were chosen to be $70 sm^{-1}$ and $430 sm^{-1}$ respectively (Donatelli et al., 2006; Oke, 1983; Prenger et al., 2002).

4.2.3. Panda Greenhouse Location and Construction

The experiments were carried out from 17 September to 22 September, 2005 in a commercial, multi-span fan-ventilated greenhouse (figure.4-1), E-W oriented, located at Panda, North-East Naivasha, Kenya (latitude 0.4^{o}S, longitude 36^{o}E, altitude 1990m). The geometric characteristics of the greenhouse are follows: eaves height of 3.8m, ridge height 5.6m, total width of 96m, length 100m, constituting a ground area of $9600 m^2$, and volume of $48000 m^3$. The greenhouse constitutes of fifteen adjacent 6.4 m wide arc, covered with plastic film and was equipped with a fan ventilation system consisting of fifteen fans. The airflow rate for each fan was $11.1 m^3 s^{-1}$. The fans are set to operate automatically after two hours irrespective of the microclimate inside the greenhouse.

The greenhouse was planted with a rose crop (*golden gate*) planted in double rows, parallel to the air flow axis with a plant density of 10 plants m^{-2}. Water and fertilizer was automatically controlled by a fertigation computer.

The greenhouse structure was covered with a 150 µm thick polyethylene sheet. Rosa (*golden gate*) plants had been planted in July, 2005 in double row crops creating 10 plants per m^2. The plants were grown following the "bending" technique (Kool and van de Pol, 1996) which consists of bending the stems that are not considered useful to flower production. This technique allows obtaining more leaf area for sustaining photosynthesis and increasing the contribution of the canopy transpiration to greenhouse cooling. The growing medium consisted of imported loamy soil. Forced ventilation was used to cool the greenhouse.

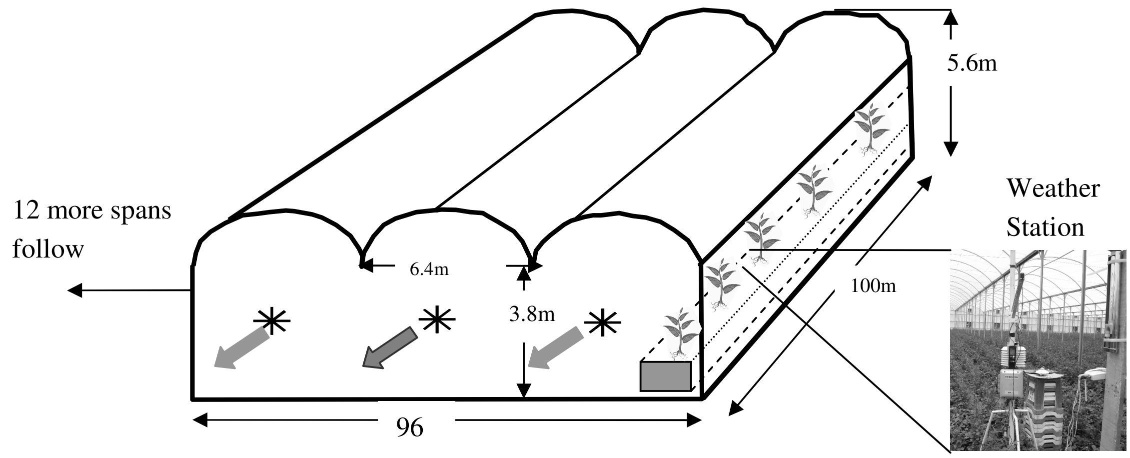


Figure 4-1: Schematic plan of Panda fan ventilated greenhouse.

Leaf temperature was measured by means of temperature sensors (Hobo). The sensors were glued to the underside of leaves. The canopy temperature was calculated as the mean value of measurements on 3 healthy and mature leaves distributed randomly along layers of the canopy (bent shoots and flower stems). During some selected days canopy temperature was measured by means of an IR thermometer.

The leaf area index (LAI, m^2 leaf m^{-2} ground) was estimated from leaf length measurements, using the relationship $LAI = 0.26L^2$ linking the LAI (m^2) of a leaflet to L (m) (Katsoulas et al., 2001).

4.2.3.1. Irrigation in Panda Greenhouse

Water and plant nutrients, with electrical conductivity of 200-300 μScm^{-1} and a pH. of 6.5 is applied 3 times per day, through automatic drip irrigation system, at a rate 2.7-3.9 mm day^{-1}. The only data available was that of water applied but not drainage as the plants were grown in natural soil making it difficult to measure drainage.

4.2.3.2. Ventilation Requirement in Panda Greenhouse

The ventilation requirement of a greenhouse can be established using equation 4-7 presented below (Kittas et al., 2005). Considering the fact that the calculation of ventilation needs in a greenhouse takes into account extreme climatic conditions namely maximum solar radiation during clear sky conditions and zero wind speed then;

$$V_a = \frac{0.0003\tau R_{s,o-Max}}{\Delta T} \quad \textbf{(4-7)}$$

Where,
V_a is the ventilation rate ($m^3s^{-1}m^{-2}$).
$R_{s,o\ -Max}$ is the maximum outdoor global radiation [Wm-2],
ΔT is difference between outdoor air temperature and greenhouse air temperature [^0C],
τ is the transmissivity of the cladding material[-].

4.2.4. Bigot Greenhouse Location and Construction

The experiment was carried out from 23 September to 1 October, 2005 in a commercial natural ventilated greenhouse figure 4-2, E-W oriented, located at Bigot farm. The geometric characteristics, of the greenhouse is as follows: each span was 7.5m wide by 104m, eaves height 4m and ridge height 4.8m, total width 300m and length 104m.
The cladding material was 200µm polythene film with UV absorbing additives. Rosa (*golden gate*) was planted in August 2005 in row crops creating 10 plants per m^2. The plants were also grown following the bending technique. The growing medium consisted of pumice (a non-inert volcanic material).The greenhouse was equipped with a continuous roof vent to provide natural ventilation for cooling the greenhouse. The vent was designed in such a way that it remained opened at 100% irrespective of the microclimate inside the greenhouse.

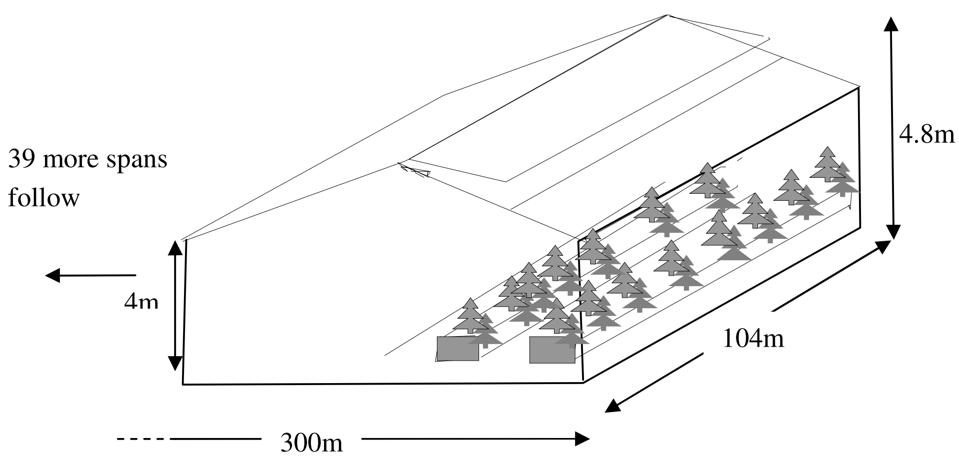


Figure 4-2: Schematic plan of the Bigot natural ventilated greenhouse.

4.2.4.1. Brief Description of Hydroponics

Hydroponics may be defined as "any method of growing plants without the use of soil as a rooting medium, which involves supply of all inorganic nutrients exclusively via the irrigation water" (Savvas, 2003). This is achieved by the supply of a nutrient solution, i.e.

water containing dissolved fertilizers at proper concentrations, in place of raw irrigation water. Various non-toxic porous materials are used as plant growth substrates, including rock-wool, perlite, pumice etc. A balanced distribution of small and larger pores is required in a substrate to ensure adequate availability of water to the plants without affecting the supply of oxygen to the roots.

The main part of a hydroponics installation is the fertigation head unit, which enables accurate dosing of nutrients and water to the crop in form of balanced nutrient solution. Figure 4-3 shows a layout of a hydroponics system.

Measurement of actual ET in hydroponics involves determining water applied and drainage. The difference between the water applied and drainage is the actual ET (equation 4-9).

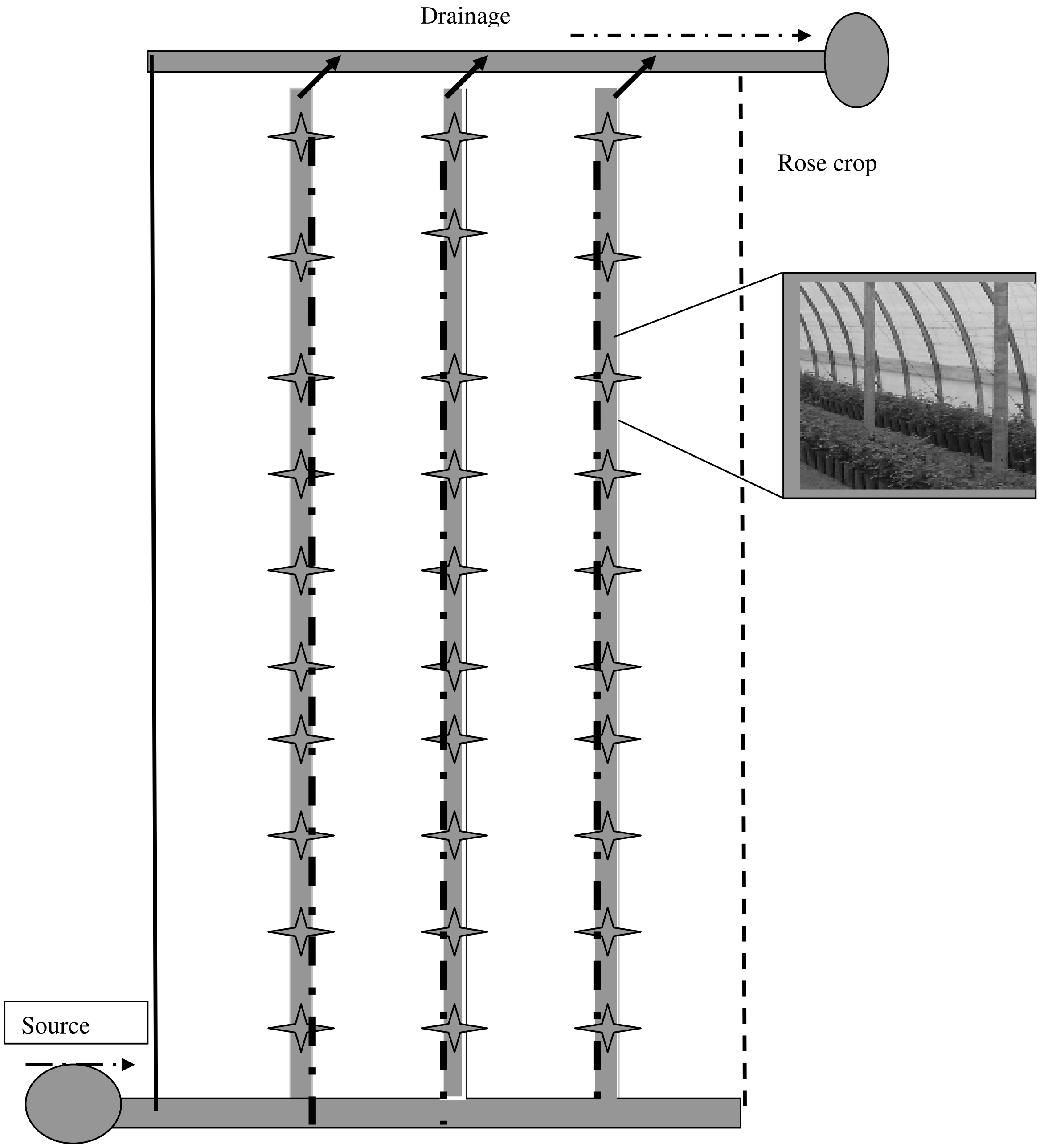
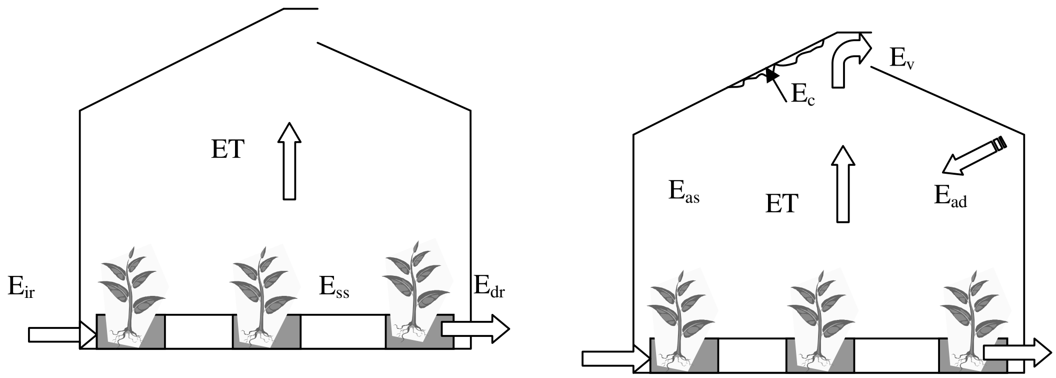


Figure 4-3: Layout of the hydroponics irrigation system at Bigot greenhouse

4.2.4.2. Water Balance in a Greenhouse with a Hydroponics

Figure 4-4 presents different fluxes in a greenhouse environment. The water balance could be established at different time steps (hourly, daily). The amount of Evapotranspiration (ET) can be related to the water supplied by the irrigation system (E_{ir}), the change in water stored in soil or substrate (E_{ss}) and the amount of water drained out of the greenhouse (E_{dr}):

$$ET = E_{ir} - E_{ss} - E_{dr} \qquad \textbf{(4-8)}$$



a: Greenhouse water balance

b: ET partitioning for air within greenhouse

Figure 4-4: Water fluxes in the greenhouse (a) greenhouse water balance (b) ET partitioning for air within a greenhouse

The water storage capacity in the soil depends strongly on growing medium; compared to the daily uptake, it is high in real soil but considerably less for artificial substrates or systems using nutrient film techniques (NFT) (Jolliet, 1999). The water stored in the artificial substrate has been ignored in calculation of ET in this study due to its limited influence.

Equation 4-8 reduces to

$$ET = E_{ir} - E_{dr} \tag{4-9}$$

For the air within the greenhouse, two water sources can be considered: the crop evapotranspiration (ET) and the water added by fogging (E_{ad}), if any. The water can be removed from the air either by condensation on the cladding (E_c), by leakage and ventilation (E_v) or by a dehumidification heat pump (negative values of E_{ad}). For water condensed on the cladding the fraction which has not been removed could be re-evaporated (negative value of E_c).

The general form of water vapour balance (figure 4-4b) of the greenhouse air volume can be written as follows

$$ET = E_c + E_v + E_{sa} - E_{ad} \qquad \textbf{(4-10)}$$

Where E_{sa} is the variation in the water vapour stored in the air.

During the day and in arid climates, the greenhouse water balance depends mainly on the evapotranspiration and on loss from ventilation. Condensation seldom occurs during the day (Bailey, 2000) however, condensation occurs during night time. There are a number of reasons for condensation not to be allowed to take place. First, condensation can modify a number of physical processes in the greenhouse; drops on the inside of the cladding material will modify the transmission of rays of light passing through the cladding. Total internal reflection in the water drop can result in a ray that would have previously entered the house being reflected away, thus decreasing the internal light level. Some greenhouse plastics are designed to prevent condensation from forming by incorporating a wetting agent. Secondly, at night, as air cools to the dew point, condensation occurs and water droplets are formed on cooler surfaces such as the leaves and the inside skin of the greenhouse. This moisture promotes the germination of fungal pathogen spores such as Botrytis or powdery mildew (Papadoupolos, 1991). The formation of water film will intercept part of the long-wave radiation exchange resulting in less heat loss from the greenhouse by this mechanism.
Evapotranspiration is limited during the night, when condensation is the main water sink, while the water stored in air is limited and can be neglected for long term calculation (Jolliet, 1999).

Then, in majority of cases (no supply from a mist/ fogging system), we have

$$ET = E_V \qquad \textbf{(4-11)}$$

ET can be assumed equal to ventilation air flow.

4.2.4.3. Drainage Measurement in Bigot Greenhouse

To measure the freely draining water a structure had to be selected. Discharge measurement structure is based on the relationship between water level over the structure and discharge. Water level is measured and converted to discharge. Bos, (1989) discusses many of these structures. First, a suitable structure for measuring discharges in the prevailing conditions had to be found. A V-notch weir was chosen because it allows for measurements of both small and large discharges(van den Elsen et al., 2003). A disadvantage of the weir is that it has a low debris and sediment passing capacity, which means that the area before the weir would fill up with debris and sediments. To solve the problems, pipes and a polythene sheet were installed in the canal see Figure 4-5.

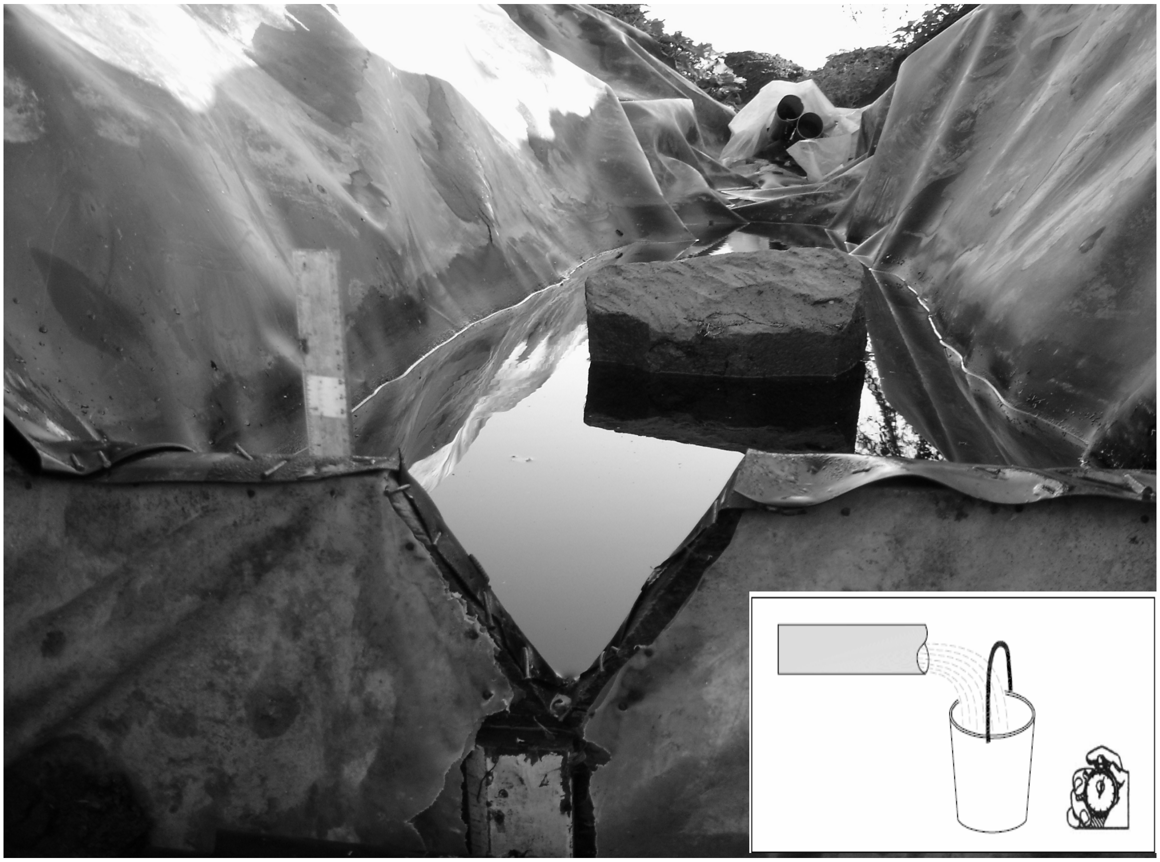


Figure 4-5: Measurement of discharge. Inset is the device used to calibrate the v-notch.

There were also practical reasons for selecting this type of structure; it is one of the simplest to build which was an important factor, considering the short time for the field work (three weeks). The V-notch design causes small changes in discharge to have a large change in depth allowing more accurate head measurement than with a rectangular weir.

4.2.5. Discharge Equation

The Q-h relationship of a v-notch weir can be derived from the law of Bernoulli and the equations for width (B) and area (A) of triangular cross sections Figure 4-6

$$B = 2h\tan\left(\frac{\theta}{2}\right) \quad \textbf{(4-12)}$$

$$A = B\frac{h}{2} \quad \textbf{(4-13)}$$

Where $\theta =$ total angle of the weir [^{o}] (Bos, 1989),

$$Q = C\sqrt{\frac{g}{2}}h_c^{5/2}\tan\left(\frac{\theta}{2}\right) \qquad \textbf{(4-14)}$$

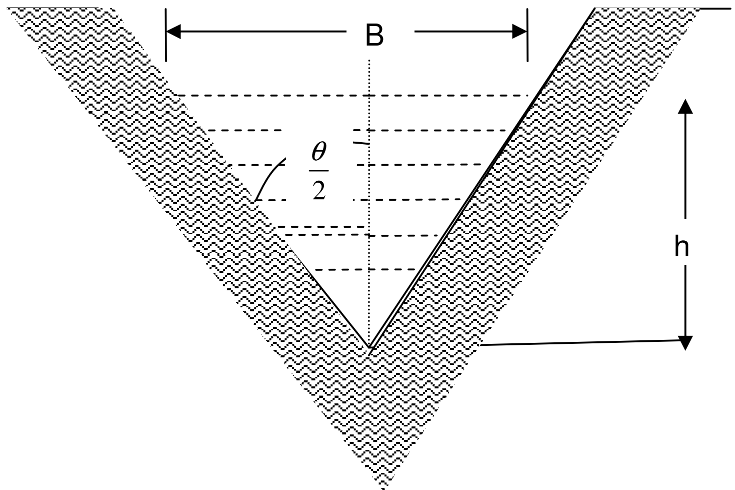


Figure 4-6: The triangular cross-section of a weir. h, represents the water level, B is the width of the water over the weir, and θ is the weir angle

C is the correction factor necessary for correcting for non-ideal circumstances and consists of two parts: Cd and Cv.
Cd is correction factor that is called discharge coefficient. It has to be applied to correct for effects such as viscosity, turbulence and non-uniform flow distribution (Bos, 1989).
These effects cause energy loss. As the equation was derived under the assumption of no energy loss (Bernoulli), a correction must be made. The discharge coefficient depends on shape and type of measurements structure, but is generally between 0.93 and 1.02 (Bos, 1989).

C_v is a correction for neglecting the velocity in the approach channel. Normally, the water level is measured upstream of the measurement structure. When this is done, it has to be assumed that the water velocity upstream of the structure is 0. As this is not always the case, a correction must be applied. If the critical water level is measured directly C_v can be assumed to be 1 (van den Elsen et al., 2003). The actual value of the correction factor depends on whether the weir is broad-crested (crest width several meters) sharp-crested (crest width is 2 mm maximum) or short-crested (between sharp-crested and broad-crested). The weir used was 12 mm and therefore short-crested.

Using measured discharge on several days and theoretical discharge calculated from data recorded by the diver at intervals of ten minutes the discharge coefficient C was determined in the field. For this study the value of C was found to be 0.92.

Figure 4-7 shows the discharge head curve determined in the field

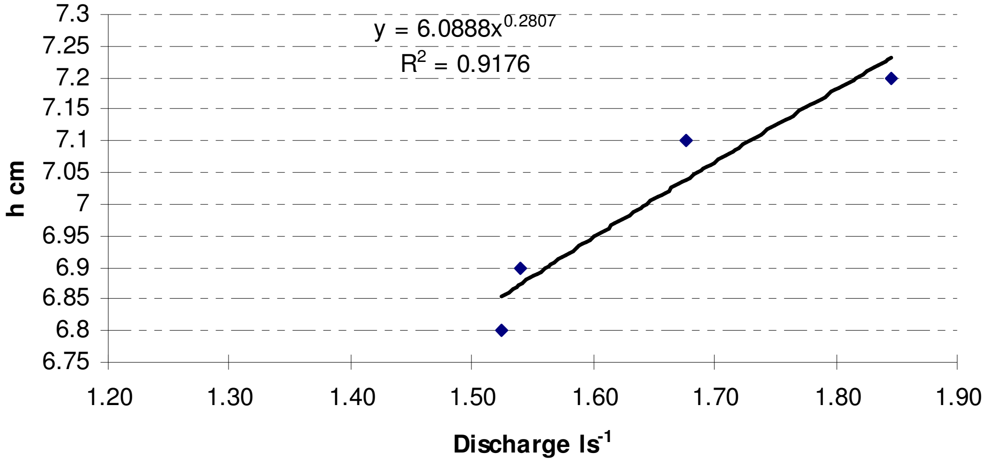


Figure 4-7: Discharge head relationship for the v-notch.

4.2.6. Oserian Greenhouses

Data for these commercial greenhouses was provided by the farmer for the period 1 September to 30 September, 2005. The greenhouses is E-W oriented located at (0^{o}51'20"S, 36^o 15', 00"E). Natural ventilation was provided automatically when the air temperature within the greenhouse exceeded 25^{o}C and/or humidity above 85% the vents opened, while temperatures below 18^{o}C and /or humidity below 65% closed the vents.

The cladding materials, growing medium and greenhouse geometry was similar to the above (Bigot greenhouse); however the area under crops varied between 9600m^2 to 10560m^2. A variety of roses had been planted between October 2004 and July 2005 at a plant density of 10 plants per m^2. The varieties include (*Amani, Akito, Wild Calypso* and *Tropical Amazone).*

Figure 4-8: Oserian farm manager Mr. Fulson explaining how the roof vents operates during field work

4.3. Irrigation

Water and plant nutrients, with electrical conductivity of 200-300µS/cm were applied 3 times a day for Panda greenhouse. While Bigot greenhouse (hydroponics) water was applied 12-16 times a day. Automatic drip irrigation system controlled by a fertigation system was used in both cases. Water supply scheduling was done in an ad-hoc method. No evaluation was done before application. Excess water for the hydroponics drained freely outside the greenhouse.

Oserian greenhouse had a complete re-circulating system and irrigation was done with 30-50% leaching fraction in order to prevent decreased osmotic potential and built up of both essential (boron, potassium, magnesium, calcium etc) and non-essential (lithium, zinc, sodium etc) ions in the root zones. Appendix 2 shows the water applied and drainage.

4.4. Albedo Measurements

Albedo determination involves two measurements: the incident global radiation and the radiation reflected by the canopy (covering 320–3000 nm).Owing to lack of a net radiometer for measurement of net radiation (R_n) an attempt was made to estimate the radiation. The Pyranometer (Kipp Zonnen) was kept at intervals of 5 minutes facing downwards (rose canopy) and upwards in number of times. Simultaneously to the above measurements another pyranometer was installed outside to measure incoming global radiation R_{so} on 22 September, 2005. Figure 4-9 shows the relationship between radiation obtained by keeping the pyranometer facing downwards and upwards at intervals of 5 minutes. Also shown is the incoming global radiation outdoor.

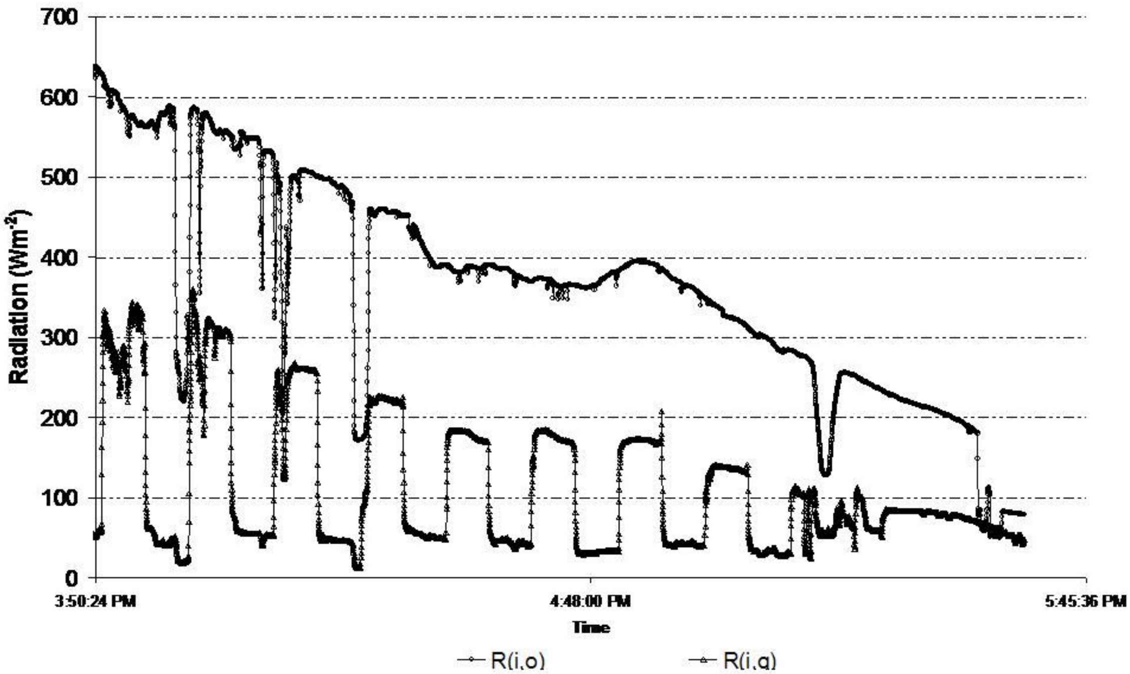


Figure 4-9: Incoming radiation measured outdoor ($R_{i,o}$) and Incoming radiation in Panda greenhouse ($R_{i\ g}$)

4.5. Reliability of Data

Various techniques for assessing quality of measured weather data are outlined by Allen, (1996). One of the methods includes employing duplicate instruments in the weather station.

4.5.1. Clear sky comparison

For solar radiation pyranometer operation and calibration accuracy can be evaluated by plotting hourly or daily average pyranometer readings against computed shortwave radiation expected under clear sky conditions.

Figure 4-10 shows the weather characteristics during a test day of 24 September 2005. The figure show hourly measured solar radiation (R_s) compared against solar radiation expected for a complete clear sky and clean air conditions (R_{so}) predicted using equations in

(Allen, 1996)that consider the impact of sun angle, air pressure and atmospheric water content. The calibration of the pyranometer was judged to be correct due to close agreement between R_s and R_{so} on a day that had clear air.

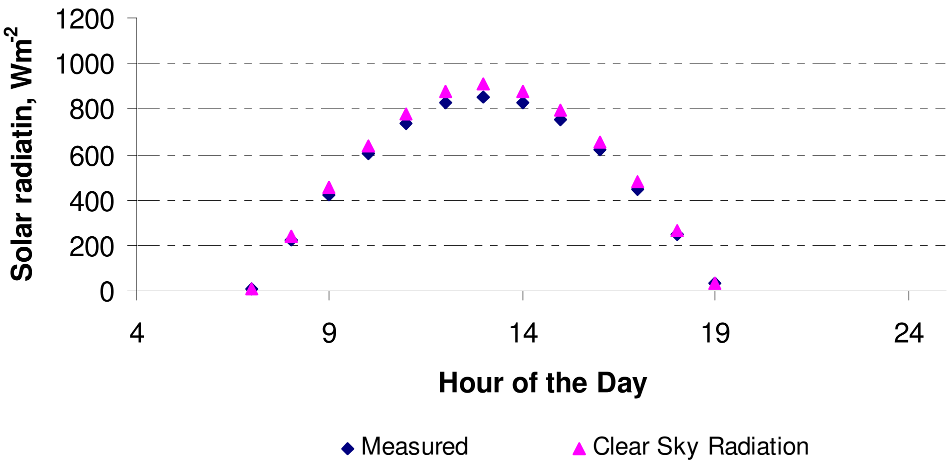


Figure 4-10: Hourly shotwave radiation (Measured) and predicted (calculated) clear sky radiation

The Kipp Zonen pyranometer was installed together with the silicon pyranometer for correction of the later. The readings taken by the silicon sensor deviated systematically (figure 4-11.

The results after correction is shown in figure 4-11

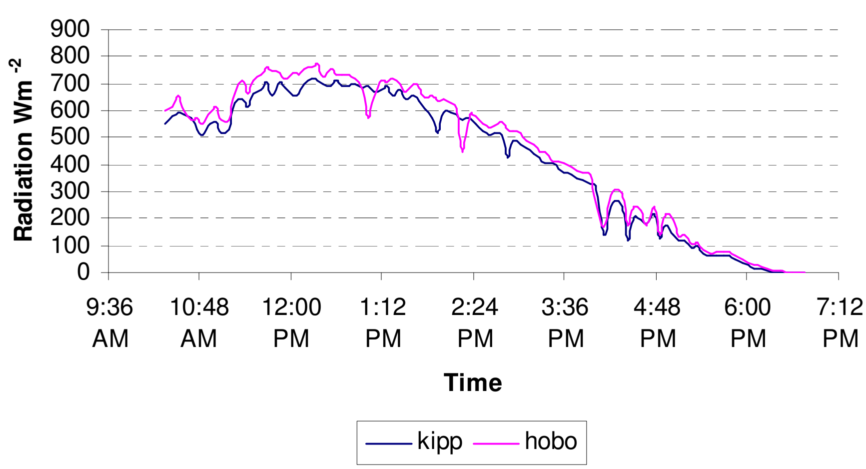


Figure 4-11: Comparison of shortwave radiation recorded by silicon pyranometer (Hobo) sensor and Kipp Zonen pyranometer (Kipp) before correction.

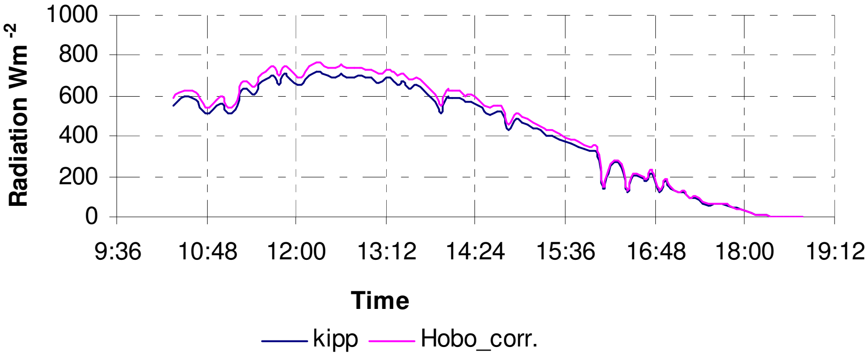


Figure 4-12: Comparison of short wave radiation recorded by silicon pyranometer (Hobo) sensor and Kipp Zonen pyranometer (Kipp) after correction.

4.5.2. Air Temperature and Due Point Temperature

Figure 4-13 and Figure 4-14 show relationship between air and due point temperature on two days during the experiment. These are typical of agricultural area where minimum air temperature during early morning approached the due point. These occurred on many days and the fact that the due point temperature was relatively constant indicate that the relative humidity sensor was functioning well.

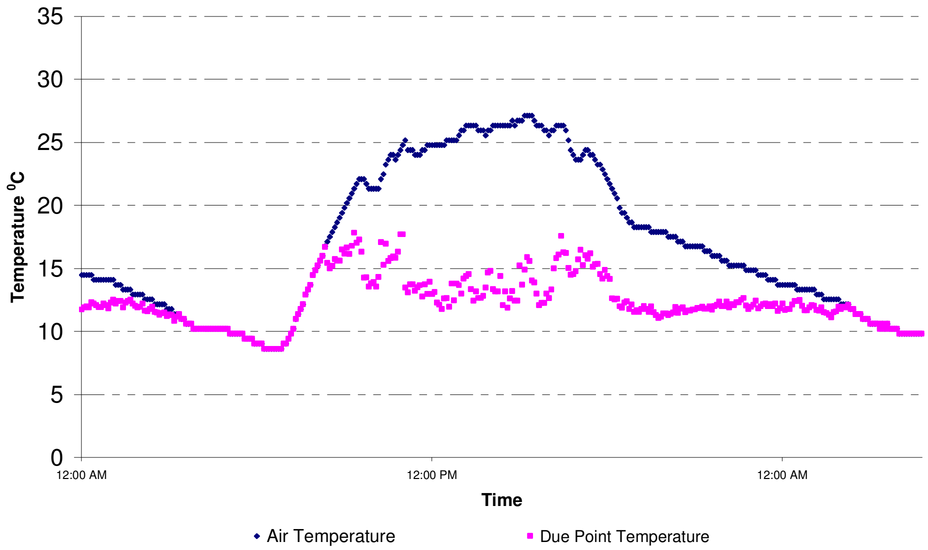


Figure 4-13: Air temperature and due point temperature on test day 20-September, 2005

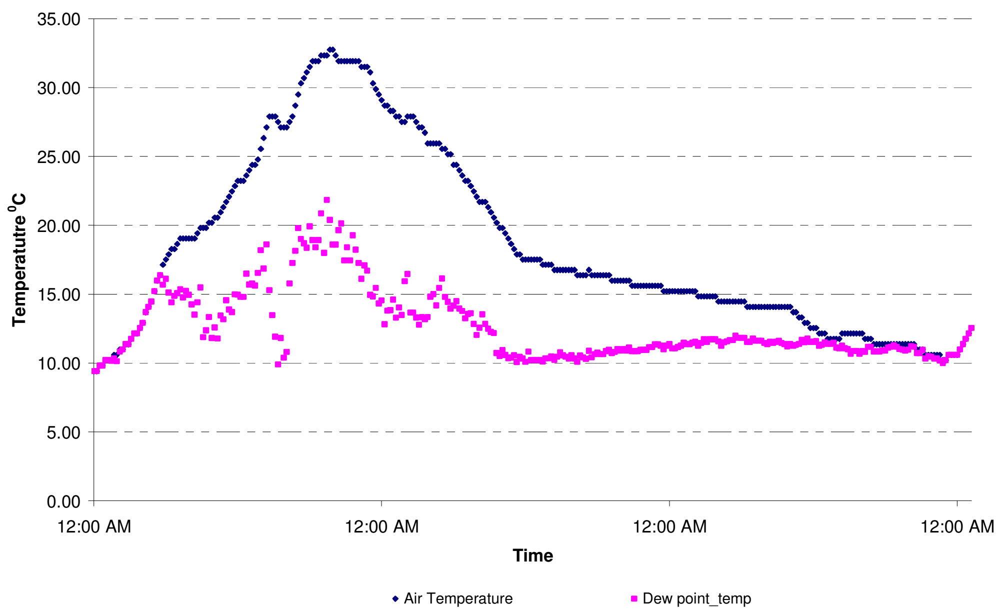


Figure 4-14: Air temperature and due point temperature on test day 21 September, 2005

The temperature sensors (New_Hobo_sensor and Old_Hobo_sensor) gave similar readings (Figure 4-15.); however, the old sensor gave higher readings at high radiation load. This was attributed to improper shielding as only one radiation shield was available. The new sensor gave similar readings as aspirated psychrometer; hence measurements from this sensor are used in all the calculations.

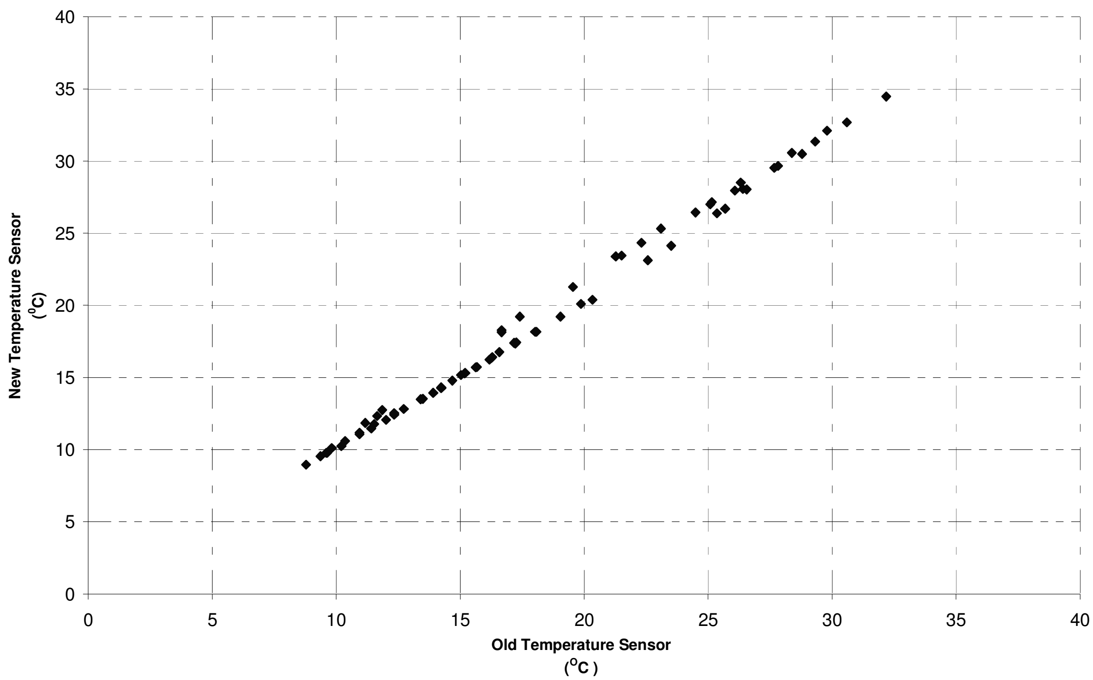


Figure 4-15: Air temperature from two sensors

The soil moisture content readings, taken directly by soil sensors and probes, deviated unsystematically and significantly. Hence the soil moisture/substrate readings are not used in any of the calculations.

4.6. The Simplified Model

Evapotranspiration can be calculated using the Penman-Monteith equation given as

$$ET = \frac{\Delta(R_n - G) + \rho C_p / r_a [e_s(T) - e_a]}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \qquad \textbf{(4-15)}$$

If

$\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right)$, the above equation (1) can be re-written as

$$ET = \frac{\Delta(R_n - G) + \rho C_P / r_a [e_s(T) - e_a]}{\Delta + \gamma^*} \quad \textbf{(4-16)}$$

The coefficients α and β can be considered as estimations of the following terms appearing in the Penman-Monteith equation

$$\alpha = \frac{1}{\lambda}\left(\frac{\Delta}{\Delta + \gamma^*}\right) \quad \textbf{(4-17)}$$

$$\beta = \frac{1}{\lambda}\left(\frac{K_t \rho C_p / r_a}{\Delta + \gamma^*}\right) \quad \textbf{(4-18)}$$

α corresponds to the coefficient of the radiative component, and β to the advective component. For greenhouse conditions, r_a can be considered to be roughly constant (Stangellini, 1987).While, net radiation (Rn) can be assumed equal to short wave radiation at the top of the canopy (Baille, 1994).

To take into account the influence of LAI, equation (2) can be written in the following format as expressed by (Baille, 1994)

$$ET = \alpha f_1(LAI)R_n + \beta . f_2(LAI).VPD \quad \textbf{(4-19)}$$

Then,

$$ET = \alpha.(1 - EXP(-kLAI))R_{i,g} + \beta.LAI.VPD \quad \textbf{(4-20)}$$

Where,

1-exp (-kLAI) represents the classical relationship for radiation interception by a canopy. The value of k is taken as 0.64 (Stangellini, 1987). LAI can be considered as multiplicative factor in the “advective” term of the Penman-Monteith equation.
The terms to be solved would be α and β

4.7. Review of Estimated Irrigated Area

4.7.1. Data

Table 4-4 shows images used to identify the irrigated area. Using the local extension officer knowledge and field visits the area under greenhouse and outdoor cultivation was identified and later screen digitized.

Table 4-4: Brief description of imageries used in delineating irrigated area

Platform	Sensor	Date	Comments
TERRA	ASTER	March, 8, 2003	Completer coverage; 0% cloud coverage
		March, 29, 2005	Partial coverage ; 0% cloud
		September, 30, 2005	Partial coverage; 0% cloud
		November, 1, 2005	Complete coverage; Partially cloudy
IKONOS	IKONOS	June, 3, 2001	Partial coverage; 0% cloud

ArcView and ILWIS software's were used to screen digitize the irrigated area and classified either as outdoor cultivation or greenhouse cultivation.

4.7.2. Lake Naivasha Water Balance

The water balance of Lake Naivasha can be presented using the equation show below (Gitonga, 1999).

$$P-ET+R+GWin-GWout = dS \qquad \textbf{4-21}$$

Where;

P = direct precipitation into the lake

ET = Evapotranspiration

R = Surface Runoff into the lake

GW_{in} = ground water inflow into the lake

GW_{out} = ground water out flow from the lake

dS = Change in lake storage.

Using an average lake area of 145 km^2 (1932-1997) Gitonga, (1999) found an average change in Lake level of -0.047m. This was attributed to data errors, but he observed that the Lake level had a downward trend.

4.8. Other Experiments

4.8.1. Comparison of Transpiration Outdoor and in Greenhouse

Simple potometers were designed to determine and compare transpiration of rose flowers outdoor and in the greenhouse. Stem cuttings with same number of leaves were place simultaneously outdoor and in the greenhouse. Figure 4-16 shows the arrangements of simple potometers in the greenhouse and outdoor. Transpiration was estimated by measuring the distance the water level drops in the graduated tube over a measured length of time. It was assumed that the drop was due to the cutting taking in water which in turn is necessary to replace an equal volume of water lost by transpiration.

(a) (b)

Figure 4-16: (a) potometer in the greenhouse (b) potometer outdoor

It must be emphasised that the experiment was not conducted to represent evapotranspiration both in the greenhouse and outdoor but rather to give a general indication of climatic differences between indoor and outdoor. The cuttings outdoor wilted shortly after being taken outdoor at high radiation load. This was attributed to drastic change of microclimate (indoor to outdoor). Sealing the potometer to avoid direct water loss was difficult affecting the rate of transpiration.

Due to the above mentioned problem the results of the experiment are not discussed further.

4.8.2. Cooling Effect Produced by a Transpiring Leaf

Both sides of a rose flower leaf were sprayed at Bigot greenhouse. Surface temperature of the sprayed leaf was monitored using infrared thermometer and compared with the temperature of unsprayed plants. Some results are presented in appendix 7. Due to time constraints and lack of a logger, the results are not discussed further.

5. Results and Discussion

5.1. Comparison of Outdoor vs. Greenhouse Irrigation

Figure 5.1 shows the ET for roses in the greenhouse and potential ET outdoor during the month of September, 2005 at Oserian farm. The daily actual ET estimated by Penman-Monteith outdoor was higher than those estimated inside the greenhouse. Many authors have also observed that evapotranspiration inside the greenhouse was lower than outdoor (Fernandes et al., 2003; Stanghellini, 1993). These results can be explained by the influence of the main factors of evaporative demand of the atmosphere, such as attenuation (absorption and reflection) of incident solar radiation by the plastic covering, lower wind speed values and higher relative humidity in a greenhouse.]

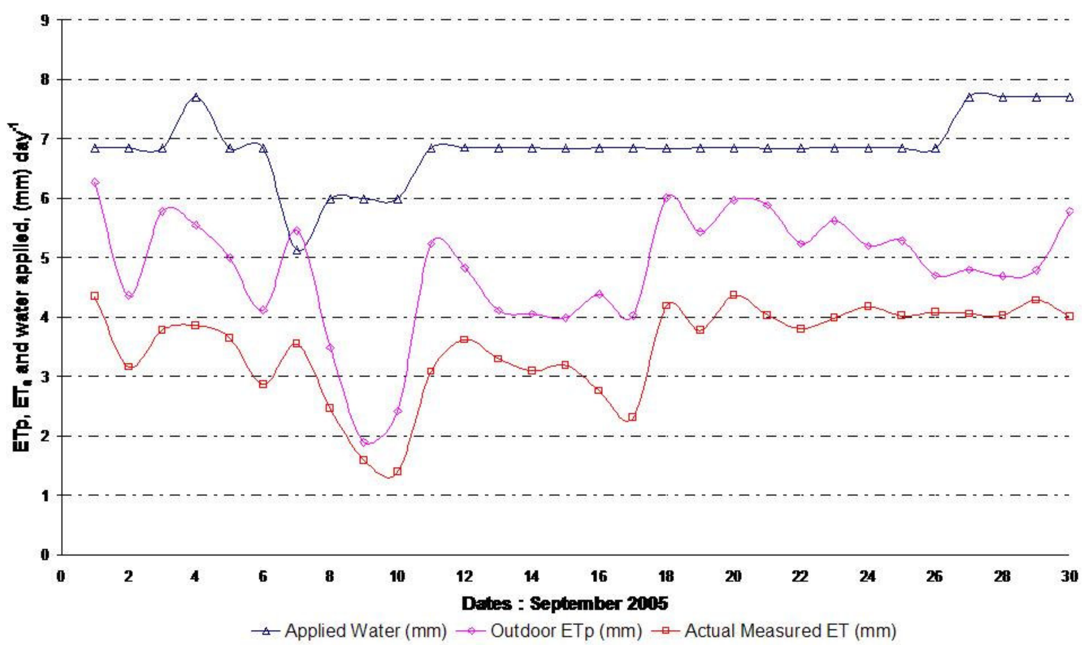


Figure 5-1: Crop evapotranspiration for rose flower inside (ET in) and (potential ET out) as well as water applied in mm day^{-1} at Oserian Farm

On an overcast day (day 9 and 10 September, 2005) the outdoor ET is almost equal to ET in the greenhouse (the ambient air temperature was 14.1 and 13.9^{o}C while in the greenhouse the temperatures were 16 and 16.3^{o}C on respective days). The results can be explained by the fact that the vapour pressure deficit increases rapidly with increasing temperatures, because the thermal energy of the water molecules in the liquid phase becomes closer to the energy required to break the bonds with adjacent molecules and escape through the water-air interface. Thus, the same relative humidity represents a much larger saturation vapour pressure deficit at higher temperatures and corresponds to the potential for much larger evaporation rates. This gives an indication of the reason why evapotranspiration rates in the greenhouse can, in some circumstances, be closer to rates in the open field. Although greenhouses are generally environments with high relative humidity, they operate at higher temperatures than the ambient value, thus restoring some of the driving force for water vapour diffusion (Day and Bailey, 1999).

The highest water consumption occurred on 20 September, 2005, and was 4.4 mm day^{-1} for a mature crop in Oserian greenhouse. This value has also been reported by (de Pascale and Paradiso, 2005) who reported the highest consumption of roses in Summer at Naples. A sharp variation can be noticed on 30 September, 2005 between Potential ET outdoor and actual ET in the greenhouse. This was probably a day when rose flowers were harvested and/or pruning occurred in the greenhouse.

Using remote sensing Mekonnen, (1999) estimated the actual evapotranspiration of flowers outdoor. The average value was estimated as 5.4 mm day^{-1}. In the present work the mean actual evapotranspiration in the greenhouse approximately is found to be 3.5 mm day^{-1}. In other words, the actual ET in the greenhouse at Oserian farm is 65% of actual ET outdoor. The results corroborate other authors who reported a lower ET in greenhouse compared to outdoor.

Stanghellini, (1993) found that the actual evapotranspiration inside a greenhouse in Mediterranean was 70% of that observed outside. While, (Monterro et al., 1985; Rosenberg et al., 1989), observed that potential evapotranspiration inside a greenhouse is around 60 to 80% of that verified outside. There seems to be a relationship between radiation and actual evapotranspiration. The radiation in the greenhouse was calculated as 65% outdoor during the test days. Figure 5.2 shows the comparison of outdoor radiation and radiation observed in the greenhouse.

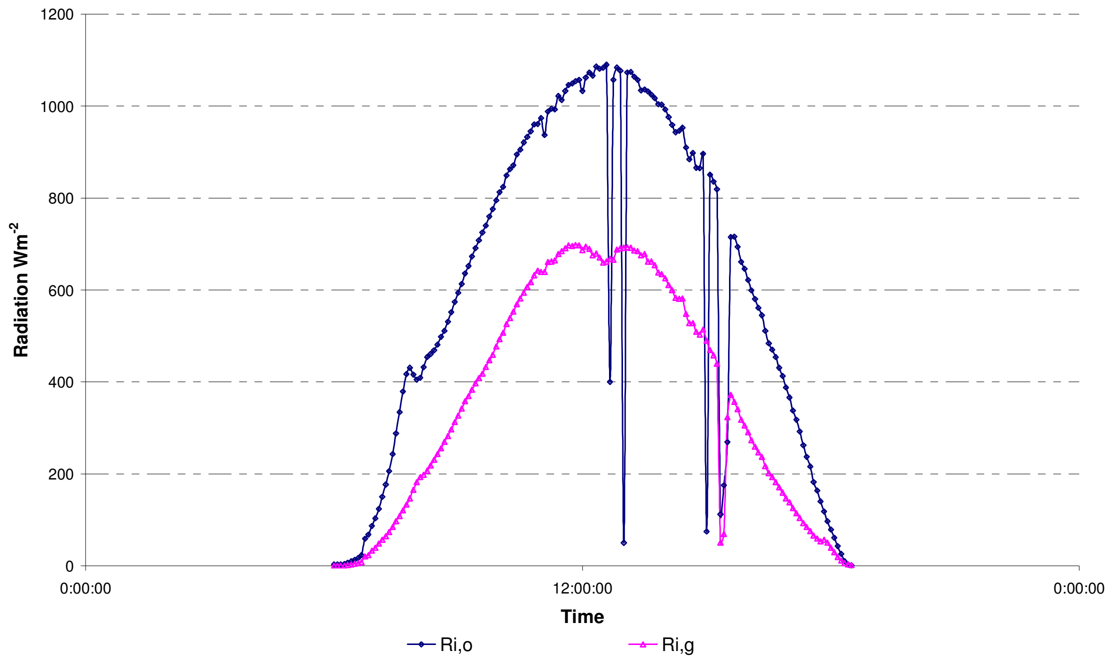


Figure 5-2: Incoming radiation observed in the greenhouse ($R_{i,o}$) (Wm^{-2}) and incoming radiation outdoor ($R_{i,o}$) (Wm^{-2}) for 24 September 2005 at Bigot greenhouse.

Figure 5-3 illustrates potential ET outdoor, actual ET in the greenhouse and water permitted by the Ministry of Water and Irrigation. It can be seen that the permitted abstraction for rose flower is consistently lower than the greenhouse actual ET and also potential ET outdoor. The calculation of permitted abstraction is not clear. However, this value has been disputed by irrigation engineers as well as farmers since it is the same value used in all areas of Kenya despite variability in climate. Care need to be taken when calculating Lake Naivasha water balance based on abstraction permits as this can give misleading conclusions since the permits show low water abstraction.

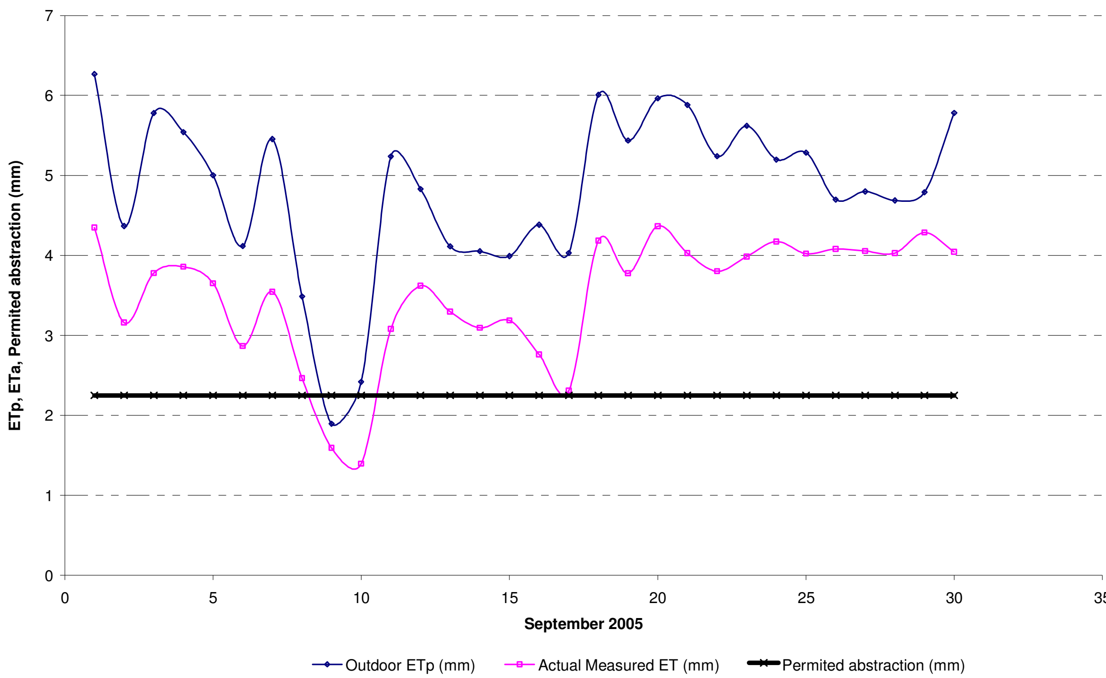


Figure 5-3: Actual ET in the greenhouse (ET in) and (outdoor ET_p) as well as permitted abstraction by Ministry of Water and Irrigation in mm day^{-1} at Oserian Farm

Table 5.1 shows water applied, drainage, actual ET inside the greenhouse and outdoor from 26 to 30 September, 2005 in Bigot greenhouse. Only data for five days is available as the data logger malfunctioned on 1 October, 2005. For calculation of potential ET outdoor, a K_c of 0.4 was assumed for rose flowers with an equivalent LAI of 0.85.

The system is designed to maintain near 50% drainage, in order to maintain optimal conditions of water supply. However, the average drainage in the greenhouse was 66%. The level of potential pollution is very high when drainage is allowed to flow downstream. However, the problem can be solved by collecting and then recycle the drainage. These systems commonly referred to as closed hydroponics are becoming popular with farmers.

As the level of potential pollution is high water drainage should be totally recycled. In the coming years, this issue will become a condition for the survival of greenhouse horticultural industry as environmental criteria become more and more important in public opinion. In the Netherlands, total recycling of nutrients became compulsory as from 2000 (Jolliet, 1999).

Table 5-1: Daily values of applied water, drainage and actual ET indoor for bigot greenhouse. Outdoor potential ET calculated using Penman-Monteith equation is also shown.

Date September 2005	Applied Water (m^3)	Drainage (m^3)	Greenhouse Actual ET (mm)	Outdoor Potential ET (mm)
26th	107.5	70.72	2.36	3.13
27th	107.2	70.57	2.35	3.19
28th	109.3	74.18	2.25	3.12
29th	96.2	65.82	1.95	3.19
30th	117.5	78.94	2.49	3.85

5.1.1. Albedo

Figure 5-4 illustrates the albedo of rose canopy determined at Panda greenhouse. The estimated albedo was found to be 0.1. The albedo remains constant since the experiment took a short period (2 hours), for longer periods (e.g.24hrs) albedo changes with solar zenith angle, but remains approximately constant in the mid-day (Prof Jun Wen, 2005). Since the pyranometer was originally designed to measure the incoming global radiation and therefore not well adapted to measure crop canopy albedo, the results are not used in any calculation. However, its worth noting that net radiation (R_n) can sometimes be estimated as being equal to shortwave radiation on top of crop canopy as in equation 4-20 (Baille et al., 1994).

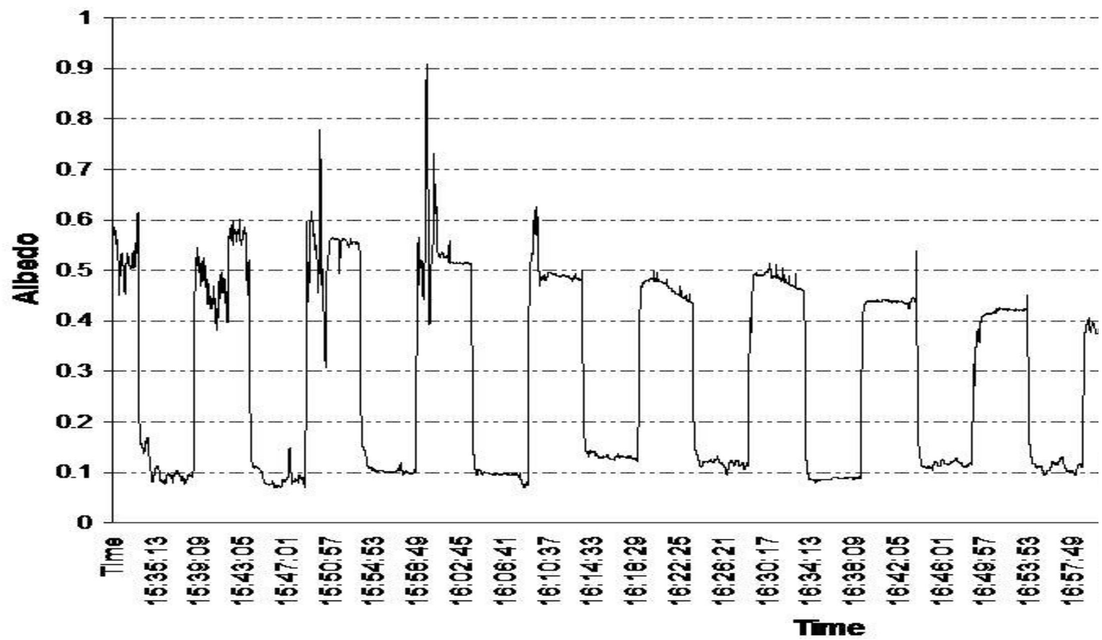


Figure 5-4: Albedo of the rose canopy at Panda greenhouse the lower curve (indicate an albido of 0.1)

5.2. Panda Greenhouse (Forced ventilated)

5.2.1. Radiation, Vapour Pressure Deficit (VPD) and Estimated Evapotranspiration

Figure 5.5 Illustrate diurnal variations of estimated evapotranspiration, expressed in mm as affected by incident radiation and vapour pressure deficit for measurement taken on 20 and 21 September, 2005.

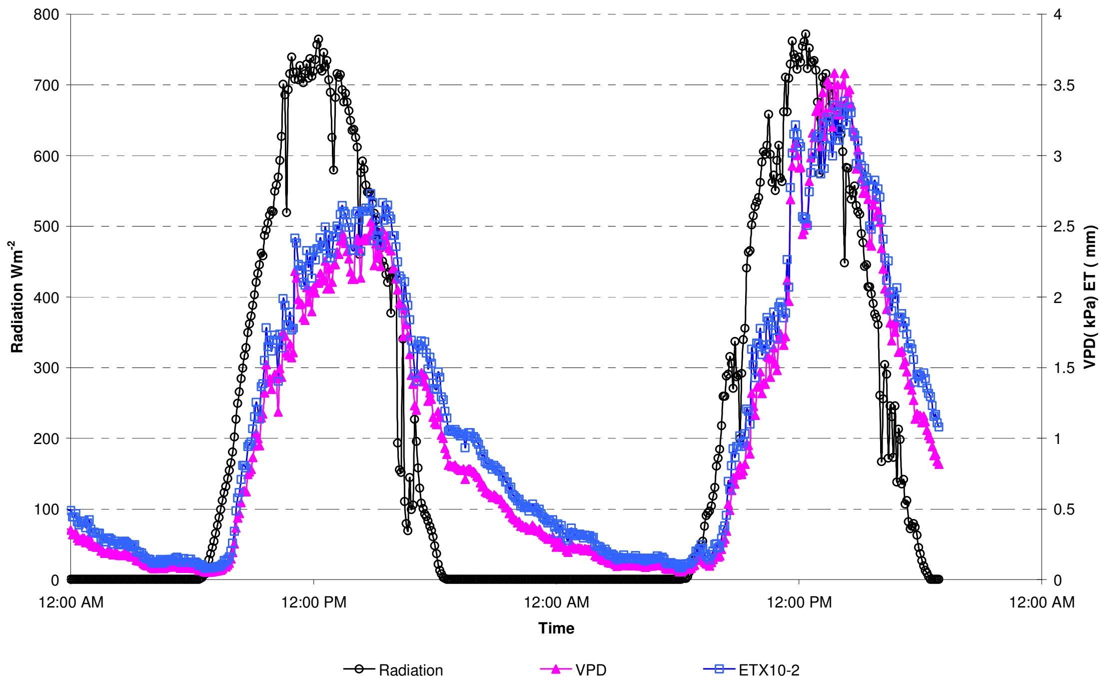


Figure 5-5: Diurnal variation of Radiation, vapour pressure deficit and evapotranspiration for two sunny days in Panda greenhouse

Evapotranspiration estimated by Stanghellini equation followed changes of solar radiation and vapour pressure deficit. Environmental measurements inside this greenhouse suggest that a time lag exists between maximum values of recorded Radiation and vapour pressure.

For a sunny day in Panda greenhouse (20 September, 2005); the maximum vapour pressure deficit value was 2.7 kPa, observed at approximately 14:50. However, the maximum solar radiation was observed at 12:15pm approximately (764 Wm^{-2}). While on 21 September, the maximum VPD was 3.4 kPa observed at 14:15. However, the maximum solar radiation (772 Wm^{-2}) was observed at 12:20 pm.

For the two day's solar radiation was clearly symmetrically related to chronological time. In contrast, vapour pressure deficit was clearly skewed towards post mid day hours and dropped sharply towards the end of the afternoon.

5.2.2. Air and Leaf Temperature

The diurnal variation of leaf temperature and air temperature at Panda greenhouse is presented in Figure 5-6. Leaf and air temperature are similar during sunrise and sunset hours, but during the rest of the day it can be observed that leaf temperatures is consistently lower than that of air. For Panda greenhouse which was fan ventilated the maximum air and leaf temperatures occurred near noon on 20 September, 2005 and were 34.9 and 33.6 ^{O}C respectively. The results can be explained by the fact that high evapotranspiration associated with high vapour pressure deficit and high radiation loads is responsible for the fact that the leaf is cooler than the surrounding air.

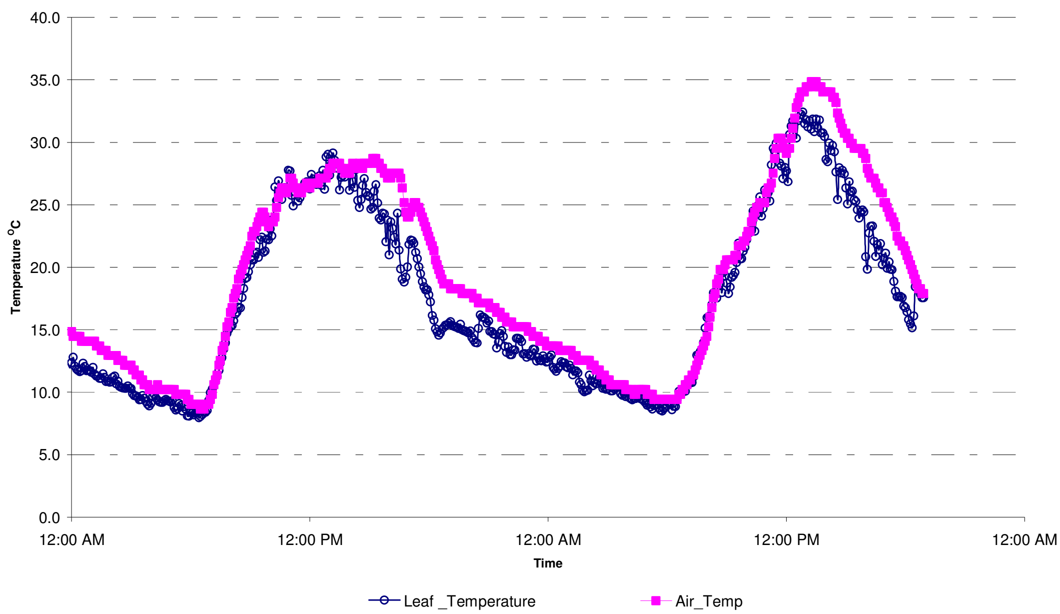


Figure 5-6: Diurnal variation of air temperature (air_Temp) and leaf temperature (leaf_Temperature) in Panda greenhouse for two clear sky days

5.2.3. Microclimate

Figure 5-7 illustrates diurnal variation of relative humidity, air temperature, solar radiation and vapour pressure deficit. At high radiation loads the vapour pressure deficit was high reaching a maximum of 3.4 kPa. The high VPD experienced had corresponding very low humidity level 26.8%. High values of VPD indicate the possibilities of water stress. Despite the prevailing conditions no apparent stress was detected on the rose crops. The observation is supported by the fact that the leaf temperature was cooler than the air temperature. However, Panda management reported low quality roses (short stems and thin stems) being produced in the greenhouse compared to a similar greenhouse in the farm. Due to lack of adequate sensors and owing to the short field work period the greenhouse with better quality roses was not investigated.

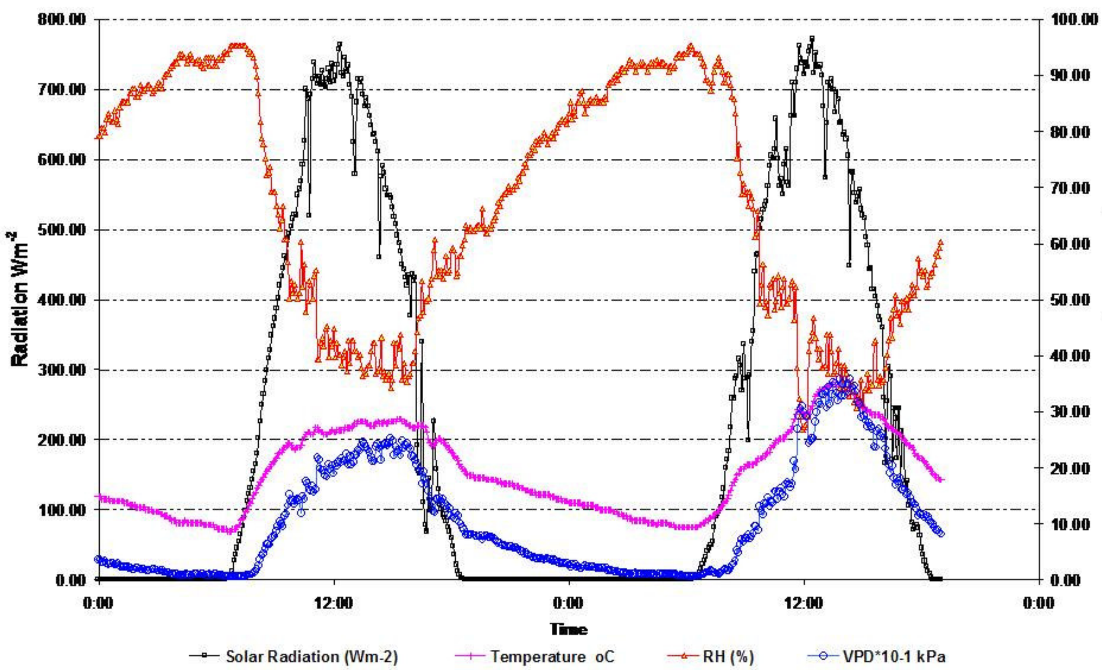


Figure 5-7: Diurnal variation of relative humidity (RH %), air Temperature (Temperature), solar radiation and vapour pressure deficit (VPD*10^{-1}) in Panda greenhouse for two clear sky days

Rose flower stems adapt to high VPD by decreasing leaf area for maintaining high sap flow rate per unit area (Liu et al., 2005). Dayan, (2000) reported that rose flowers produced in greenhouse in Israel during summer have short thin stems carrying small buds with pale petioles, but cooling the air in the greenhouse improved flower quality.

As illustrated in table 5-2 the minimum relative humidity in panda greenhouse was as low as 26.8% on 21 September.

Table 5-2: Panda Greenhouse Maximum and minimum climatic variables

Date	Max. VPD (kPa)	Max. Radiation (Wm^{-2})	Max. Air Temperature (^{O}C)	Min. RH%
9/20/2005	2.5	764.4	28.7	34.3
9/21/2005	3.6	771.9	34.9	26.8

5.2.4. Temperature Regime in Panda Greenhouse

Figure 5-8, shows ventilation requirement for Panda greenhouse for different transmissivity of global radiation. The global radiation outside the greenhouse exceeds a value of 1100 Wm^{-2} resulting in 750 Wm^{-2} indoor. A ventilation rate of about 0.06 $m^3s^{-1}m^{-2}$ is needed in order to maintain a ΔT of about 4^oC for transmission to solar radiation of 0.65. However, Willits, (2003) indicates that increasing air flow rates beyond about 0.05 $m^3m^{-2}s^{-1}$ is not beneficial when evaporative pad cooling is not used. Air temperature may actually increase under conditions of low outside humidity. Ventilation rate installed at the farm had a ventilation rate of 0.017 $m^3s^{-1}m^{-2}$. The fan can only maintain a ΔT of over 12^oC. A greenhouse cover with a transmissivity of 0.3 can reduce the difference outdoor to indoor (ΔT) to less than 2^oC for a ventilation rate of 0.06$m^3s^{-1}m^{-2}$.

Reducing the incoming radiation by either whitening the cover or shading forms an effective way of cooling a greenhouse as illustrated in figure 5-8. The problem with shading is that the material tends to have decreased transmittance to photosynthetic radiation. Partial shading in a dynamic way, covering the crop when the irradiance is above a certain threshold value and removing when irradiance has fallen can solve the mentioned problem.

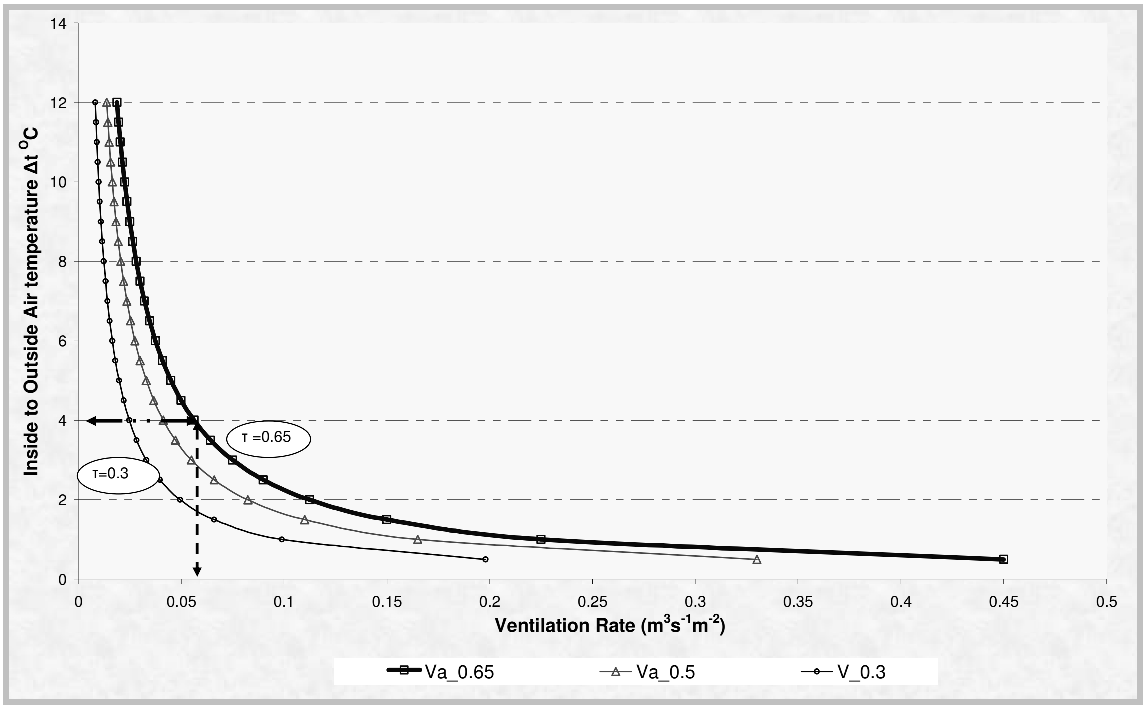


Figure 5-8: Inside-to-outside air temperature difference ΔT (°C) as a function of ventilation rate Va ($m^3s^{-1}m^{-2}$) as calculated using equation 4-5, for a greenhouse with a regularly transpiring rose crop. The thick line corresponds to a greenhouse cover transmissivity to solar radiation τ of 0.65.

The effectiveness of ventilation in reducing temperature is very dependent on the value of indoor global radiation absorbed by the canopy. Thus a much higher ventilation rate is required to cool a greenhouse containing few plants than one with full crop canopy (Day and Bailey, 1999). These explain the high quality of rose flowers (shoots with length between 30 and 60 cm) in the greenhouse reported by Panda management with similar conditions as those in the test greenhouse. The later had a young crop while the former had a mature rose with full grown canopy. The mature rose with full crop canopy reduced the temperature in the greenhouse by providing a cooling effect.

Rose crop has the capacity to recover rapidly and function normally within a short time period when the microclimate are made favourable (Baille et al., 2001). Thus, it is expected that as the leaf area increases as the crop matures the management in Panda farm will notice a substantial improvement of the quality of roses (i.e. long stems with thicker stems) in the greenhouse. A notable observation in design of Panda greenhouse is lack of side vents to allow for exchange of air from outside with that of inside. This is necessary and is supposed to be relatively large and must extend across the entire wall to allow for uniform pattern of airflow and distribution of temperature in the greenhouse.

5.3. Bigot Greenhouse (Natural ventilated)

5.3.1. Diurnal Variation of Radiation, VPD and Estimated Evapotranspiration

Figure 5-9 Illustrate diurnal variations of estimated evapotranspiration, expressed mm as affected by incident radiation and vapour pressure deficit for measurement taken on 28 -30 September, 2005.

Environmental measurements inside the greenhouse suggest that a time lag exists between maximum values of recorded Radiation and vapour pressure.
Evapotranspiration estimated by Stanghellini equation followed changes of solar radiation and vapour pressure deficit. For a sunny day in Bigot greenhouse (28 September 2005); the maximum vapour pressure deficit value was 3.56 kPa, observed at approximately 14:45at that time solar radiation was 494 Wm^{-2}. However, the maximum solar radiation was observed at 11:30pm approximately (705.6 Wm^{-2}). Table 5.3 gives a summary of the parameters and day of occurrence.

For this sunny day (28 September 2005.), solar radiation was also clearly symmetrically related to chronological time. In contrast, vapour pressure deficit was clearly skewed towards post mid day hours and dropped sharply towards the end of the afternoon. 29 September, 2005 was a cloudy /rainy and it can be seen that vapour pressure dropped sharply at around mid-day. Due to this behavior in the greenhouse conditions, it is evident that the nutrient solution should be applied at different time intervals according to crop evapotranspiration.

On the night of 29 September 2005 a peak can be seen at midnight i.e. rise and fall of all three parameters temperature, vapour pressure deficit and ET. On a cloudy night the clouds absorb almost all of the terrestrial radiation emitted by the earth. They reradiate much of it back to the surface, so that the net loss of energy is small. Consequently, the overnight temperature fall is also small. Cloudy nights tend to be warm nights. During the day clouds do not act like greenhouse gases. They still absorb the terrestrial radiation, but they also strongly interfere - in this case reflect - the solar radiation.

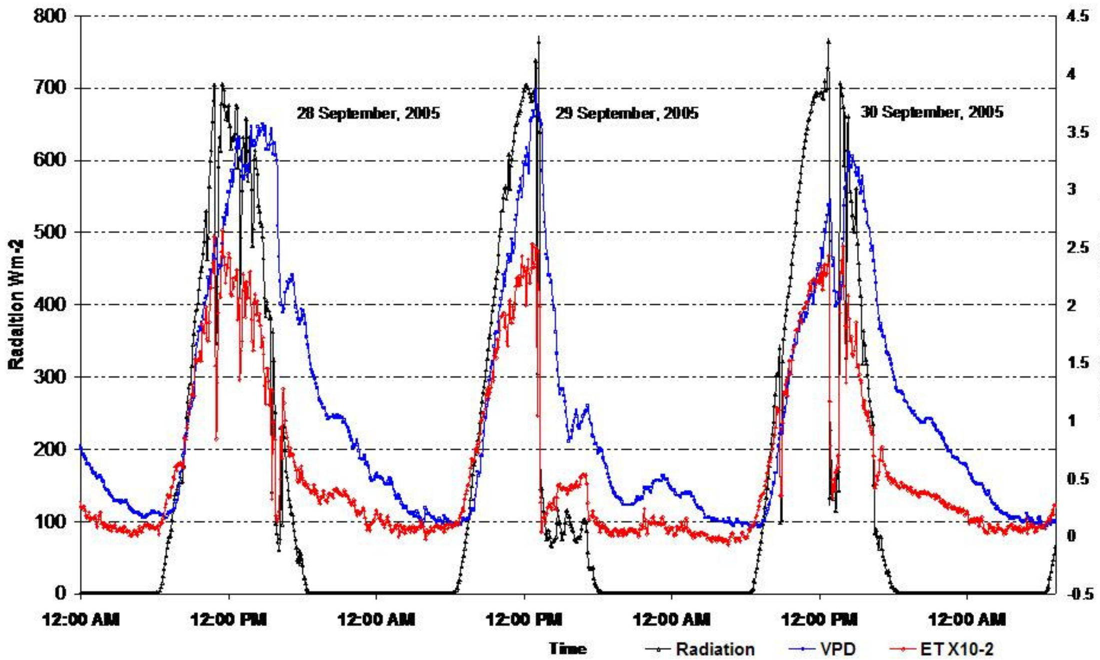


Figure 5-9: Diurnal variation of Radiation, vapour pressure deficit and evapotranspiration for two sunny days and a cloudy day (Bigot natural ventilated greenhouse)

Table 5-3: Bigot Greenhouse Maximum and minimum climatic variables

Date	Max. VPD (kPa)	Max. Radiation (Wm^{-2})	Max.Air Temperature(^oC)	Min. RH%
9/28/2005	3.5	705.6	32.3	21.3
9/29/2005	3.8	764.40	33.6	25.8
9/30/2005	3.3	764.40	31.1	25.8

5.3.2. Leaf and Air Temperature

The diurnal variation of leaf temperature and air temperature Bigot greenhouse is presented in Figure 5-10. Leaf and air temperature are similar during sunrise and sunset hours, but during the rest of the day it can be observed that leaf temperatures is consistently lower than that of air. For Bigot greenhouse which was natural ventilated the maximum air and leaf temperature occurred near noon on 29 September 2005, and was 33.6 and 32.6 ^OC respectively. The results can be explained by the fact that high evapotranspiration associated with high vapour pressure deficit and high radiation loads is responsible for the fact that the leaf is cooler than the surrounding air.

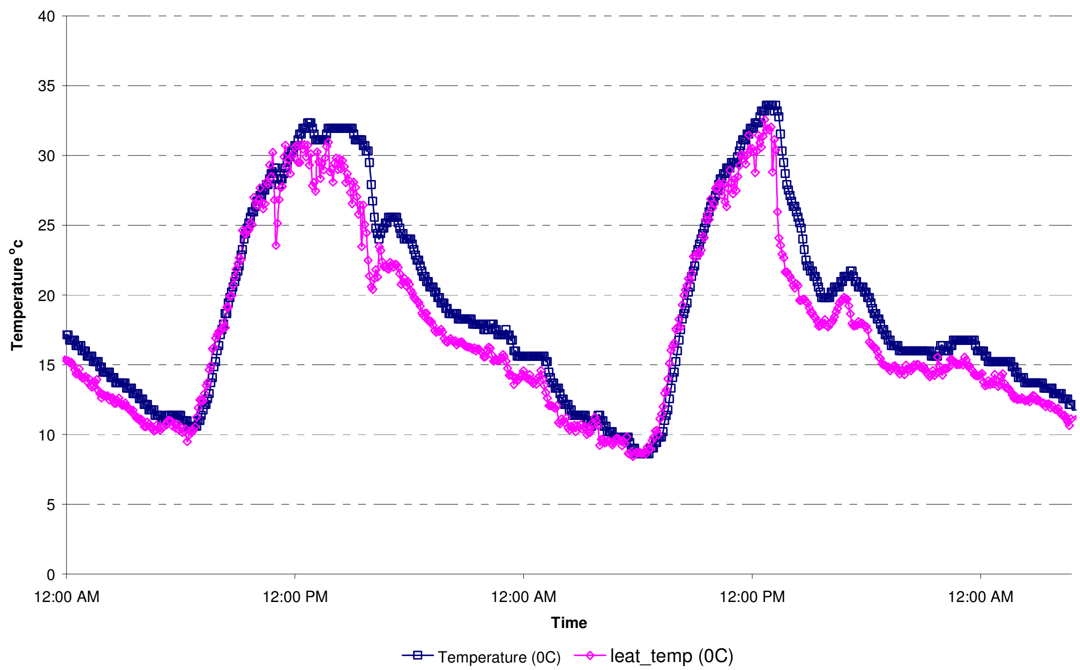


Figure 5-10: Diurnal variation of air temperature and leaf temperature on a sunny day and cloudy day in Bigot greenhouse on 28 and 29 September 2005

5.3.3. Microclimate

Figure 5-11 illustrates diurnal variation of relative humidity, air temperature, solar radiation and vapour pressure deficit. At high radiation loads the vapour pressure deficit was high reaching a maximum of 3.8 kPa on 29 September. The high VPD experienced had corresponding very low humidity level 21.8% %. Despite the prevailing conditions no apparent stress was detected on the young rose crops. The observation is supported by the fact that the leaf temperature was cooler than the air temperature. Bigot greenhouse had young roses that had not been harvested hence the quality of the flowers could not be assessed. The results corroborate other authors who have reported similar findings e.g. (Bailey et al., 1993; Monterro et al., 2001) for different greenhouse crops.

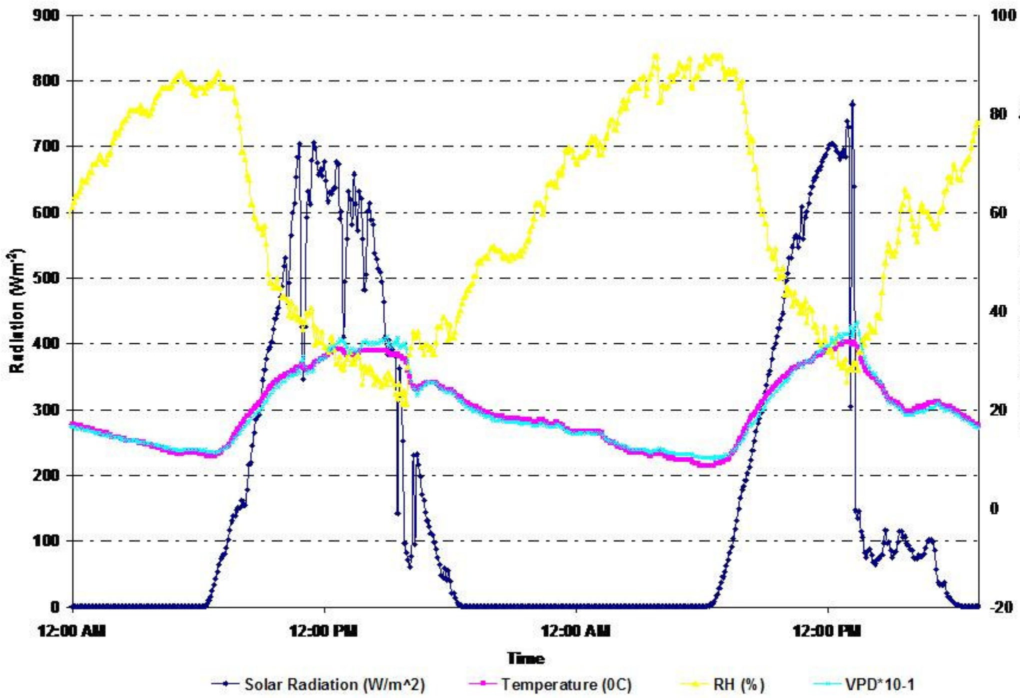


Figure 5-11: Diurnal variation of relative humidity (RH %), air Temperature (Temperature), solar radiation and vapour pressure deficit (VPD*10^{-1}) in Bigot greenhouse for two clear sky days on 28 and 29 September 2005

Application of water and nutrients starts at 6:00 am (see appendix: 4). However, between 6:00 am and 7:30 am the relative humidity in the greenhouse remains at 100% i.e. the air temperature and due point temperature are similar. Water and nutrients would go to waste when applied during this period. The way forward is to start application of water and nutrients 90 minutes after sunrise.

5.4. Comparison of the Panda and Bigot Greenhouses

The fact that evapotranspiration estimated by Stanghellini equation follows changes of solar radiation and vapour pressure deficit in the two greenhouses indicate that these are the two environmental factors that mainly determines evapotranspiration in a greenhouse apart from the stage of crop i.e (LAI). Baille, (2004) noted that the hypothesis that evapotranspiration of greenhouse crops is mainly driven by radiative component suggested by several authors and validated for closed or poorly ventilated greenhouses should be revised. He recommended using preferably the dual α and β coefficients that allow expressing the Penman-Monteith equation in a simplified form as given below:

$$ET = \alpha.R_i + \beta.VPD \qquad \textbf{(5-1)}$$

Where α and β are the “radiative” components and “advective” component respectively.
From the above equation it is seen than when high vapour pressure deficit occurs at night evapotranspiration will also take place. Although this might seem minimal there is need to have an irrigation gift (at least once) for hydroponics to avoid plants having water stress especially on cloudy days.

Compared to Bigot greenhouse, Panda greenhouse had slightly lower VPD. For instance on 20 September the air VPD was 2.5 kPa in Panda, while in Bigot the air VPD was 3.8 kPa on 29 September, with corresponding maximum Radiation being 764.4 Wm^{-2} in both greenhouses. (Table 5-2 and 5-3). The results can be explained by the fact that Panda greenhouse had a slightly mature rose crop hence, high leaf area index compared to Bigot greenhouse. High leaf area index has beneficial effect on the greenhouse microclimate in the Mediterranean and arid areas, (Katsoulas et al., 2002). The high level of transpiration by the canopy enhanced cooling process in Panda greenhouse thereby raising slightly the relative humidity (lower VPD) compared to Bigot greenhouse. In addition Panda greenhouse was fan ventilated. Low level of humidity (less than 50%) encourages red spider mite infestation; cases of the pest were reported in the greenhouse. Since in both greenhouses the leaf temperature stayed lower than the air temperature, the evapotranspiration can be presumed to be at maximum rate throughout the experiment.

An important problem to be solved in the Naivasha greenhouses for a more profitable production is an efficient climate control. It is necessary to get a better control of temperature and humidity, in order to avoid a too high climatic demand during high radiation loads and its negative consequences on the crop water status, even when adequate soil or substrate moisture is ensured by adequate irrigation management.

5.5. Simplified Model

For a greenhouse with a climate control system where the relative humidity ranges between 65% and 85% while temperature ranges between 18^{o}C and 25^{o}C, typical of greenhouses in Naivasha with an average transmissivity of the cladding material 65% of the outside global radiation.

The values of constants α and β are shown in table 5-4 with corresponding average values for microclimate on 4 September, 2005.
For hourly evapotranspiration β is divided by 24 hours.

Table 5-4: Simplified Model Parameters and microclimate data during a test day

Date	Radiation (MJm^{-2}day-1)	Average Temperature (^{O}C)	RH (%)	VPD(kPa)	α	β (mm day^{-1} kPa^{-1})
4 September 2005	24	21	65	0.89	0.29	0.48

Figure 5-9 shows simulated daily ET for a rose crop with LAI of 2.0 m^2 m^{-2}. The results indicate that the simplified model was able to estimate the ET to acceptable values. Several authors identified the values of α and β under different greenhouse conditions and for different species e.g. (Jolliet, 1999; Jolliet and Bailey, 1992; Katsoulas et al., 1999).

Jolliet, (1999) estimated the coefficient α and β for greenhouse young tomato leaves and gave the following values for α of 0.12 (dimensionless) and for β of 0.435 Wm^{-2} K^{-1}. While, Baille, (1994) found that values α ranged from 0.12 to 0.67 and β ranged from 14×10^{-3} to 37×10^{-3} kg m^{-2} h^{-1} kPa-1 for different potted ornamental crops.

The non-perfect goodness of fit between simulated ET by the simple model and measured ET can be attributed to several reasons.

- The water delivery pipes installed at Oserian greenhouses experiences frequent bursts. For instance, on 3, 14th, 22nd and 27 September the bursts did occur and this has drastic effect as can be seen from the curves.
- the model assumed constant leave area index, however, variability is expected to occur among different rose plants
- The fact that roses, unlike most other crops are being constantly harvested and thereby exhibiting large fluctuation of transpiring area was not considered while calculating the ET.

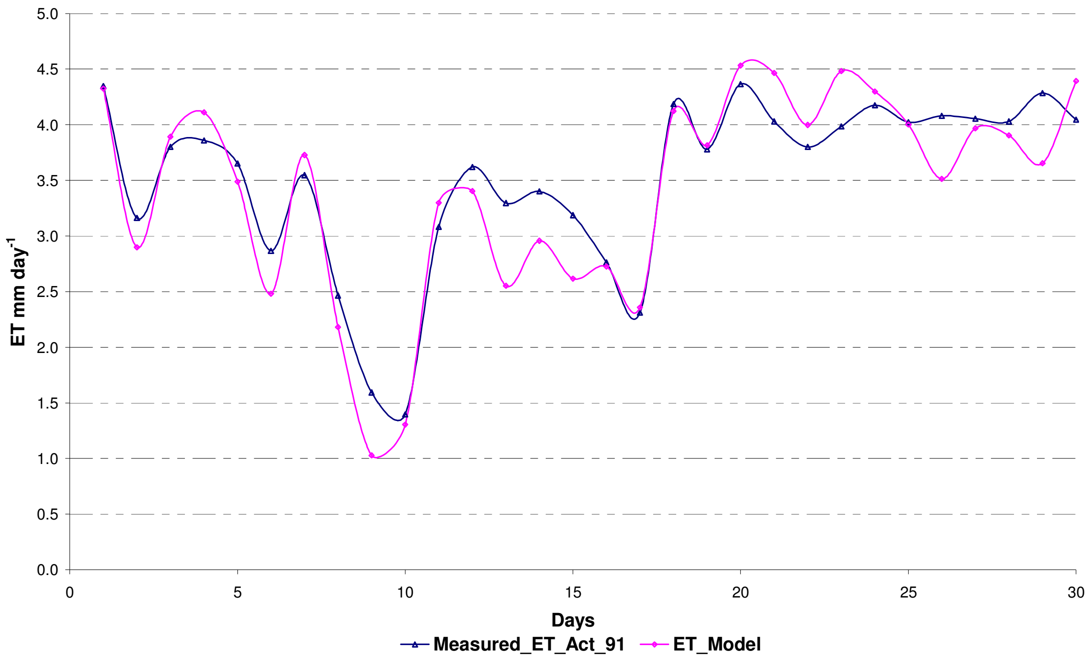


Figure 5-12: comparison of measured actual evapotranspiration and potential evapotranspiration using simplified model [equation, (4-20)]

5.5.1. Radiative and Advective Terms

Figure 5-13 shows the contribution of radiative and advective terms to overall ET. Solar radiation is the main factor affecting ET. To a lesser extent, ET is controlled by vapour pressure deficit. The Oserian greenhouse had a computerized system where the microclimate is controlled. This explains the fairly constant curve obtained for advective term.

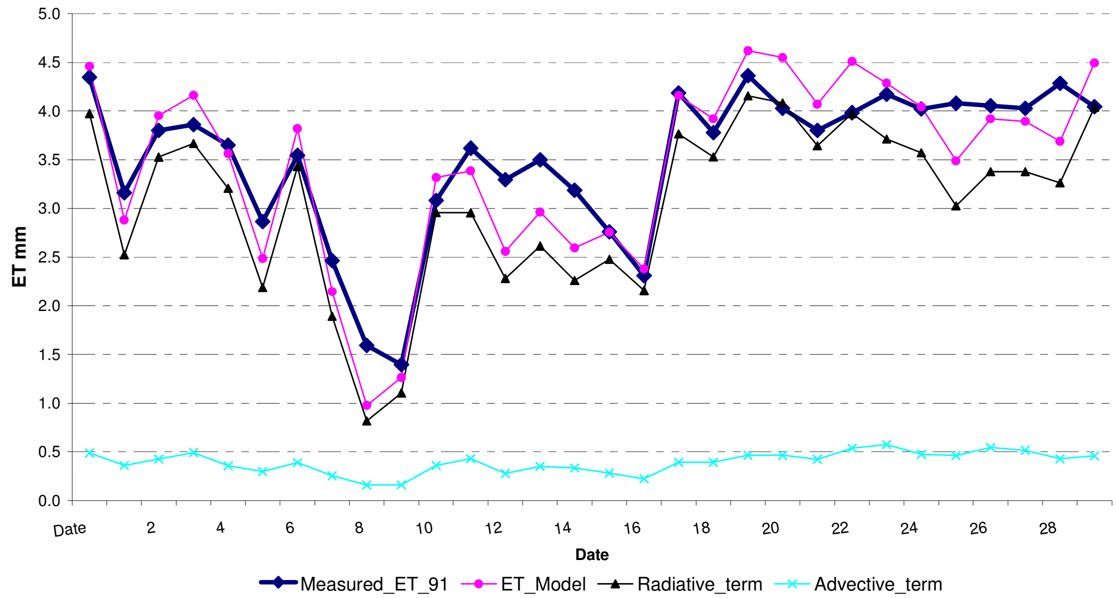


Figure 5-13: Measured ET (mm), simulated ET (mm) by simple model, Radiative and advective contributions to overall ET For the month of September 2005 at Oserian farm

5.5.2. Sensitivity Analysis

Figure 5-14: Shows the sensitivity analysis of LAI on ET potential estimated by the simple model. The graph shows that LAI is sensitive to ET potential calculation. This implies a limitation on the model as LAI has to be estimated with high accuracy.

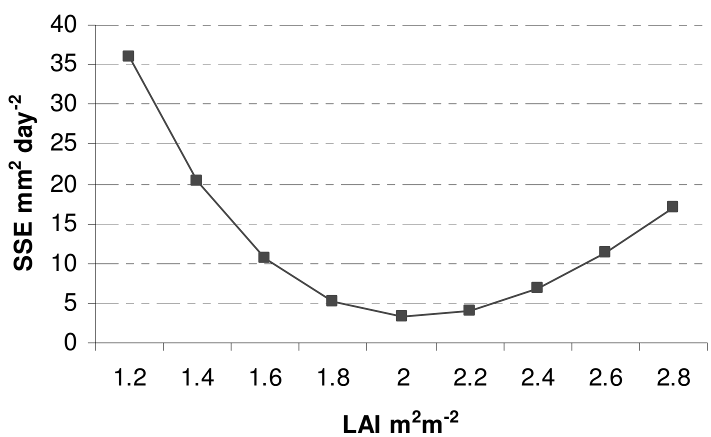


Figure 5-14: Sensitivity analysis of leaf area index based on 30 test days.

5.6. Comparison of ET Obtained by Different Models

Table 5-5 shows ET obtained by the three models used in the study. Although Stanghellini's equation was based on an empirical evaluation of radiation flux (in a greenhouse system notably different from that used in this study), the results reflect a better representation of radiation absorption in a greenhouse canopy due multiple layers of dispersion and reflection. The equation give satisfactory results (r^2=0.73) for a young rose crop. See appendix 4c for statistics results.

The simple model was tested using 10 minutes interval data obtained in Bigot greenhouse. The results obtained were remarkably good (r^2=0.75). See statistics results appendix 4b.

At present, the irrigation of greenhouse roses is mainly controlled on the basis of solar radiation due to unavailability of sensing devices and cost consideration. The simplified model equation 5-2 can be used as a rational basis for scheduling plant irrigation. From a practical point of view such a model could be easily implemented in algorithms for rose irrigation control as radiation and VPD are two variables currently being monitored in greenhouses. The problem is determination of leaf area index (LAI). Correlation between LAI and radiation intercepted by canopy would be the most convenient way to estimate LAI (Jolliet, 1999)**.**

Table 5-5: Measured ET and calculated using simplified model and Staghellini model for Bigot greenhouse.

Date	ET_Measured (mm)	ET_Model (mm)	ET_Stangellini (mm)
26	2.36	2.26	2.10
27	2.35	2.18	2.08
28	2.25	2.24	2.11
29	1.95	1.82	1.95
30	2.49	2.20	2.09

5.7. Estimated Irrigated Area

Ahammad, (2001) reported the area under irrigation as 5031 ha. The outdoor irrigation was 4,417 ha and under greenhouse 614 ha. Alfarra, (2004) reported total irrigated area of 4,292ha, outdoor and greenhouse 3101ha being 1,191 ha respectively. Table 5-6 shows the estimated irrigated area in different studies and the present study. The low value of irrigated area under greenhouse by Ahammad, (2001) does not include all greenhouses in the catchment, but rather the area in the vicinity of the lake.

Figure 5-15 shows the distribution of irrigated agriculture as of 1 November, 2005. In this study the area under greenhouse is found to be approximately 1,600 ha, while, the area under outdoor cultivation is approximately 3,800 ha. There seems to be an increase in greenhouse cultivation, while outdoor cultivation has dropped significantly. The results can be explained by the fact that the area under greenhouse is replacing outdoor cultivation i.e. farmers seems to be attracted to indoor cultivation. There are a number of reasons for the observed shift outdoor to greenhouses;

- Incidence of most fungal diseases is reduced.
- Incidence of bacterial diseases is reduced.
- Insect vectored viruses are not a problem in screened greenhouses hence use of pesticides is minimized.
- Increased efficiency of water use.
- Rainfall damage to crops is reduced
- Due to increasing concerns about groundwater pollution by agricultural chemicals, hydroponics with complete recycling of nutrient is currently a good alternative to open field irrigation systems.

Table 5-6: Estimated irrigated area by different studies (all figures in ha)

	WRAP 1996-97	Salah 1999	Ahammad 2001	Alfarra 2004 2004	Present study, 2006
Outdoor	3581	3548	4417	3101	3800
Greenhouse	-	1020	614	1191	1600
Total	3581	4568	5031	4292	5400

Table 5-7 shows total water use by different land use in Naivasha basin. The mean actual evapotranspiration for thirty test days in this study is found to be 3.5 mm day^{-1} while the actual evapotranspiration for outdoor estimated using remote sensing was 5.4 mm day^{-1} (Mekonnen, 1999).

Flowers are irrigated for 365 days while vegetables and grass/fodder are irrigated for 330 days. This explains the lower value of actual evapotranspiration for the vegetables and grass/fodder crops. Shifting from outdoor to greenhouse does not necessarily mean saving in terms of water consumption. Shifting from outdoor vegetable production to flower production would mean more water consumption as illustrated in table 5-7.

For this study the total water consumption by irrigated agriculture is found to be 65.8 M. m^3 year^{-1}. The value corroborates other studies, Becht and Harper, (2002) reported the estimated abstraction from the Lake to be over 60 Million m^3 year^{-1}.

Table 5-7: Water consumption in Naivasha basin (million cubic metres per year)

Crops	mm day^{-1}	mm $year^{-1} ha^{-1}$	$m^3 ha^{-1} year^{-1} ha^{-1}$	Irrigated area. ha	Total water consumed $M.m^3 year^{-1}$
Greenhouse Flowers	3.5	1277.5	12775	1600	20.44
Outdoor Flowers	5.4	1981	19810	1135	22.37
Grass/fodder	0.86	306	3060	286	0.86
Vegetables	2.65	966	9660	2290	22.15

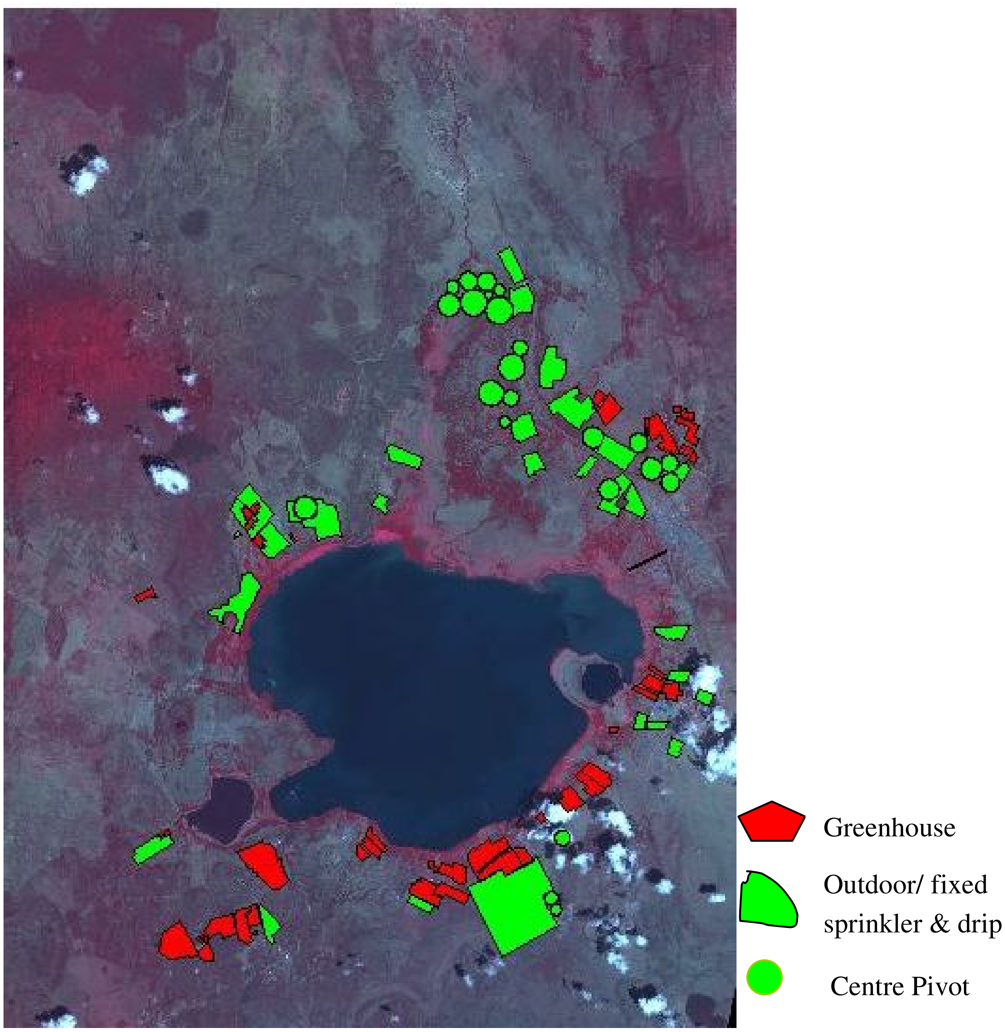


Figure 5-15: Irrigated agriculture around Lake Naivasha.

5.7.1. Lake Naivasha Water Balance

Using the parameters regarding water balance (Gitonga, 1999) of Lake Naivasha shown in Appendix 5 the following balance has been achieved see table 5-8:

Table 5-8: Long term water balance of lake Naivasha

Water Balance		Average Year
Inputs		M.m^3 year^{-1}
Rainfall		70.87
River flows		
	Malewa	
	Gilgil	
	Karati	
	Total	223
GW inflow		0.068
Total inputs		**293.9**
Outputs		
Evaporation		271.2
GW Outflow		55.2
Abstraction		65.83
Total Outputs		**392.23**
Change in storage		-98
Drop in level		**-0.68**

For this study, out of the total outputs irrigation abstraction contributes 16.8%. Ahammad, (2001) reported a contribution of abstraction to the total output of 18%. Data on lake levels was not available during the field work hence reduction in abstraction could not be verified.

6. Conclusions and Recommendations

In the present work, the actual ET for greenhouse roses was found to be 65% of actual ET outdoor estimated by remote sensing.

The solar radiation and vapour pressure deficit was shown to follow the same trend as evapotranspiration. This implies that the driving forces for evapotranspiration are the solar radiation and vapour pressure deficit. This suggests that an empirical model for predicting evapotranspiration in greenhouse conditions should include solar radiation and the vapour pressure deficit.

A simplified model for predicting potential evapotranspiration for a controlled greenhouse microclimate for roses under study give satisfactory results (r^2=0.87). The model linking potential ET, radiation in the greenhouse ($R_{i,g}$), vapour pressure deficit (VPD) and leaf area index (LAI) is proposed, based on Pen-man Monteith equation $ET=\alpha f_1(LAI)R_i+\beta f_2(LAI)$ The coefficient α and β were found to be 0.29 (dimensionless) and 0.48 (mm day^{-1} kPa^{-1}). From a practical point of view such a model could be easily implemented in algorithms for rose irrigation control as radiation and vapour pressure deficit are two variables currently being monitored in greenhouses.

It has been shown that a time lag exist between recorded maximum solar radiation and vapour pressure deficit. Due to this behavior in the greenhouse conditions, it is evident that the nutrient solution should be applied at different time intervals according to crop evapotranspiration. While, for practical purposes application of nutrients in hydroponics should be delayed by 90 minutes after sunrise.

The limitation of the simplified model involves estimation of LAI. There is need to study the relationship between LAI and radiation absorbed by the canopy. Such a relationship would eliminate the need to estimate LAI directly.

In addition the Penman Monteith equation modified by Stanghellini for conditions in greenhouse gave remarkably good results (r^2=0.73) for a young rose crop.

Water permitted for abstraction 2.25 mm day^{-1} by the Ministry of Water and Irrigation was found to be lower than actual evapotranspiration both in the greenhouse and outdoor. The highest actual ET was 4.4 mm day^{-1} on a clear sunny day in Oserian greenhouse while the average actual ET for September 2005 was 3.5 mm day^{-1}. There is need to review the irrigation water abstraction policy. Mapping of regions practicing irrigation and assigning water requirements for major crops would go along way in assisting water apportioning boards in the Ministry of Water and Irrigation.

The microclimate in a natural and a fan ventilated greenhouse was studied. The short, thin stems rose flowers observed in Panda greenhouse is attributed to high vapour pressure deficit>3.0 kPa and air temperature greater than 30^{o}C. The very low LAI (about one) in Panda and Bigot greenhouses limits evapotranspiration rate and does not allow sufficient cooling and humidification of the greenhouses. There is need to incorporate evaporative cooling (evaporative pads, misting and fogging) for roses in the greenhouses both for natural and fan ventilated greenhouse in the study area. Forced ventilation alone is inadequate as the microclimate (vapour pressure deficit, relative humidity, and temperature) in Panda greenhouse did not significantly change despite application of forced ventilation.

Natural ventilation in Bigot greenhouse did not meet set points (65%< RH<85%, 18^{o}C<temperature<25^{o}C) for roses grown in greenhouses. Probably the combination of both natural and forced ventilation would enhance cooling effect. There is need for an irrigation application to hydroponics roses during the cloudy nights as vapour pressure deficit increases in such days hence increasing ET. Use of substrate moisture sensors can be handy as it would trigger irrigation water application.

Bending of blind and weak shoots should be encouraged as increase in LAI enhances cooling effect. Panda and Bigot greenhouse did not have microclimate sensors, there is need to incorporate the sensors. Automatic sensors can trigger closure/opening of whenever the microclimate reaches set points. The same is true for fan ventilated greenhouse.

Due to increasing concerns about groundwater pollution by agricultural chemicals, hydroponics with complete recycling of nutrient will ultimately become a survival condition for greenhouse industry in the study area.

The net radiation outdoor compared with net radiation in greenhouse need to be studied with respect to influence to actual ET.

Finally, the area under greenhouse has increased from 1191 ha in 2001 to 1600 ha, while outdoor cultivation has decreased from 4,417ha to 3,800ha in the study area.

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Appendices

Appendix 1: Solar Radiation; clear sky comparison

The following equations for calculating extraterrestrial radiation are taken from Richard Allen (1996). All triangulation functions and angles are expressed in radians with the exception of L_z and L_m . ω_s

For 24-hour periods

$$R_a = \frac{G_{SC}}{\pi} d_r \left(\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s\right)$$

Where Ra=daily average extraterrestrial radiation (W m^{-2}); G_{sc}= solar constant (1367 W m^{-2}); d_r= relative distance factor from earth to sun; δ=solar declination (rad); φ=latitude (rad) ($\varphi$is negative for southern hemisphere); and ω_s=sunset hour angle (rad).

ω_s =arcos (-tanφtanδ)

Or as

$$\omega_s = \frac{\pi}{2} - \arctan\left[\frac{(-\tan\varphi\tan\delta)}{(1-\tan^2\varphi\tan^2\delta)^{0.5}}\right]$$

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}J\right)$$

$$\delta = 0.409 Sin\left(\frac{2\pi}{365}J - 1.39\right)$$

Where J = number of day in year. For daily values, j can be determined by

$$J = \text{int}\, eger\left(275\frac{M}{9} - 30 + D\right) - 2$$

Provided that the following corrections are made: if M<3, Then J=J+2, and during leap years when M.2, then additionally J=J+1, where M= Month (1-12); and D= day in month (Graig 1984).

For hourly or shorter periods

$$R_{ah} = \frac{12}{\Delta t\pi} G_{sc} d_r \left[(\omega_2 - \omega 1)\sin\varphi\sin\delta + \cos\varphi\cos\delta(\sin\omega_2 - \sin\omega_1)\right]$$

Where R_{ah} =extraterrestrial radiation during period (Wm-2);

ω_1 =solar time angle at beginning of period (rad); and ω_2 = solar time angle at the end of period (rad).

$$\omega_1 = \omega - \frac{\pi \Delta t}{24}$$

$$\omega_2 = \omega_2 + \frac{\pi \Delta t}{24}$$

Where ω =solar time angle at mid point of period (rad); and Δt =length of calculation period (h)

For example, $\Delta t = 0.5$h for 30-min period.

$$\omega = \frac{\pi}{12}\{[t + 0.06667(L_z - L_m) + S_c] - 12\}$$

Where t =standard clock time at mid point of period (h) for example, (for a period between 1400 and 1500 h, t= 14.5); L_Z = Longitude of center of local time zone (in degrees west of Greenwich, England); L_m = longitude of measurement site (in degrees west of Greenwich, England) and Sc= seasonal correction for solar time (h). Note that L_z and L_m are in degrees rather than radians.

$$S_C = 0.1645 \sin 2b) - 0.1225 \cos(b) - 0.025 \sin(b)$$

$$b = \frac{2\pi(J - 81)}{364}$$

R_{so}= K_t R_a

Where

Rso is the computed short wave radiation expected under clear sky conditions. Kt = clearness index. A simple prediction for Kt where only site elevation is considered was developed by allen et al. (1994).

Kt = 0.75+ ($2*10^{-5}$) z

Where z=station station (m)

Appendix 2: Oserian greenhouse data

Date	Applied water (m^3)	Drainage (m^3)	Actual ET (m^3)	Actual ET (mm)	Average Temperature (^0C)	RH	Radiation_Day Jcm^{-2}
1	72.31	26.4	45.91	4.35	19.9	64	2649
2	72.28	38.9	33.38	3.16	19.4	73	1696
3	72.26	56.6	15.66	1.48	20.6	69	2324
4	81.35	40.6	40.75	3.86	21.7	65	2373
5	72.25	33.7	38.55	3.65	20.5	74	2116
6	72.26	42	30.26	2.87	19.9	78	1459
7	54.24	16.8	37.44	3.55	21.2	72	2237
8	63.23	37.2	26.03	2.46	17.5	80	1317
9	62.23	46.4	15.83	1.50	16	87	587
10	63.25	48.5	14.75	1.40	16.3	87	787
11	72.24	39.7	32.54	3.08	19.4	73	1989
12	72.32	34.1	38.22	3.62	19.7	68	1977
13	72.31	37.5	34.81	3.30	18.9	79	1548
14	72.28	39.6	32.68	3.09	19.5	74	1745
15	72.25	38.6	33.65	3.19	19.5	75	1518
16	72.26	43.1	29.16	2.76	19.4	79	1665
17	72.3	47.9	24.4	2.31	18.5	83	1474
18	72.2	28	44.2	4.19	21.4	70	2574
19	72.29	32.4	39.89	3.78	20.3	72	2295
20	72.29	26.2	46.09	4.36	20.4	66	2752
21	72.25	29.7	42.55	4.03	20.5	66	2700
22	72.24	20.7	51.54	4.88	20.6	69	2405
23	72.27	30.2	42.07	3.98	21.3	61	2618
24	72.27	28.2	44.07	4.17	21.2	59	2418
25	72.28	29.8	42.48	4.02	20.2	66	2330
26	72.28	29.2	43.08	4.08	20.2	66	2007
27	81.34	30.9	50.44	4.78	21.2	60	2240
28	81.35	38.8	42.55	4.03	21.2	63	2204
29	81.35	36.1	45.25	4.29	20.8	69	2142
30	81.32	38.6	44.72	4.00	21	67	2642

Source: Oserian Farm

Appendix 3: Drainage percentage in Bigot greenhouse.

Date September 2005	Applied Water m^3	Drainage m^3	Drainage (%)	Water Consumption (mm)
26th	107.5	70.72	66	2.36
27th	107.2	70.57	66	2.35
28th	109.3	74.18	68	2.25
29th	96.2	65.82	68	1.95
30th	117.5	78.94	67	2.49

Appendix 4: summery of regression analysis for comparison of (a) Simple model Oserian greenhouse (b) simple model Bigot greenhouse (c) Stanghellini equation and measured data Bigot greenhouse

a) ET simple model and measured ET (Oserian)

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.93
R Square	0.87
Adjusted R Square	0.87
Standard Error	0.28
Observations	30.

(b) ET simple model and measured ET (Bigot)

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.86
R Square	0.75
Adjusted R Square	0.66
Standard Error	0.12
Observations	5

(c)ET Stanghellini and measured ET (Bigot)

SUMMARY OUTPUT	
Regression Statistics	
Multiple R	0.85
R Square	0.73
Adjusted R Square	0.64
Standard Error	0.12
Observations	5

Appendix 5: Water application guidelines provided by the drip installation expert at Bigot greenhouse

Time	Water Application (m^3)	Water Application (mm)
6:00	7	0.59
6:00	7	0.59
7:00	7	0.59
8:00	7	0.59
9:00	7	0.59
10:00	7	0.59
10:40	7	0.59
11:20	7	0.59
12:00	7	0.59
12:40	7	0.59
1:20	7	0.59
2:00	7	0.59
2:40	7	0.59
3:20	7	0.59
4:20	7	0.59
5:20	7	0.59
6:20	7	0.59
Total	**112**	**9.36**

Appendix 6: Long-term (1932 to 1997 water balance of [Gitonga, 1999])

Month	Disch. (m.m^3)	Rain (m.m^3)	GW in (m.m^3)	GW out (m.m^3)	Evap. (m.m^3)	Storage (m.m^3)	Level (m)
January	11	4.87	0.0948	4.6	25.4	-14.0	-0.097
February	8.03	5.32	0.272	4.6	24.2	-15.0	-0.103
March	9.19	8.12	0.323	4.6	26.5	-14.0	-0.097
April	21.9	1.69	0.300	4.6	20.8	14.0	0.097
May	34.7	1.16	-0.116	4.6	22.2	19.0	0.131
June	20.1	6.81	-0.339	4.6	20.2	1.80	0.012
July	19.8	5.73	-0.139	4.6	20.3	0.42	0.003
August	24.1	6.79	-0.067	4.6	22.0	4.20	0.029
September	22.1	7.15	-0.125	4.6	23.2	1.60	0.011
October	19.3	7.89	-0.0846	4.6	24.5	-1.90	-0.013
November	19.8	9.22	0.0138	4.6	19.6	4.90	0.034
December	13	6.12	-0.0649	4.6	22.3	-7.90	-0.054
Total	223	70.87	0.068	55.2	271.2	-6.88	-0.047

Appendix 7: (a) leaf temperature monitored by Infra Red thermometer

Time	upper leaf Temperature °C	Middle leaf Temperature °C	Lower leaf temperature (shaded) °C	
12:42	37.5	33	29	
12:43	35	32	29	
12:44	33	30	30	
	35	32	29	
	33	31	30	
Shading The Leaf With an Umbrella				
12:53	26.3	23.8	23.5	

At 13:03 the leaf was sprayed on both sides. The temperature increased from 36°C reaching a maximum of 39.5°C, while the surrounding leaves remained at a temperature between 32-33°C.

Appendix 8: Potometer readings on 22 September 2005

Time	Outdoor (ml)	Greenhouse (mm)
6:46 PM	0.05	0.8
7:00	0.4	1.2
7:30	0	0.7
8:00	0.1	0.5
8:30	0.2	0.2
9:00	0.1	0.2
9:30	0.2	0.2
10:00	0.1	0
10:30	0.2	0.2
11:00	0.1	0.2
11:30	0	0
12:00	0	4.6***
0:30	0.1	0.2
1:00	0	0
1:30	0.1	1.1
2:30 AM	0.1	0.1
3:00	0.1	0.1
3:30	0.1	0.1
4:00	0.1	0.1
4:30	0	0.1