INFLUENCE OF DRIP IRRIGATION AND GROUND WATER ON SOIL WATER BALANCE OF A FLUVISOL, IN KAPSENGERE, KENYA

By

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1992

DEDICATION

This Thesis is dedicated to my parents;

Gikonyo and *Njeri*

for their remarkable insight to send me to school.

DECLARATION

I hereby declare that this thesis is my original work and has not been presented for a degree in any other University. All sources of information have been acknowledged.

Gikonyo .... 31ST AUGUST, 1992.

J. Karanja Gikonyo Date

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

Biamah .... 31ST AUGUST, 1992.

E. K. Biamah Date

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ABSTRACT

Effect of drip discharge rate, spacing, duration of water application and antecedent soil moisture content was studied in a sandy loam soil. Four drip discharge rates of 2, 3, 4, and 8 l/hr were used with a maximum duration of water application of 8 hours at three levels of initial soil moisture content as indicated by soil matric suctions of 0.2, 0.3, and 0.5 bars determined at 60 cm soil depth. Soil matric potential in the soil profile wetted by drip water application was monitored at three locations for each test by means of bourdon type or jet tensiometers installed at different depths upto 150 cm (at 30 cm interval) below the soil surface.

The final soil wetting pattern for each test was determined by cutting the soil profile across the point of water application exposing the wetted soil and directly measuring the wetted diameter at 5 cm interval down the soil profile and at 1 to 2 hours time interval.

The influence of a fluctuating shallow ground water table on soil water flow in the soil above the water table level due to upward soil water flux (capillary rise) was studied by measuring soil matric suctions using tensiometers installed at depths of 30, 60, 90, 120 and 150 cm below the soil surface at three different locations.

Ground water table depth fluctuations were monitored at each of these locations by sinking observation wells next to the tensiometer positions. Over the experimental period of about seven months, the ground water table depth varied from about 40 cm to 200 cm.

The wetted soil volume increased with drip discharge rate, duration of water application and higher antecedent soil moisture content. As the initial soil moisture decreases, the wetted soil volume for a particular drip discharge rate and duration of water application decreases. This is due to the fact that as the soil dries, more pore spaces are emptied hence becoming available for water storage.

The capillary forces are relatively weak in sandy loam soils and gravity has relatively more influence on the resulting wetting pattern most significantly beyond six hours of continuous drip water application for 4 and 8 l/hr; and 8 hours for the 2 and 3 l/hr discharge rates.

The extent of the vertical component of the soil water flow for these discharge rates is greater while the horizontal one is smaller; which enhances the elongation of the wetting pattern. On allowing water to redistribute upon water application, the final wetted soil volume was at 30-180 cm (i.e. 0.03-0.180 bars) soil matric suction.

Results obtained showed that when the ground water level was at 100-150 cm below the soil surface, the unsaturated soil above it had an average soil matric suction below 1.0 bar. Hence upward soil water flux adequately supplied soil moisture to meet the crop water requirements of the citrus crop whose rooting pattern explored the soil profile upto that depth.

1.0 INTRODUCTION

1.1 General Background

The need for increased crop production (food and fibre) has become more apparent in Kenya due to the ever increasing human and livestock population. To meet this demand for food and fibre, intensive land use becomes the only viable alternative of optimizing agricultural production on the limited available arable land. Since soil moisture shortage is a major constraint to increased food production especially in arid and semi-arid lands (ASAL), the introduction of water harvesting and conservation; and appropriate irrigation techniques would certainly improve crop performance and ultimately increase yields. Without these technologies in ASAL, other attempts at increasing crop production per unit area would be futile.

Irrigated agriculture in Kenya covers an area of about 33,000 ha. (330km^2) of arid and semi arid lands (G.o.K, 1986). Irrigation has significantly improved crop yields and farm incomes of many smallholder farmers in marginal rainfall areas. Irrigated agriculture has also significantly contributed to the production of high value crops (e.g horticultural crops and flowers) for export. Horticultural produce has become a major foreign exchange earner in Kenya. Most high valued crops in ASAL have been produced under pump fed irrigation systems (i.e. drip and sprinkler irrigation). Private and commercial pump fed irrigation in Kenya occupy about 23,000 ha. (G.o.K, 1989); mainly in the form of furrow and sprinkler irrigation (e.g of coffee and fruit tree crops) and of late in the production of flowers.

Drip irrigation is now widely recommended for producing high value crops (e.g oranges, flowers, bananas and vegetables etc.) in marginal rainfall areas. Its application started about ten years ago with the focus being on large scale commercial farms growing high value crops like flowers, vegetables and fruits mainly for the export market. Of late a few small scale farmers are using drip irrigation in growing fruit crops.

Though not widely practised by small scale farmers, drip irrigation has already proven to be quite successful on large scale farms in ASAL. It is a highly efficient irrigation method that economizes on water use and hence producing better crop yields and high economic returns per unit area. Where water availability is the limiting factor to irrigated agriculture, the possibility of applying water of low quality is also possible with drip irrigation.

The major factors limiting any wide application of drip irrigation in Kenya are the high initial investment costs, lack of adequate operational and maintenance skills and services and non availability of cheap and readily made systems in the market. Opportunities for bringing more cultivated areas under drip irrigation would depend (among other factors) upon:

(i) Availability of adequate agricultural extension services.

(ii) Availability of capital incentives (e.g subsidies) to farmers.

(iii) Reduction of high investment costs (e.g through local manufacture of equipment and simple designs).

Drip irrigation systems though complex in design offer many benefits such as; water savings, better crop response, minimal labour requirements, low fertilizer application rates, less weed growth, low inputs in pesticides and disease control and possible use of saline water (upto 4 mmhos/cm).

Besides these potential benefits, drip irrigation has limitations in its application such as sensitivity of equipment to clogging, soil moisture distribution problems, high cost of equipment, obstruction of mechanical land operations and high technical skill requirements (i.e. for design, installation, operation and maintenance). Further research and development of drip designs is needed to make it more cost effective, efficient and applicable to area specific environmental and socio economic conditions.

Currently, horticulture (particularly floriculture) holds the fourth position after tourism, tea, coffee as good foreign exchange earners for Kenya. The export of horticultural produce is reported as having a big potential of becoming the second if not the top cash earner in Kenya. The rapid and seemingly successful use of drip irrigation in this sector of our agricultural economy makes it the most efficient and economically viable irrigation method of producing high value crops in areas with limited water supply as is the case in ASAL.

So far in Kenya, no intensive drip irrigation research has been done. At the Department of Agricultural Engineering, University of Nairobi, there has been three third year design projects devoted to finding cheap and simple alternative gravity fed drip irrigation designs to the rather expensive pump fed drip systems available in the market. The design has a cheaper gravel filter (as an alternative to the expensive conventional filtration unit) and uses the existing plastic (pvc) pipes and in line emitters for water distribution and discharge respectively.

Besides drip irrigation, another subsurface irrigation method that is widely practised in marginal rainfall areas of Kenya is that of utilizing shallow ground water (through capillary rise) to grow vegetable and fruit crops. This practice is common downstream of water reservoirs (earth dams) or close to perennial rivers.

Base flow from such rivers raises the ground water table along riverine floodplain areas and hence facilitating the occurrence of a capillary fringe within the crop rooting zones of most crops.

Subsurface irrigation from ground water is a very efficient irrigation method in terms of water use and distribution and has minimal water losses. Soil texture and structure do significantly influence the resulting capillary fringe and hence the reliability of the shallow ground water in sustaining crop growth during the dry season. The reliability of subsurface irrigation from shallow ground water depends on:

(i) Existence of impermeable sub soil at reasonable depth (2 to 3 m).
(ii) Occurrence of permeable soils such as loam or sandy loam in the crop rooting zone.
(iii) Topographic conditions (uniform or gentle slopes).
(iv) Degree of soil saturation (to avoid waterlogging).
(v) Quality of ground water.
(vi) Presence of reliable water source (i.e earthdam or perennial river).

Downward flux of excess water out of the root zone at one time of the year (during heavy rains) can provide a store of water available for capillary rise at another time of the year (during drought).

Where feasible, subsurface irrigation can have some reasonably high irrigation (water use) efficiency. Often water loss through evaporation is minimized under this irrigation system and hence there is optimal water use by crops. The applicability of sub irrigation requires regular monitoring of the ground water table and water losses (i.e. through seepage) at representative points in the irrigated area.

Where water movement to the plant is upwards from the water table, there is also an upward movement of salts within the soil. In marginal rainfall areas, occasional rainfall counteracts this effect but during prolonged dry periods, provision should be made for periodic leaching out of salts. During the rainy season when the water table is quite high, appropriate drainage ditches could be used to drain excess water and thus avoid any waterlogging.

1.2 Relevance of Study

The success of any irrigation method depends on appropriate system design and management. In turn this requires a knowledge of the factors and processes that control the movement and storage of water in the soil and crop response to different soil moisture conditions. Drip irrigation provides water in small frequent doses at the base of plants so that an optimum soil moisture content in the crop root zone can be maintained. This enables control and manipulation of soil moisture both temporally and spatially and thus enabling the supply of water to meet the consumptive use of crops.

The study of soil moisture dynamics by measuring changes in soil water is important in estimating irrigation water requirements and crop evapotranspiration rates. These changes include vertical downward movement of moisture from the crop root zone, upward flow from a shallow saturated zone (ground water table) where it exists and radial flow towards plant roots. The flow and distribution of water in drip irrigated soils is extremely important from an agrotechnical point of view since it determines the boundaries of root zones and the concentrations of water and salts. To avoid moisture stress, it is recommended that matric suctions do not exceed 0.30 to 0.50 bar for sensitive crops and 0.30 to 0.80 bar for less sensitive crops (Goldberg *et al.*, 1976). Taylor and Ashcroft (1965) indicated that for oranges (grown in deep, well drained soils fertilized and managed for maximum production) water should be applied upto a soil water suction of 0.2 to 1.0 bar if maximum yields are to be realized. For sandy soils, Gardener (1983) stated that plant growth is reduced when soil water potential is below -100 KPa which corresponds to between 0.03 and 0.04 m^3m^{-3} water content.

The method of water application under study hence provides us with a possibility of establishing a soil moisture regime in which the amplitude of matric and osmotic potential fluctuations during the irrigation cycle is limited and controlled; the maximum values reached at the end of a cycle may be kept within a narrow range.

In many areas, rain water stored in the soil or capillary rise of ground water provides some of the crop water requirements for part of the season which calls for supplemental irrigation (Vermeiren and Jobling, 1980). The favourable moisture supply from a water table near the soil surface may cause high yields and irrigation farmers sometimes point out at the advantages of keeping the water table within a few centimetres of the soil surface because of high yields obtained during the dry season (Hansen *et al.*, 1979).

In areas influenced by shallow ground water tables, one must regulate the irrigation regime carefully in order to avoid the development of waterlogged conditions unfavourable for plant growth. For such areas, calculations of irrigation water requirements have to be modified to allow for these lower irrigation water requirements and local research on particular crops and soil types will be necessary to establish the proportion of the water requirements that is being supplied from sources other than irrigation.

Irrigated agriculture depends on the control of moisture in the soil, hence a fair understanding of the interrelations between soil and water is essential. According to Throne and Peterson (1954) this understanding must be based on the principles controlling infiltration of water into the soil, its movement through the soil and the force with which it is attracted to the soil particles.

The movement and distribution of water in the soil profile under drip irrigation has attracted the attention of many researchers who have considered it necessary to approach the subject through field observations, theoretical and laboratory studies.

Presently in Kenya, there is a great emphasis on the development of appropriate water harvesting technology for crop production in arid and semi-arid lands that occupy about 80% of the country's total land area. Current agricultural research efforts in these areas are geared towards intensive and efficient utilisation of these limited land and water resources. Due to the erratic and unreliable rainfall in these areas, low yields are common and the risk of crop failure fairly high; hence exploitation of ground water resources seems to be one of the most reliable alternatives (where available in reasonable quantities and quality) for providing adequate soil moisture for plant growth.

Most ground water resources in ASAL areas are saline due to leaching out of soluble salts during the rainy seasons. Hence it is necessary to maintain acceptable levels of salt concentration within the crop root zone by applying adequate water to this zone.

Drip water application makes it possible to keep the salt concentration low and maintain a low osmotic potential at the crop rooting zone, which is one of the major characteristics and advantages of drip irrigation. The need of developing appropriate irrigation technology for ASAL areas calls for the study of the soil-water regimes under possible drip irrigation systems. Such studies would provide basic soil-water relationship data required to assess the applicability and performance of drip irrigation to area specific conditions.

Drip irrigation is recommended for steep slopes or rocky areas with shallow soils, a common feature in ASAL areas where land levelling for conventional irrigation is prohibitively expensive and degradation is prevalent when these areas are opened to other types of farming. With drip irrigation it is possible to cultivate tree crops in these rather fragile areas without destroying the entire natural vegetation and thus undertaking farming in harmony with environmental conservation by clearing only small portions around trees where water and nutrients are applied. Dasberg and Bresler (1985) reported successful use of drip irrigation on marginal soils, growing avocadoes on steep rocky hills in San Diego, U.S.A.

This study was undertaken by monitoring the effects of drip discharge and spacing, ground water table depth on soil moisture conditions within the effective crop rooting zone of a citrus crop (oranges).

The results obtained provide useful information and data on the interrelationships between the wetting patterns, wetted soil volume, emitter discharge rates, time or frequency of water application and antecedent soil moisture content, upward soil moisture flux fluctuations (due to a shallow ground water table) for the selected soil type (sandy loam).

1.3 Objective and Scope of Study

1.3.1 Objectives of Study

Overall Objectives

1. To study the effects of drip discharge rates and emitter spacing on soil water flow and distribution.
2. To study the contribution of a shallow ground water table to upward soil water flux (capillary rise).

Specific Objectives

1. Determine physical soil properties (i.e. bulk density, hydraulic conductivity, porosity, organic matter content, water retention capacity and available moisture capacity at the Experimental Site.
2. Examine the effect of drip discharge rates, emitter spacing, duration of water application, and antecedent soil moisture on soil water potential.
3. Monitor upward soil water flux (capillary rise) and soil matric potential as influenced by varying depths of ground water and establish a soil water balance for the specific soil type.

1.3.2 Scope of Study

This study was conducted on sandy loam soils which are typical of the Footslopes of the Nandi Escarpment. Four drip emission rates (2, 3, 4, 8 l/hr) and two emitter spacings (0.75, 1.0 m) were used in this experiment. The experiment was conducted at three antecedent soil moisture levels as indicated by soil matric suctions of 0.2, 0.3 and 0.5 bar. For each drip discharge rate and initial soil moisture conditions, monitoring of soil water flow and soil matric potential was done at three representative sites.

Monitoring of the upward soil water flux (capillary rise) and soil matric potential as influenced by a fluctuating ground water table were conducted at three representative locations using an array of tensiometers. The tensiometers were installed at each site at varying depths ranging from 30 to 150 cm.(at intervals of 30 cm). Rainfall was recorded at the site using a non recording rain gauge. Infiltration measurements were done using a double ring infiltrometer.

1.4 Experimental Site

The Experimental Site used in this study is located at Soy Area, Kapsengere, Nandi District, Kenya. This area is about 15 km Northeast of Kisumu Town. The study area lies on the leeward side of the Nandi Escarpment and is located in Agro-ecological Zone III (annual rainfall to annual open evaporation ratio in the range of 0.5-0.65) with soils predominantly sandy loam (Jaetzold and Schmidt, 1983). These light textured soils are prone to soil moisture deficits especially during the dry season (October to February). It is during this period that application of supplemental water through irrigation is essential. The climate of this area is semi-humid with a total mean annual rainfall of 1536 mm based on nineteen years rainfall record (1972-1990).

Table 1.1. Mean monthly rainfall, evaporation, temperature at Kibos Agro-Meteorological Station.

Month	Mean Rainfall (mm) (1972-1990)	Mean Potential evaporation (mm) (1972-1990)	Mean Temperature (°C) (1972-75,77-80) Max	Min
Jan	81	187	30.6	14.9
Feb	114	185	30.9	14.7
Mar	173	197	30.6	14.6
Apr	230	158	29.4	15.2
May	171	152	28.5	14.9
Jun	101	136	27.8	14.4
Jul	92	150	28.0	14.0
Aug	123	161	28.7	13.8
Sep	120	158	29.1	13.8
Oct	95	175	30.3	15.2
Nov	138	152	29.8	15.1
Dec	100	170	29.8	14.8
Year	1536	2052	29.5	14.6

Climatological data (see Table 1.1) collected at Kibos Sugar Research Station (closest Agro-Met. Station; about 8 km away) is representative of the Soy Study Area which lies in the same rainfall belt and has similar physiographical conditions. The rainfall pattern of this area is bimodal with two rainfall seasons.

The long rains occur between the months of February and June with the peak rainfall in April. The short rains occur within the months of August and September (see Figure 1.1).

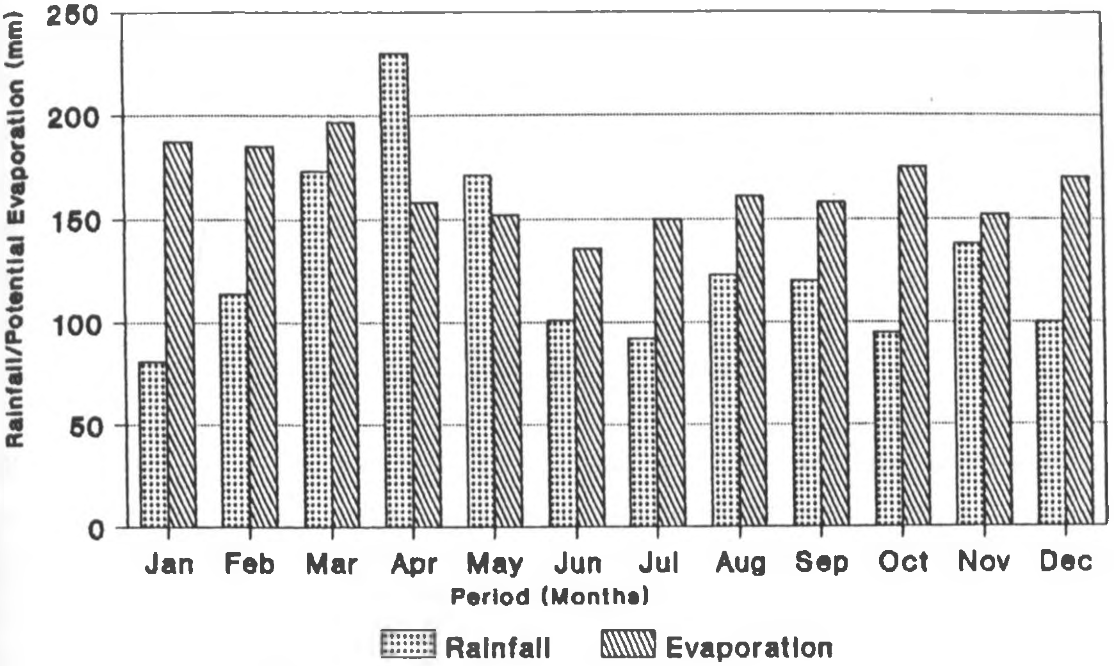

Fig. 1.1. Mean monthly Rainfall and Potential evaporation at Kibos Agro-Met. Station (data based on 19 years record).

There are some pronounced showers within the month of November but are of no significance to crop production in the area. The wettest month of the year is April with an average rainfall of 230 mm and January being the hottest and driest month with an average total rainfall of 81 mm and a potential evaporation of 187 mm. The mean maximum and minimum monthly temperatures are 29.5°C and 14.6°C respectively. Mean monthly potential evaporation (based on Class A Pan data) is based on nineteen years of record with a mean total annual potential evaporation of 2052 mm. Potential evaporation exceeds the rainfall and hence the soil moisture deficits experienced in the study area.

The farm (Ruguju) on which the study was conducted is about ten acres in area with about six acres under citrus, bananas, pawpaws and mangoes. Onions, simsim, tomatoes, groundnuts, beans, cowpeas are also grown as intercrops with the young fruit crops.

About 0.5 acres of citrus grove is under drip irrigation. There are plans to extend the irrigation system to cover the whole orchard when fully established. As the farm expands, plans are there to diversify the crops to include other tree crops like avocado and local berries. Water is pumped from a nearby perennial stream (Chepkurgei) to two storage reservoirs located on elevated ground from where it flows to the drip system via a two-stage filtration unit and to the rest of the farm where irrigation is by sprinklers and/or hose pipe.

The riverine area of the farm has a fluctuating shallow ground water table. This water table is dependent on base flow from a perennial river (Chepkurgei). The depth of the water table varies from about 0.40 m during the rainy season to 2.0 m in the dry season.

2.0 REVIEW OF LITERATURE

2.1 Drip Irrigation Design

2.1.1 Drip Irrigation System

The major components of a drip irrigation system consists of a pressure head, filtration unit, mainline, submains or delivery pipes, laterals and emitters (see Figure 2.1).

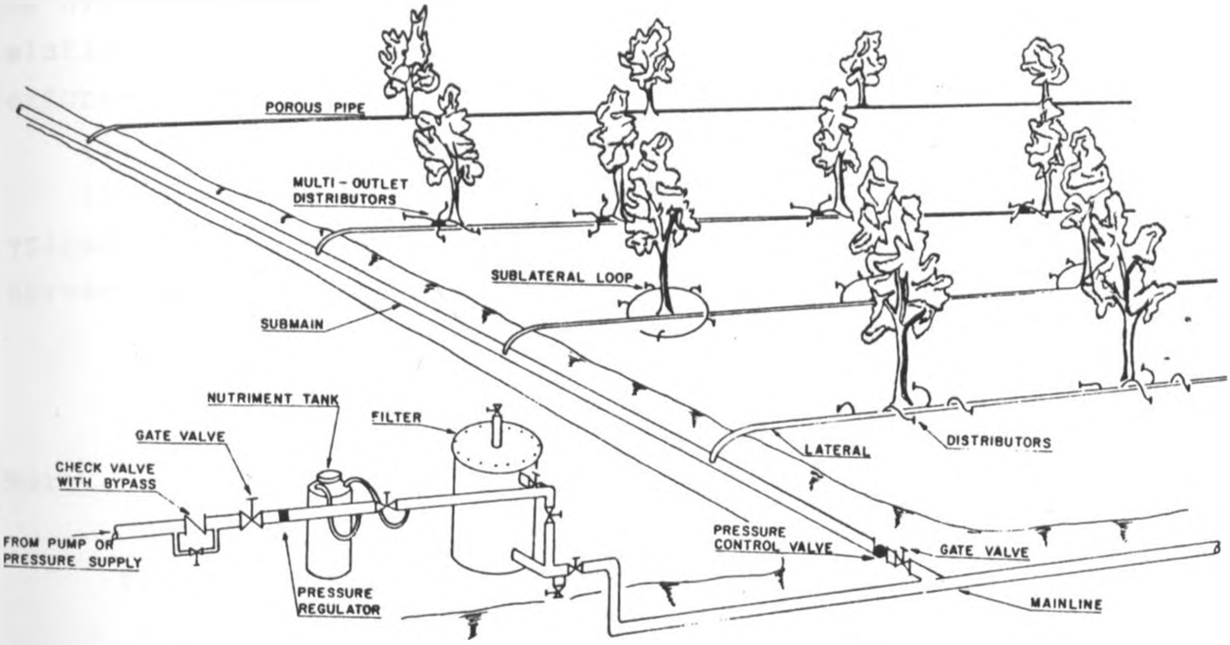

Figure 2.1. Basic components of a localized drip irrigation system (after Vermeiren and Jobling, 1980).

2.1.2 Emission Rate

Karmeli (1977) indicated that the flow characteristics of emitters could generally be represented by the relation between discharge, pressure and an emitter exponent that is characterized by the flow regime which in turn is characterized by the Reynolds number, R_e. The Reynolds number is determined by the flow cross section and discharge.

Drip irrigation systems are characterized by low emission rates operating under relatively low pressure heads. Howell *et al.*, (1983), Goldberg *et al.* (1976), Baars (1976), Karmeli and Keller (1975) report that common drip emission rates are in the range of 1 to 10 l/hr and operating pressure heads for emitters range from 10 to 20 m.

The hydraulic characteristics of an emitter (pressure-discharge relationship) significantly affect such aspects of irrigation performance as:

(i) Emitter discharge rates.

(ii) Emitter wetting patterns.

Typical discharge-pressure relationship for emitters is represented by the equation: (Karmeli, 1977);

$$q = K \cdot P_e^x \qquad (2.1)$$

Where

q = Emitter discharge (l/hr).

P_e = Emitter operating pressure head (m).

x = Emitter discharge exponent that expresses the emitter flow regime.

K = Coefficient of proportionality that characterises each emitter and depends on the nozzle size (or flow cross-section) and shape.

The emitter is the most important component of a drip system that determines its characteristics. For irrigation purposes, emitters should fulfil the following requirements:

(i) Each emitter should be available in a range of sizes (i.e. flow rates).

(ii) Emitters should have a large flow area to reduce any clogging potential.

(iii) Emitters should be insensitive to temperature changes, and must withstand sunlight and general weathering.

(iv) Emitters should be cheap, robust and homogenous.

Many types of emitters are available in the market, each with its specific properties. Some of the different types are shown in Figure 2.2.

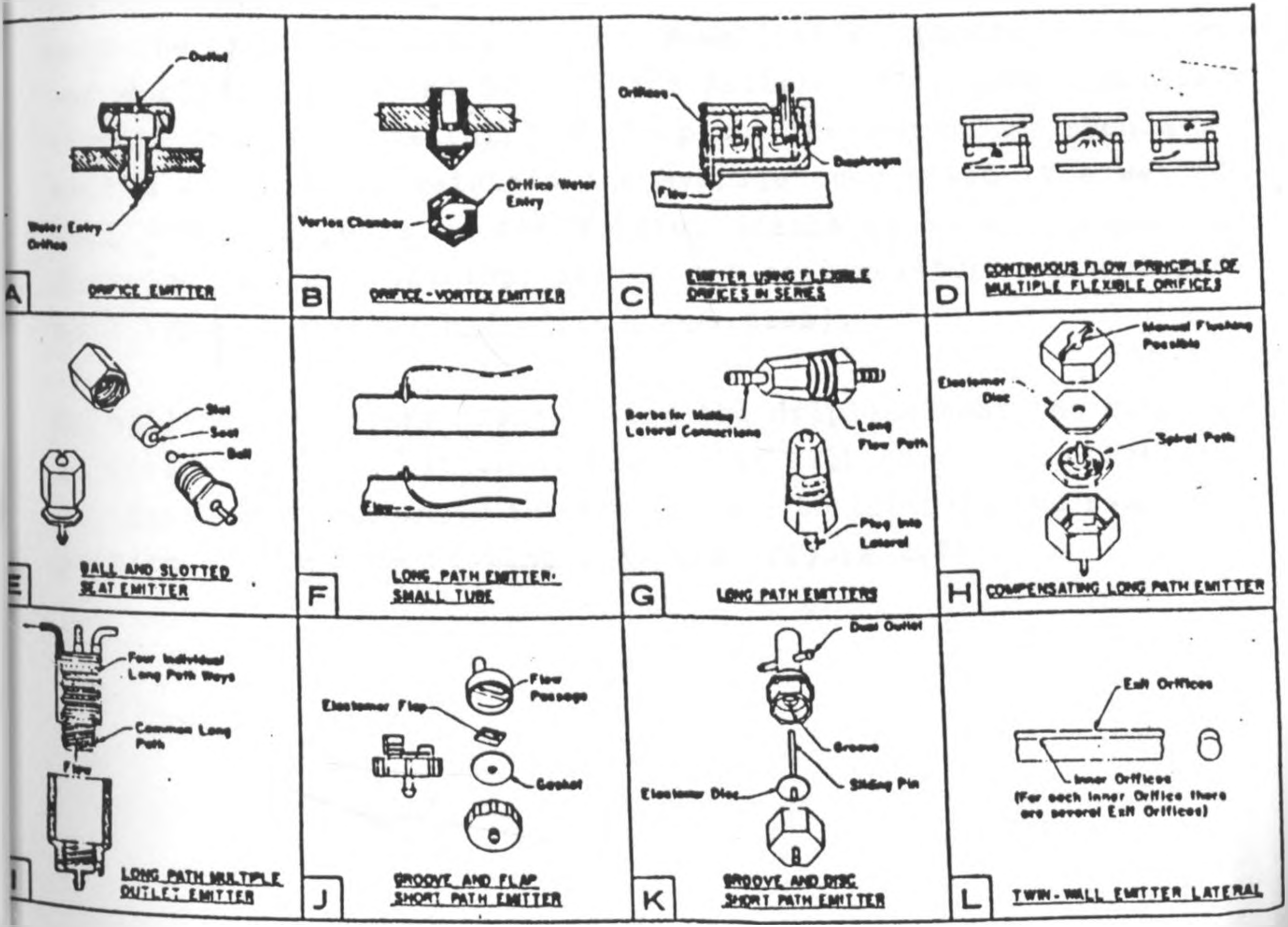

Figure 2.2. Sketches of some types of emission devices (after Solomon, 1977).

The need to regulate soil water flow through appropriate drip discharge rates is an important consideration in the design of the system. Optimum soil moisture conditions (i.e. in terms of content, suctions and wetted volumes) for plant growth would be maintained by applying water at a rate that is less than the soil intake rate.

2.1.3 Emitter Spacing

The emitters must supply enough water to the crop rooting zone to meet the crop water requirements. Howell *et al.* (1983), Vermeiren and Jobling (1980) and Karmeli and Keller (1975) have indicated that a minimum of one third of the plant rooting volume should be wetted in order to maintain the average crop yield. The wetted soil volume depends on the emitter discharge rate, irrigation duration, emitter spacing, antecedent soil moisture content and soil type (i.e. soil hydraulic properties).

Normally emitters are placed along the dripline near the crop to be irrigated and positioned in areas of high root concentration. Emitters can be arranged in several ways to irrigate the required portion of the crop rooting zone (see Figure 2.3).

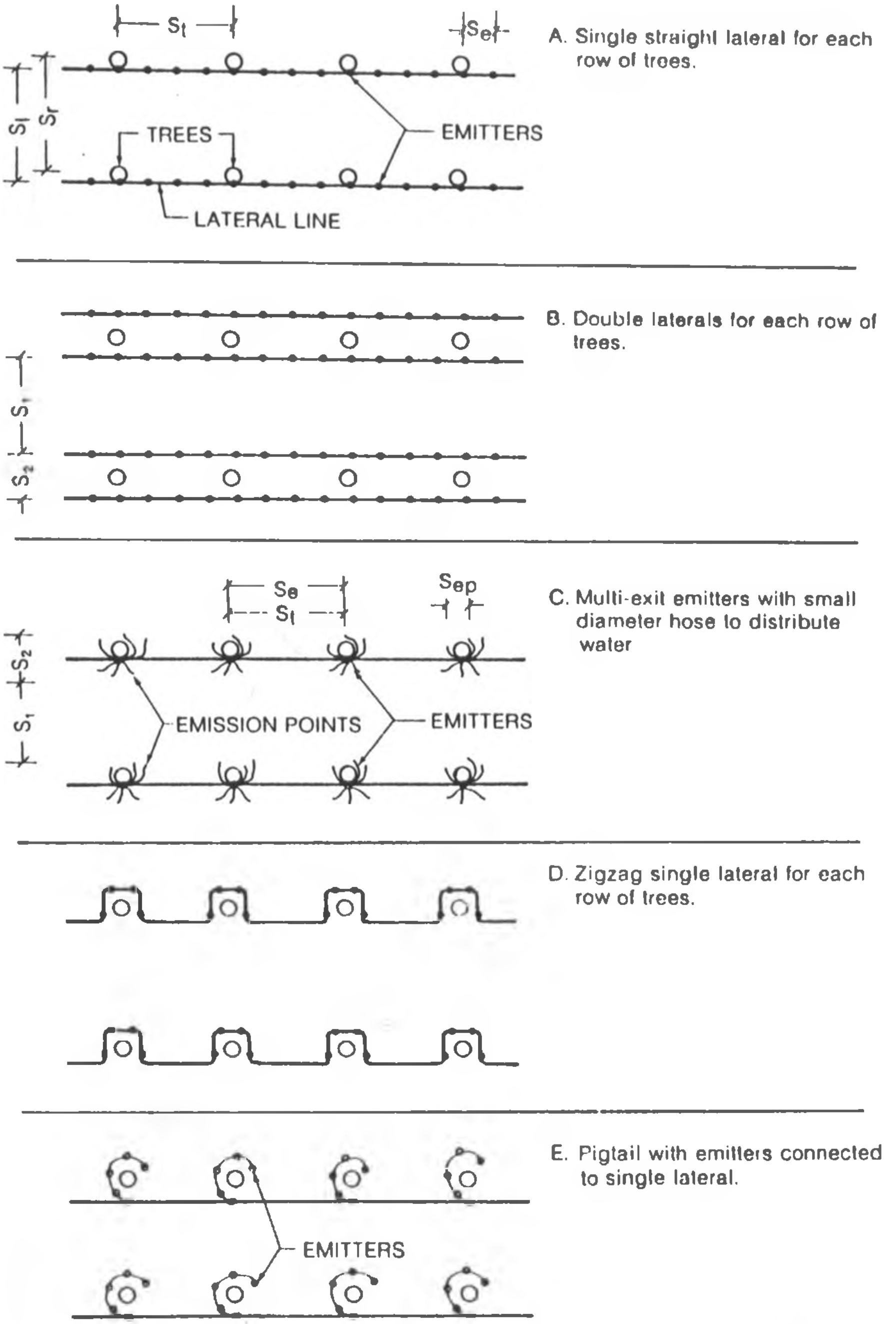

Figure 2.3. Common patterns for placing drip lateral lines to irrigate orchards (after Karmeli and Keller, 1975).

The spacing of emitters along and between laterals depends on crop water requirements. For close planted crops like forage, flower beds, the whole area has to be wetted necessitating the overlap of wetted zones of each emitter. With row crops (i.e. citrus, coffee) it might be necessary to wet only the portion near the tree trunk leaving the areas between rows dry (see Figure 2.4).

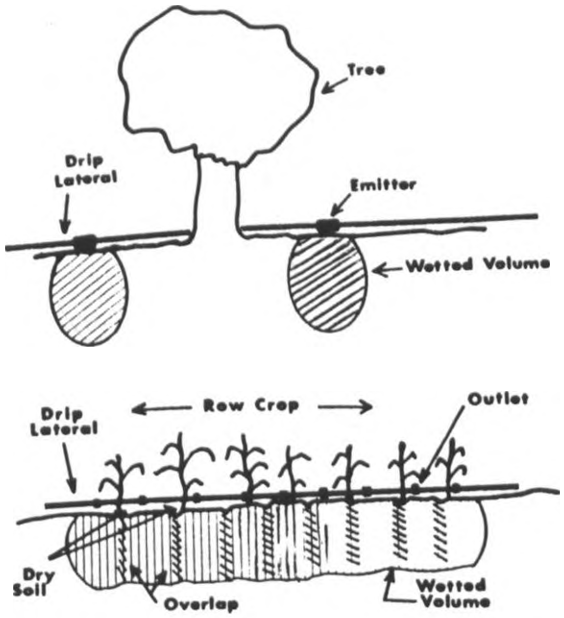

Figure 2.4. Drip Irrigation Soil Wetting Patterns at different Emitter Spacings (after Howell *et al.*, 1983).

2.1.4 Soil Intake Rate

The flux or rate at which water enters the soil surface is referred to as the infiltration or intake rate. Infiltration (intake rate) of a soil is an important consideration when choosing irrigation methods, in the design and layout of irrigation and drainage systems, appraising suitability of a soil for irrigation and selecting proper irrigation management techniques (FAO, 1974; Sharma, 1969). The most important factors influencing soil intake rates are permeability of the soil profile, condition of soil surface and the prevailing soil moisture content. Soil structure, soil moisture conditions, bulk density of surface and upper soil horizons significantly influence infiltration rates of irrigated soils. These factors affect the pore size distribution and cleavage planes of the soils.

Sharma (1969) when considering volume balance method of determining infiltration in an irrigation border recommended the use of continuity principles as compared to use of variable head cylinder infiltrometer. This was due to the fact that the former method is more representative of average conditions in soil properties such as structure, presence of non uniform vegetal cover, biopores and cracks on infiltration capacity (i_c).

During water application, the initial soil intake rate is relatively high (its actual value depending on initial soil moisture conditions), but then decreases with time as schematically shown in Figure 2.5.

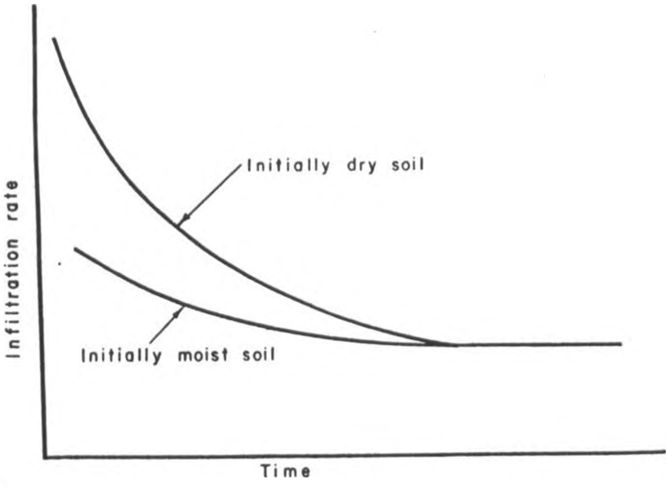

Figure 2.5. Infiltrability as a function of time in an initially dry and in an initially moist soil (after Hillel, 1982a).

The decrease in infiltration rate is primarily due to the reduction in the hydraulic gradients at the soil surface but may also be affected by surface sealing and crusting properties of soils.

The infiltration characteristics of a soil can be represented by parameters of infiltration equations (Hillel, 1982a). Of these equations the most common is Kostiakov's equation, $i = a\ t^b$ where i is the infiltration rate ,a, and ,b, are constants and ,t, the time factor. When designing drip irrigation systems, it is important to consider water application rates not exceeding the soil intake rate. High water application rates may leach out soil nutrients or generate high runoff rates and subsequently cause soil erosion. Emitter discharge rates and spacing should be based on soil hydraulic properties.

2.1.5 Crop Water Requirements

Crop water requirements has been defined as the rate of evapotranspiration necessary to sustain plant growth (Doorenbos and Pruit, 1977; Hillel, 1982a). The primary objective of irrigation is to provide plants with sufficient water to prevent moisture stress that would cause reduction in yields or poor crop growth.

The prevailing climatic conditions, crop growth stage, soil moisture holding capacity, and extent of root development significantly influence timing and amount of water to be applied.

Since drip water application to the soil is usually a three dimensional pattern, Howell *et al.* (1983) reports that the energy or water balance techniques are difficult to apply in drip irrigated fields and suggests that heat pulse velocity measurements offer reliable estimates of daily transpiration rates of tree crops.

The effect of soil water content on evapotranspiration varies with crop rooting characteristics and the meteorological factors determining the level of transpiration. Since any reduction in evapotranspiration may affect crop growth and yields, the timing of irrigation and magnitude of reduction in evapotranspiration are important criteria for determining the irrigation schedule.

The amount and rate of water uptake depend on the ability of the roots to absorb water from the soil with which they are in contact as well as the ability of the soil to transmit water towards the roots at a rate sufficient to meet transpiration requirements. These in turn depend on soil and plant properties such as:

(i) Soil properties; hydraulic conductivity, diffusivity, matric suction, soil wetness and to a considerable extent on the climatic conditions that dictate the rate at which the plant is required to transpire and hence the rate at which it must extract water from the soil in order to maintain its own turgidity.

(ii) Plant properties; rooting depth, rooting density, rate of root development, leaf area index, stomata behaviour and physiological ability of the plant to continue taking in water from the soil at field capacity while maintaining its vital functions even when its own water potential decreases.

A well operated drip system allowing frequent application of small quantities of water can provide nearly constant low soil moisture tensions in the major portion of the root zone and supply water at nearly the consumptive use of the plant as illustrated in Figure 2.6.

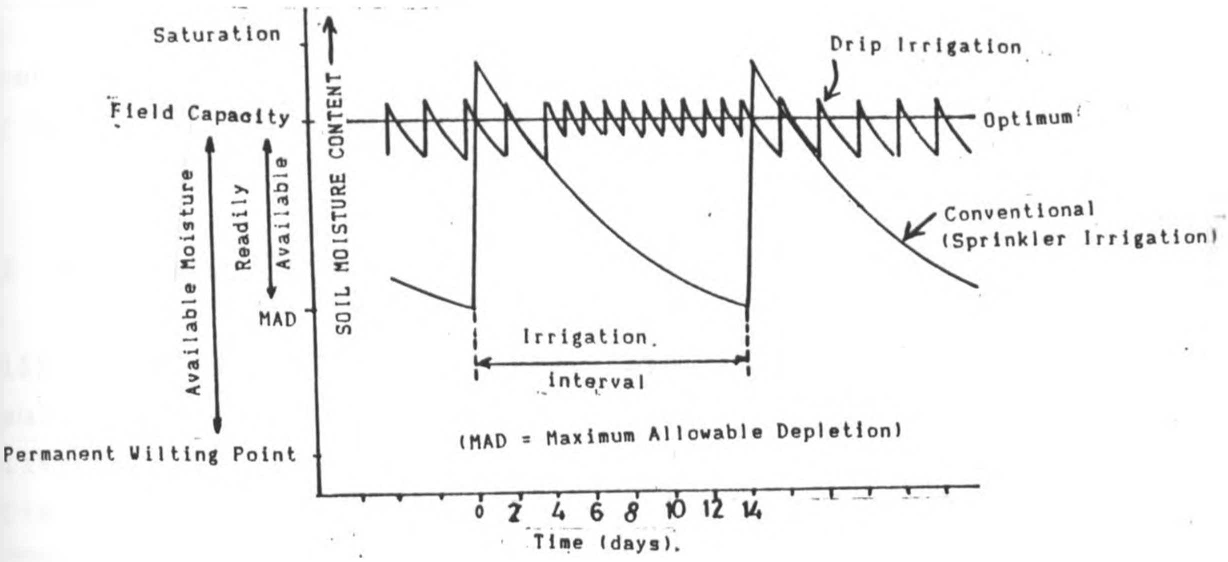

Figure 2.6. Difference between drip and conventional irrigation methods with regard to soil moisture content and suction (after Nakaya and Bucks, 1986).

This gives drip irrigation an advantage over other irrigation systems due to the adequacy and effectiveness with which crop water requirements can be met. It is therefore essential that variations in emitter discharge rates and the uniformity of water application be known in order to establish the required irrigation time and water application rate. However, the high water use efficiency can be attributed to improved water conveyance and distribution to the crop root zone.

In drip irrigation systems, the allowable soil water depletion, type of crop and soil and type of emitters, determine the design discharge rate. For a selected level of soil water depletion, knowing the actual crop evapotranspiration and soil infiltration rate, the frequency and duration of water application can be determined.

Drip irrigation represents a distinct advance in irrigation as it can slowly apply precise amounts of water (and nutrients) to precise locations. Gregory (1990) observed that there is scope for the adoption of drip systems especially where water is expensive and scarce or where soils are sandy, rocky or difficult for levelling as in conventional irrigation practices.

2.2 Soil Water Potential

Unlike surface or overhead irrigation, soil water distribution resulting from a drip is not one dimensional. At the point of delivery, drip irrigation causes a three dimensional infiltration pattern. According to Bell *et al.* (1990) and Hodnett *et al.* (1990) simple soil water content concepts such as field capacity and available water are inappropriate when applied to soil water potential considerations under drip irrigation.

Many researchers have made attempts to calculate the water distribution patterns on the basis of physical properties of the soils (Baars, 1976). Ghanim *et al.* (1985) reported of attempts that have been made to determine water distribution on the basis of soil physical properties using complex mathematical models which require detailed experimental input data and extensive computer time, hence making it of little practical application. Vermeiren and Jobling (1980); Goldberg *et al.* (1976) indicated that these methods are complicated, laborious and not quite reliable since soil profiles are seldom homogeneous. They recommended use of field trials and empirical methods in predicting soil wetting patterns. Yaron *et al.* (1973a) described mathematically the moisture flow in the soil from a point source such as a drip nozzle and showed that the extent of vertical and horizontal flow in a three dimensional system depends on soil hydraulic conductivity, rate and time of water application.

Gardner (1983); Lambert and De Penning (1973) observed that misleading conclusions drawn from static concepts like field capacity, permanent wilting point and available water, critical moisture, capillary water, gravitational water etc. based on supposition that processes in the field bring about static levels of soil-water content or potential could be misleading in drip application. Soil water flow under drip takes place almost incessantly though in varying fluxes and directions, and static situations are exceedingly rare.

Field capacity, which is defined as the moisture content in a soil after free drainage varies widely within one soil type and depends on whether the soil is under the influence of a shallow ground water table or a free draining soil (i.e. soils with a deep ground water table). Permanent wilting point, defined as the moisture content at which plants can no longer take up water from the soil and suffer irreversible wilting not only depends on the plant species but also on stage of growth and health status of the crop among other factors. Both field capacity and permanent wilting point are affected by soil hysteresis which influences soil water distribution.

Like any other irrigation technology, drip technology has to undergo a phase of dissemination. In this respect, Ah Koon *et al.* (1990), Bell *et al.* (1990) have reported research findings in soil water potential as a concept for characterizing soil water conditions beneath a drip irrigated row crop. This concept is believed to be the new approach to plant-soil-water relations in drip irrigated row crops. Hodnett et al. (1990) detailed the advantages of drip irrigation practice solely based on soil water potential measurements. Levin *et al.* (1973a) concluded that yields could be higher if the soil water content is maintained at a high level but still compatible with adequate root aeration. This can be realized by irrigating frequently with small amounts of water thus keeping the soil continuously wet and accepting a given amount of deep drainage loss which is inherent in drip farming of salt affected soils.

To obtain the necessary soil water potential data, vertical array of tensiometers set out across the crop row/dripline are used to plot and quantify the soil water distribution resulting from many different treatments and regimes. The same data can be used in computing upward flux from a saturated zone beneath the plant root zone. Several FAO experimental plots equipped with drip have been set-up in Senegal, Spain and Tunisia directed at a search for optimum irrigation regimes (FAO, 1973).

2.3 <u>Interactions of Soil and Water</u>

The physical, biological and chemical interactions of soil and water influence the hydrologic characteristics and tilth of a soil. The manifestation of these interactions is the water surface tension and the curved air water interfaces within the soil pores (Hadas, 1973).

Soil consists of a solid skeleton (matrix) with pores in between of different sizes, shapes and spatial distribution and provide the space for storage and transport of soil water and gas.

Storage and retention of water by soils is as a result of attractive forces between the solid and liquid phases. The matric forces enable the soil to hold water against forces or processes such as gravity, evaporation, and water uptake by plant roots. Sandy soils release more water at low suctions than do clayey soils. Furthermore a sandy soil of fairly uniform particle size releases more water over a small range of suctions. The amount of water held by a soil at a given suction is influenced by several properties of the soil including structure, texture, organic matter content and nature of clay minerals. Marshall and Holmes (1988) reported the establishment of regression equations showing the effect of these properties on water content at various suctions.

Water in the soil is seldom in the static state but often under non-equilibrium conditions. The tendency for soil water to move at a given point in a given direction results from the combined effects of hydrostatic pressure and gravity among other forces. Koorevaar et al. (1983) gave the three mechanisms by which water is bonded to the soil matrix as:

(i) Direct adhesion of water molecules to the solid surface by Van der waals forces.
(ii) Capillary binding of water.
(iii) Osmotic binding of water in double layers.

As the soil is a dynamic system of water removal by drainage, evaporation and absorption by plant roots; and the addition of water by rain, dew, irrigation, or by capillary rise from a ground water table, the soil moisture content is seldom in a steady state (Yaron *et al.*, 1973b). The amount of water in a soil is not in itself an indication of its availability; a better indicator is the force (matric potential) with which the water is held by the soil.

Therefore soil variability makes it preferable to use the matric potential as an unambiguous measure of soil water status. Matric potential is a pressure potential that arises from the interaction of water with the matrix of solid particles in which it is embedded (Marshall and Holmes, 1988; Hillel, 1982b; 1971). As the matric suction increases in a soil drying from saturation to air-dryness, the water content decreases.

Flow of water in soils involves two distinct processes:

(i) Movement of water from point of high to that of lower concentration.
(ii) Accumulation in terms of increase or decrease of water with time at a given point in the soil matrix.

The amount of water retained at relatively low matric suctions (i.e. between 0 to 1 bar) depends primarily upon the capillary effect and soil pore size distribution hence is strongly affected by soil structure and texture (James, 1988; Hansen *et al.*, 1979).

2.4 Unsaturated Soil Water Flow

Most of the processes involving soil water flow in the field and in the rooting zone of most plant habitats occur while the soil is in an unsaturated condition. The pore spaces of unsaturated soil contain both water and air so that its pore water pressure is negative with respect to the pressure in the air phase; customarily assumed to be atmospheric.

Since unsaturated flow processes entail changes in the state and content of soil water during flow hence involving complex relations among the variables; water content (wetness), suction, and hydraulic conductivity which may be affected by hysteresis, makes the process complicated and difficult to describe quantitatively (Lafolie *et al.*, 1989; Marshall and Holmes, 1988; Hillel, 1971; and Kemper, 1961). Marshall and Holmes (1988) proposed that changes with time caused by wetting and drying under unsaturated flow could be expressed explicitly with space and time variables.

The hydraulic conductivity of unsaturated soil is regarded as depending strongly upon the water content (or matric potential). Matric potential in unsaturated soil can be measured in the field using tensiometers and together with the soil moisture characteristic curve can be used to make inferences on soil water retention and suction.

When soil is unsaturated, some pores become air filled and the conductive portion decreases correspondingly. Large pores which are the most conductive empty first leaving water to flow only in the smaller pores resulting in development of a suction.

Darcy's law can be extended to unsaturated flow with conductivity now being a function of the matric suction head. According to Klute (1982) in the usual Darcy-based theory of water flow in unsaturated soils, the two hydraulic functions that come into play are the hydraulic conductivity and the water retention capacity; the former being a function of water content or the capillary pressure head of the soil water and the latter as rate of change of water content with capillary pressure head. Most water flow in unsaturated soils occurs during the process of redistribution.

Soil moisture distribution is an important design and management consideration of a drip irrigation system. Ghali and Svehlik (1988) remarked that detailed analysis of soil water dynamics under drip irrigation regimes is a prerequisite in the search of optimum operation conditions. When the emitter is turned on, water drips onto the soil surface and the wetted area gradually expands. However the wetted area remains finite and tends to stabilise after infiltration has occurred for some time. In general, the higher the discharge rate, the larger will be the wetted area.

Water in the soil moves from points of higher to lower energy status. The energy status of water (i.e. water potential) is often given as a sum of various potentials (Hillel, 1971):

$$\psi = \psi_m + \psi_g + (\psi_o + \psi_p) \qquad (2.2)$$

Where

ψ_m = Matric potential arising from local interaction of soil and water forces.

ψ_g = Gravitational potential arising from gravitational forces.

ψ_o = Osmotic potential arising from osmotic forces.

ψ_p = Pneumatic potential arising from changes in external gas pressure.

The infiltration, flow and distribution from a drip as a point source results from a multiple of parameters such as soil constants and porosity, degree of soil homogeneity, hydraulic gradients, soil and water temperatures, emitter discharge rate, infiltration rate, soil moisture content before application, water table level, duration of water application, distance from adjacent outlets and consequent interaction of overlapping wetting zone profiles, evaporation and root suction (FAO, 1973).

Brandt *et al.* (1972) used numerical analysis to model infiltration from a drip and assumed that the water entry zone just beneath the drip is saturated. After some appreciable water application, the water content at any point in the vicinity of the source stabilizes depicting a situation of spatial distribution of water content which is not changing with time. Hardee and Benjamin (1977) observed that the subsurface wetting pattern with drip irrigation is much larger than the surface wetting pattern indicates. Moisture content increases only at large distances from the source.

For steady state flow from the source, one set of analysis is based on the assumption that the hydraulic conductivity K is an exponential function of the pressure head h; i.e. $K = K_0e^{ah}$. Experimental values of ,K_0, and ,a, are given by Gilley and Allred, (1974) and Braester (1973).

The wetting pattern resulting from a drip source is influenced by soil texture, horizontal and vertical permeability, hydraulic conductivity, capillary suction, volume of water applied per irrigation, rate of application, initial soil moisture content and by the presence or absence of impermeable layers. In deep sandy soils where capillary forces are smaller and gravity has relatively more influence, the vertical movement of water is greater than horizontal flow and thus causes the shape of the infiltration pattern to be elongated; while the opposite is observed in fine textured soils such as clay and clay loams. This phenomenon is illustrated in Figure 2.7.

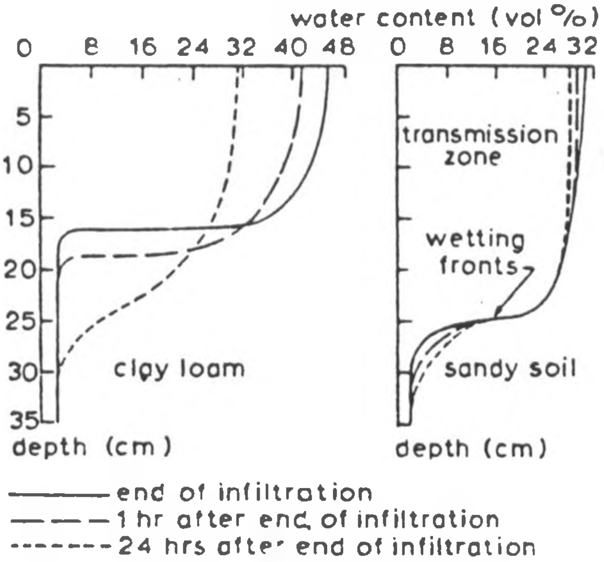

Figure 2.7. Infiltration and redistribution of soil water in a clay and sandy soil (after Groenevelt and Kinje, 1980).

The use of drip irrigation for fertilization (also called fertigation) in arid zones of the world is wide spread and has special advantage in sandy soils where accurate control of water and nutrients in the plant root zone is critical (Hall, 1974).

Soil moisture distribution has five distinct zones namely:

(i) Saturated zone; extending from the soil surface to a maximum depth of approximately 1.5 cm.

(ii) Transition zone; a region of rapid decrease of soil water content extending from the zone of saturation to the transmission zone.

(iii) Transmission zone; occurring beneath and around the emitter where the soil is nearly saturated and at constant water content and which lengthens as infiltration proceeds.

(iv) Wetting zone; where water flows into the soil and moisture content decreases proportionally to the distance from the source. This zone maintains a nearly constant shape during infiltration and culminates in the wetting front.

(v) Wetting front; at the extreme boundary of the wetting zone where the water content equals the original soil moisture; hence is the visible limit of water penetration into the soil as shown in Figure 2.8.

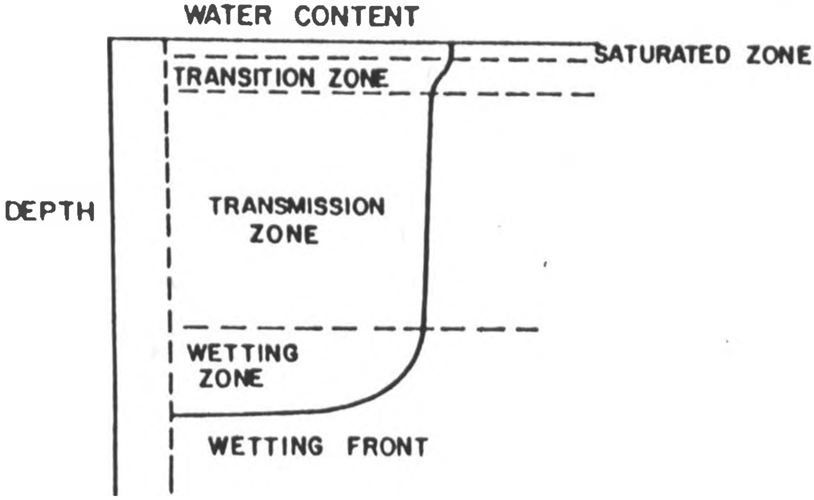

Figure 2.8. Soil moisture distribution zones (after Bodman and Colman, 1943).

As infiltration of water through the soil surface ceases there is quite a prolonged period of redistribution of water in the soil profile from the parts that have been wetted to the dry soil beyond the wetting front. When redistribution starts, the upper position of the profile which was wetted to near saturation during the preceding infiltration process begins to desorb monotonically as illustrated in Figure 2.9.

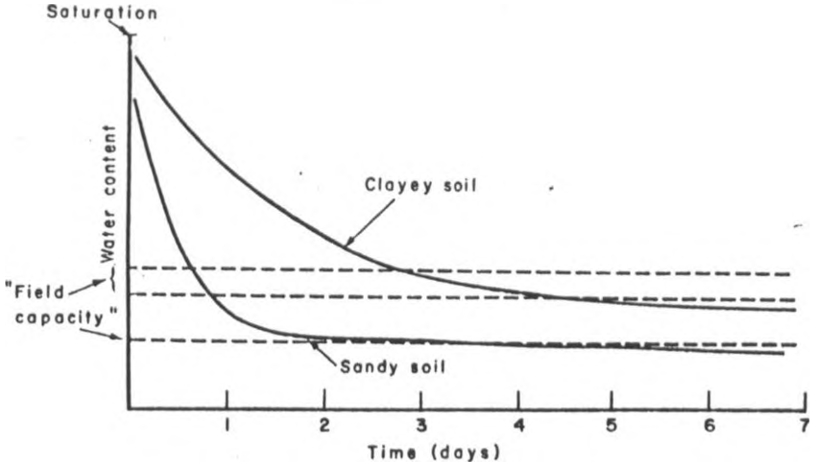

Figure 2.9. Monotonic decrease of soil wetness with time in an initially wetted zone during redistribution (after Hillel, 1982a).

Below a certain depth, soil first wets during redistribution then begins to drain and the value of wetness at which the turnabout occurs decreases with depth. Each point in the soil follows a different scanning curve and the conductivity and water holding capacity functions vary with position. Marshall and Holmes (1988) gave an example of such a redistribution chosen from many experimental demonstrations by Gardner, Hillel and Benyamini in 1970; as illustrated by Figure 2.10.

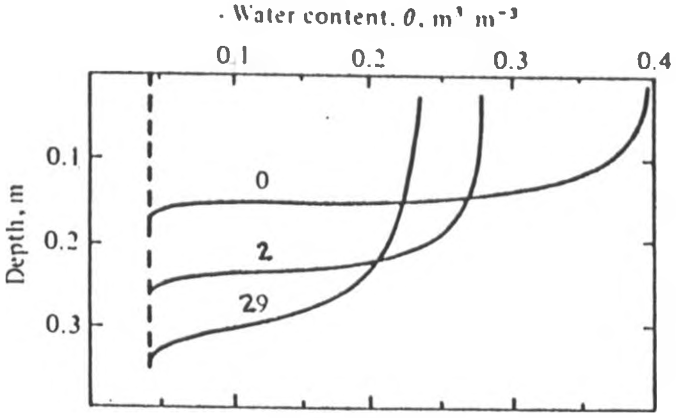

Figure 2.10. Successive water content profiles in a soil column, following application of 50 mm of water. 0, 2, and 29 are the days after irrigation (after Gardner *et al.*,1970).

The reduction of water content in the soil above the position of the wetting front at the start of redistribution of the soil water defines the draining zone. The rate of advance of the wetting front decreases accordingly; and this front which was relatively sharp during infiltration gradually flattens out and dissipates during redistribution. When water application ceases, redistribution goes on through a diminishing rate under the influence of gravity and suction gradients until an equilibrium is reached and the entire wetted volume is almost at field capacity. The time-variable of redistribution depends on the hydrologic properties of the conducting soil, initial wetting depth and relative dryness of the bottom layers. Finally the redistribution process tends to cease as the suction gradients between the wet and dry zones decrease as the former loses and the latter gains moisture; and as the initial wetted zone quickly desorbs its hydraulic conductivity decreases correspondingly and the flux falls rapidly.

The prediction of soil moisture flow under partial wetting by drip is therefore essential for efficient water management (ASAE, 1985). Goldberg *et al.* (1976); Keller and Karmeli (1974) developed a guide for estimating the size (percentage) of the wetted soil volume. Ghanim *et al.* (1985) noted that no work has been reported on the design of emitter spacing based on the actual wetting pattern of the soil or the size and shape of the wetted soil volume.

The rate of advance of the wetting front decreases accordingly and dissipates during redistribution. Redistribution determines the amount of water retained at various times by the different depth zones in the soil profile, hence it can affect the water use efficiency of plants. The rate and duration of downward flow during redistribution depends on the effective water storage capacity of the soil. Extent of redistribution is affected by such factors as; soil texture, type of clay present, organic matter content, depth of wetting and antecedent soil moisture, presence of impending layers, and evapotranspiration rate. Detailed considerations of redistribution are given by Koorenvaar *et al.* (1983) and Hillel (1980).

Oswal (1983) indicated that after water disappears from the soil surface during an infiltration process it continues to move downwards for some time under the influence of the water content gradient and the gravitational field. He further pointed out that in case a water table exists at some depth not too far below the soil surface, the soil above the water table would drain until the suction head at each point corresponds with the distance above the water table. This effect results in a higher moisture content at some point above the water table than right at the water table; but the effect on the soil surface would be small.

The equilibrium situation is approached very slowly and in the presence of plants will seldom be reached before plants use significant amounts of water. Thus the upper limit of available water for the plants will be somewhat above this equilibrium level and will depend upon the depth to the water table as well as soil properties. The distribution of water is extremely important in the agrotechnical management of drip irrigated crops, rates of evaporation and transpiration, the choice of proper combination of drip discharge rate and number of drippers per plant or unit length of row, the arrangement of drippers in the field and the distance between them.

2.5 Saturated Soil Water Flow

When water is applied at the soil surface it enters the soil profile and changes the water content distribution with depth. Over time, several wetting zones can be distinguished namely; saturated, transition, transmission, wetting zone and wetting front. The saturated zone is a thin layer near the soil surface while the transition zone is one of decreasing water content between the saturated and nearly saturated transmission zone.

The discharge rate (being the volume flowing through the soil column per unit time) is directly proportional to the cross-sectional area and to the hydraulic head drop and inversely proportional to the length of column (Hillel 1982b; 1971). Since soil pores vary in size, shape, and orientation, the actual flow velocity in the soil is highly variable. The ability of soils to retain and transmit water is measured by the hydrologic properties which in turn are determined by the geometry of the pore space.

Hydraulic gradient is the driving force and conductivity is an exclusive property of the soil depending on both soil and fluid properties that include total porosity, distribution of pore sizes and tortuosity (pore geometry), fluid density, viscosity and is greatest at the wetting front zone of water entry into an originally dry soil.

Quantitative description of water flow through a porous medium as given by Darcy (1856) is cited by Marshall and Holmes (1988) and Hillel (1971). Whilst the hydraulic conductivity of a saturated soil of stable structure is constant as the whole pore space is always filled with water. The contrast holds for unsaturated soil where it is likely to change continuously in response to the changes of matric potential, the hydraulic gradient implying changes in soil-water content.

2.5.1 Ground water Table

Water is present in every soil profile but the amount varies with time and space as a result of supply and demand by its environment. A high ground water table causes excess water in the root zone which can cause adverse effects on production of crops by reducing the soil volume accessible to plant roots.

Excess soil moisture also prevents the carbon dioxide formed by plant roots and other organisms from being exchanged with oxygen from the atmosphere; a process known as aeration (Van de Goor, 1979). Without aeration the root development and uptake capacity for water and nutrients of most plants is reduced. Most arable crops e.g root crops, cereals, and fruit trees require well drained soils for good aeration (Nwadukwe *et al.,* 1989; Don Nir, 1982).

A water table is the upper limit of a waterlogged soil (FAO, 1986). Its position depends on; amount of rainfall, soil hydraulic conductivity, the depth to the impermeable layer and other factors such as rate of plant water use, deep seepage, and soil stratification (Ochs *et al.,* 1983). Ground water is recharged by percolation through the unsaturated soil zone; and the position of its surface determined by the relative rates of recharge versus outflow. Reciprocally, the position of the water table affects the moisture profile and flow conditions above it.

Nugteren (1970) reported that adhesion in soil layers in the vicinity of a ground water table induces capillary action whereas outside reach of the water table these forces cause a distribution of any concentration of soil water. The moisture stress due to adhesion represents suction and therefore the liquid water is mechanically under tension. The entire complex of forces caused by the interaction of soil particles and soil moisture constitutes the matric forces. When water is made to infiltrate through the soil profile at a steady state that is less than the saturated hydraulic conductivity, a new profile of water content is eventually established. Incase of no downward soil water flow the whole soil above the water table is an equipotential volume (Maesschalck *et al.*, 1979).

By definition, the soil is saturated when the downward flux is equal to the saturated hydraulic conductivity, K and possesses its maximum water content at all depths (Childs, 1969; Childs and Young, 1974). At saturation, the matric potential is zero and the hydraulic potential equals the gravitational potential. Above the ground water table two zones can be distinguished; a nearly saturated zone and a zone with moisture content near field capacity into which ground water rises by capillary rise (Driessen, 1986). The latter zone is called the capillary fringe (Luthin, 1966). James (1988); Lambert and Rycroft (1983) have indicated that voids within the zone of saturation are completely filled with water; while the zone of aeration consists of voids occupied by water and air. In a narrow zone above the water table, pores fill by capillary rise from the ground water. In the lower part of this capillary fringe, pores are filled with water making it as saturated as the zone below the water table level.

According to Lambert and Rycroft (1983), the soil moisture content in the upper soil layer (down to 0.5-1.0 m) is particularly variable due to differences in daily weather conditions especially rainfall. Deeper down the soil profile, variations in soil water content occur over a longer time in parallel with seasonal weather changes. The height to which this capillary fringe extends depends on the depth of the ground water table and the texture and structure of the soil. In the capillary fringe, both aeration and water supply are favourable and the water requirements of the plants may be partly or totally fulfilled by this source.

If water flows vertically upwards from the water table, explicitly to the soil surface where it evaporates, the flow can mathematically be represented according to Hillel (1982b) as:

$$-E = K\frac{d\theta}{dz} \qquad (2.3)$$

Where

E = Evaporation rate at the soil surface (a positive quantity, assuming steady state conditions and no change in water content anywhere with time.

$d\theta$ = Change in water content.

K = Saturated hydraulic conductivity.

dz = Change in depth.

A positive hydraulic head allows upward water flow from the ground water table to the point with a matric suction. This flow is called capillary rise, CR. If matric suction is less than the gravitational potential, the resulting total hydraulic head is negative and drives downward water flow from the rooted soil surface, RD to the ground water table lower in the soil profile. The downward flow is called percolation, D. Since water flows only in one direction at a time then CR = 0 if D > 0 and D = 0 if CR > 0. The rate of influx into the potential root zone part of the soil profile is then represented by the water balance equation CR - D (Driessen, 1986).

When there is a shallow water table but no strong upward movement of water in the soil resulting from evaporation at the soil surface, an equilibrium situation will be reached between upward movement as a result of capillary rise and downward movement because of the gravitational pull (Groenevelt and Kinje, 1980).

If matric suction is compensated by an equally high but negative gravity head g_z, then there is neither capillary rise nor percolation. A zero flux plane (a plane in the profile where the hydraulic gradient is zero and which divides the profile into zones of flux moving in opposite directions) exists in such a point in the soil profile where CR - D = 0. At this point of the soil profile, the soil water suction is equal to the air-entry value for the particular soil. Frequently, this boundary is diffuse and scarcely definable especially when affected by hysteresis (Hillel, 1971). The net result of flow through the lower root zone boundary (CR - D) includes a change in ground water depth, dz (Maesschalck et al., 1979).

For practical purposes, where the ground table is shallow and time under consideration (dt) short, it is assumed that the soil moisture content of the subsoil increases linearly with depth from SM_{ϕ} at depth RD to SM_0 at depth Z_t. Driessen (1986) represented this situation as illustrated by line 'A' in Figure 2.11.

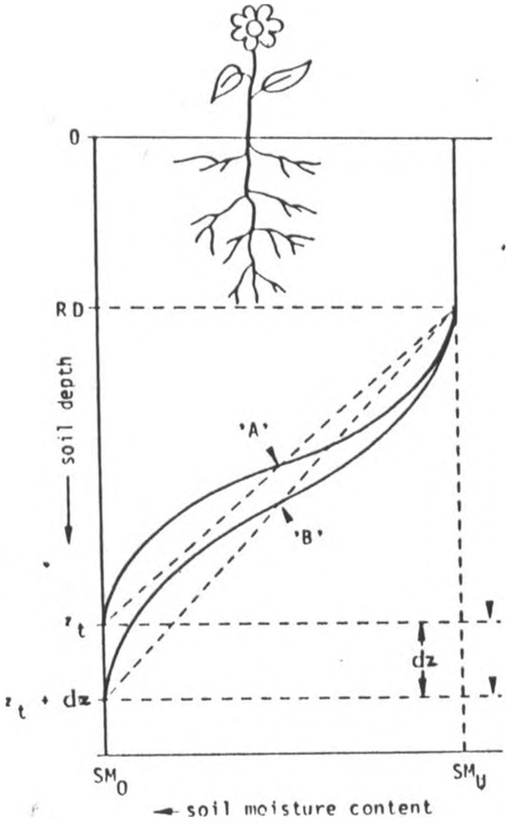

Figure 2.11. Schematic representation of soil matric suction, ϕ at various depths in the soil influenced by ground water table (after Driessen, 1986).

Further, he stated that incase of capillary rise, the water moves into the root zone causing the ground water table level to drop and simultaneously a new moisture profile is established over the subsurface layer between RD and Z_t + dz (Figure 2.11, line 'B'). The flow through the lower root zone boundary, (CR - D) x dt is equal to the surface area under line 'A' diminished by the quantity of water left in the layer between RD and (Z_t + dz) i.e the surface area under line 'B'. Kessler and Oosterban (1980) noted that a change in water table elevation is accompanied by a change in soil moisture content of the entire soil profile and in general the effective soil porosity decreases as the water table rises.

If hydrological, topographic, and soil conditions prevent the drainage of areas with a shallow water table, these areas should be used for crops that can benefit from such conditions (Landon, 1984; Van de Goor, 1979). In the drainage of excess water, a distinction can be made between the drainage of the soil surface, the root zone and ground water (Van de Goor, 1979; Nugteren, 1970). Good aeration and moisture conditions throughout the greater part of the soil profile stimulate growth and development of roots in all directions. The resulting extensive, deep root system explores a large soil volume for water and nutrients. In well drained soils, the deep root system may advantageously withdraw water from the capillary fringe of the ground water (James, 1988). The average depth to which the roots of a number of field crops penetrate in a well drained soil with an adequate moisture supply is presented in Table 2.1.

Table 2.1. Average depth of root penetration of crops under optimum soil moisture conditions (after Van de Goor, 1979).

Crops	Depth (cm)
Bulb crops, onions, lettuce.	30 - 60
Pasture grasses, cabbage, Spinach, beans, strawberries, potatoes, carrots, egg plants.	60
Capsicum spec., squash.	60 - 90
Coconut, oilpalm, datepalm.	60 - 120
Cotton, lima beans.	120
Maize, flax, small grains, sugar beet, melons.	150 - 180
Alfalfa, sorghum, sudan grass, steppe grasses, sugar cane, deciduous orchards, citrus orchard.	150 - 210

Raghunath (1987); Lambert and Rycroft (1983) noted that the downward soil water flow in field soils may be impeded due to occurrence of poorly permeable, dense layers while stratification may impede downward flow of excess water which may lead to perched ground water and near saturated soil moisture conditions above the water table. Where this occurs, horizontal gradients for water movement may exceed the vertical gradients resulting in lateral flow (referred to as interflow). Movement of soil water can also be impeded by the minuteness and tortuosity of the flow paths, which in the unsaturated zone are partially filled with water and air (Marshall and Holmes, 1988).

Van de Goor (1979) indicated that a great number of crops especially annuals have about 70% of the root volume in the first 30 to 60 cm below the soil surface. He noted that trees susceptibility to poor drainage depends on their age and the season and that potential yields of fruits are only obtained from trees growing on soils with a water table deeper than 1 m.

Where waterlogging is a problem (and salinity exists) artificial drainage becomes necessary. In such a situation the ground water table must be controlled at a minimum elevation so that sufficient upward soil water flow will reach the centre of the crop rooting zone (Nugteren, 1970). Occurrence of such situations in irrigated agriculture has prompted many studies of the minimum permissible water depth.

Marshall and Holmes (1988) reported that work by Talsma (1963) indicated that the water table should be kept deeper than 1.5 m in most soils unless heavy leaching could be employed from time to time. Nugteren (1970) reported that supply from ground water table of soil moisture to potential crop rooting zone become important when the water table level is within 1-2 m below the ground surface. He further indicated that evapotranspiration should be limited to 4 mm/day provided the ground water depth and soil permeability are adequate. He observed that the soil must provide a capillary rise of at least 60 cm for the required water supply to the crop rooting zone. This restricts capillary rise to fine textured sandy and loamy soils. Michael (1978) reported that many investigations have shown that capillary rise from a free water table can be an important source of soil moisture for crops only when its level is within 60 to 90 cm of the crop rooting zone.

According to Ragab and Amer (1986); Doorenbos and Pruit (1977) the contribution of ground water is determined by its depth below the crop rooting zone, capillary properties of the soil, soil water content in the root zone, evapotranspiration demand and the plant root system. For heavy soils, the distance of movement is high and the rate low while for coarse textured soils the distance of movement is small and the rate high.

Ragab and Amer (1986) quantified water table contribution to crop water requirements in three approaches:

1. Capillary flux computed from Darcy's law using soil water potential gradients measured at different soil depths.

2. Soil water balance either using lysimeters or by taking the water table contribution as the difference between estimated evapotranspiration values and soil water depletion in the field.
3. Using the chloride in the ground water and the increased chloride concentration in the soil above the water table to calculate the equivalent water depth necessary to affect this change.

According to Jones *et al.* (1981) and Shalhevet *et al.* (1981) ground water changes are most variable in arid regions and emphasizes its importance in providing both seasonal and long term carry over storage of soil moisture.

Where land surface elevation varies, as well as where amount of infiltration water supply varies spatially, the water table depth can vary and at times intersect the soil surface emerging as free ponding water.

Constant water table level indicates equal inflow and outflow rates. While on the other hand a rise or fall indicates a net recharge or discharge respectively. Such vertical displacements of the water table occur periodically under a seasonally fluctuating regime of rainfall or irrigation and can also be due to barometric pressure changes; hence ground water flow can geometrically be complicated where the soil profile is layered or anisotropic (i.e. where sources and sinks of water are distributed unevenly; Hillel, 1971). Nugteren (1970) noted that as long as the evapotranspiration exceeds rainfall, water is supplied to the ground water reservoir in such a degree that the total volume hereof remains approximately constant.

2.5.2 Capillary Rise

Capillary rise can be regarded as the upward flow of water from a water table or from lower soil profile layers with higher soil moisture content. Above a water table, matric suction will generally increase with height and the number of water filled pores will decrease accordingly. Hillel (1982b) remarked that the rate of capillary rise can mathematically be represented by the modified Darcy equation:

$$v = K \frac{dh}{dz} - K \qquad (2.4)$$

Reworking this equation results in the following integral for the height of capillary rise, z;

$$Z = \int_{h=0}^{h=z} \frac{K\theta}{V + K\theta}\, dh \qquad (2.5)$$

The K-h relation is an important characteristic for the moisture flow in the unsaturated soil. At low values of h (i.e. high moisture contents, near saturation) K is approximately constant up to the air entry point (where the pF curve starts to become flatter). Where soil moisture content drops below air entry point, the larger pores empty first and the moisture flow takes place through increasingly smaller pores. Thus K decreases rapidly with increasing h (with the 4th power of the pore diameter) and the flow is then referred to as capillary flow. At still lower moisture contents (or higher h values), capillary flow ceases and water transport takes place as a film flow along the outer surface of the soil particles.

If the quality of the ground water is suitable for irrigating field crops, the capillary water becomes an important contribution to the crop water requirements and this amount need not be supplied through irrigation.

Generally, soil water conditions are dynamic rather than static and in the presence of a water table does not attain equilibrium (or steady state conditions) even in the absence of vegetation since the soil surface is subject to the evaporating action of the ambient atmosphere (Hillel, 1971). Rose (1966) indicated that the relationship between water content and soil water matric suction is not unique but depends on the previous history of water intake (adsorption) or withdrawal (desorption).

Ragab and Amer (1986) reported the use of a model that utilizes the relationship between hydraulic conductivity and water content, depth of water table below the crop rooting zone and the matric suction at the bottom of the root zone to calculate capillary flux.

Hence according to Equation 2.5, the height of capillary rise is one above the water table where a given steady upward flux can be maintained for a given matric suction at that height. Reicosky *et al.* (1976) noted that the magnitude of upward flux into the crop root zone depends on soil water potential gradients and soil hydraulic properties and that the downward soil water flux at the bottom of the root zone decreased as evapotranspiration increased under similar environmental conditions.

In strongly permeable soils with a shallow water table, particularly in semi arid areas where the evaporative demand is high, accumulation of considerable quantities of soluble salts at or near the soil surface is undesirable. Keulen and Wolf (1986) reported that cropping normally required that the ground water table be kept at some depth below the soil surface and where capillary rise cannot cover evaporation losses, a very high matric suction builds up in the upper few centimetres of the soil and a thin air dry mulch layer is formed. Above the water table, matric suction generally increases with height and the number of water filled pores decrease accordingly. The rate of capillary rise generally decreases with time as the soil is wetted to greater height.

Driessen (1986) gave the steady state solution of the universal flow equation enabling the calculation of capillary rise CR as:

$$CR = K\psi\left(\frac{d\psi}{dz} - 1\right), for: Z_t > Z > RD \qquad (2.6)$$

As K ψ is described by different equations for low and high suction conditions, the integration of Equation 2.6 has two ψ ranges. For the low suction range ($\psi < \psi_{max}$), the relation between CR, ψ and the flow distance (Z_t - RD) is elaborated by anges. For the low suction range ($\psi < \psi_{max}$), the relation etween CR, ψ and the flow distance (Z_t - RD) is elaborated by

ijtema (1969); whose equation in a slightly adapted form because the ψ range below air entry point is not separately onsidered) is as follows:

$$CR = \frac{K_o(e^{-\alpha\psi} - e^{-\alpha(Z_t - RD)})}{e^{-\alpha(Z_t - RD)} - 1} \qquad if \quad \psi < \psi_{max}. \qquad (2.7)$$

he soil constants Kθ, α, and ,a, in Equation 2.7 are given in able 2.2 for various soil textural classes.

able 2.2. Values of Suction limit, ψ_{max}, saturated hydraulic conductivity K_θ, and constants ,a, and α for various soil texture classes (after Rijtema, 1969).

oil exture	ψ_{max} (cm)	Kθ (cm/day)	a ($cm^{2.4}$/day)	α (cm^{-1})
oarse Sand	70	1120.0	0.080	0.224
ine Sand	175	50.0	10.9	0.0500
oamy Sand	200	26.5	16.4	0.0398
ine Sandy Loam	290	12.0	26.5	0.0248
ilt Loam	300	6.5	47.3	0.0200
oam	300	5.0	14.4	0.0231
oess Loam	130	14.5	22.6	0.0490
andy Clay Loam	200	23.5	33.6	0.0353
ilty Clay Loam	170	1.5	36.0	0.0237
lay Loam	300	0.98	1.69	0.0248
ight Clay	300	3.5	55.6	0.0174
ilty Clay	50	1.3	28.2	0.0480
vy Clay	80	0.22	4.86	0.0380
eat	50	5.3	6.82	0.1045

or the high suction range, the relation between CR, ψ and (Z_t - D) has to be calculated by numerical integration (which does not onsider water flow over the distance (Z_t - RD) using the quation:

$$CR = K\psi\left(\frac{\psi}{Z_t - RD} - 1\right) \qquad (2.8)$$

here

$K\psi$ = Hydraulic conductivity at matric suction, (cm/day).

$K\theta$ = The texture specific saturated hydraulic conductivity (cm/day).

$K_\psi = a\,\psi^{-1.4}$.

α = A texture specific empirical constant (cm^{-1}).

a = A texture specific empirical constant ($cm^{2.4}$/day).

ψ_{max} = A texture specific suction limit (cm).

ψ = Mean suction in the increment (Z_t - RD).

Z_t = Ground water depth at the beginning of time interval, t (cm).

When the value of soil matric suction is lower than that of the gravity head, the total dynamic head is negative and water movement would be downwards. In such a situation, the rooted surface soil losses water to the subsoil and eventually to the ground water table through percolation D, whose rate is largely dictated by the gravity forces. In such a situation, according to Driessen (1986), the role of the transmission zone is taken over by the root zone with matric suction ψ so that percolation would proceed at a rate, $D = K\psi$.

Therefore there is neither capillary rise nor deep percolation if the matric suction is compensated by an equally high (but negative) gravity head g_h and in that case the total hydraulic head is nil (no driving force, hence no flow).

2.6 Soil Water Balance

The soil water balance accounts for all the water leaving the soil profile whether it be through evapotranspiration or deep flux; either upwards or downwards (Stone, 1976). If soil moisture uptake by the crop roots is not replenished, the soil dries out to such an extent that the plant wilts and finally dries.

which it reacts by curbing its daily water consumption through partial or complete closure of its stomata.

Any model of the production capacity of crops must therefore keep track of the soil water potential to determine when and to what extent a crop is exposed to water stress. This is often done with the help of a soil water balance equation; which compares for a given period of time, incoming water in the rooted soil with outgoing water and quantifies the difference between the two as a change in the amount of soil moisture stored.

The various items entering into the water balance of a hypothetical rooting zone were illustrated by Hillel (1982a) as shown in Figure 2.12.

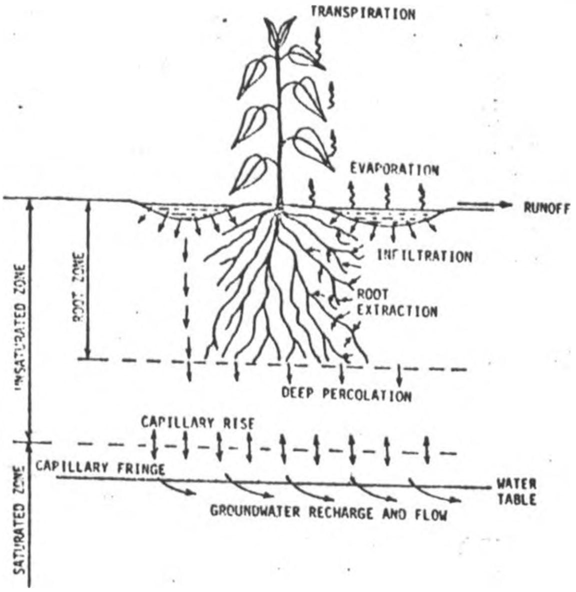

Figure 2.12. Schematic illustration of the water balance of a root zone (after Hillel, 1982a).

Driessen (1986) defined the root zone as a continuous soil layer with an upper boundary (the soil surface) and a lower boundary at a depth corresponding to the crop rooting depth. Water enters and leaves the root zone via these two boundaries but is also removed directly from the interior parts of the root zone viz the water uptake by plant roots which is almost entirely discharged as transpiration. According to Driessen (1986) the rate of change in soil moisture content of the root zone can thus be described with a water balance equation of the following form:

$$RSM = \frac{IM + (CR - D)\ T}{RD} \qquad (2.9)$$

Where

RSM = Rate of change in moisture content of the root zone (cm^3/day).

IM = Rate of net flux through the upper root zone boundary (cm/day).

(CR - D) = Rate of net influx through the lower root zone boundary (cm/day).

T = Rate of crop evapotranspiration (cm/day).

RD = Depth of the root zone (cm).

Monteith (1991) and Shanan *et al.* (1980) expressed the general hydrological balance equation for evaluating soil moisture changes as:

$$P - D - E = SM_{t1} - SM_{t2} \qquad (2.10)$$

Where during any particular time;

P = Rainfall (mm).

D = Drainage (mm).

E = Evaporation (mm).

SM_{t1} and SM_{t2} are soil moisture deficits at the end and beginning; respectively of a particular time interval (mm).

Gregory (1991); Raats and Warrick (1983) indicated that at any point in the soil, the change in water content with time is equal to the net flux towards that point minus the rate of uptake by plant roots. Further, it was indicated that for the root zone, the mass balance for the water requires that:

$$\frac{ds}{dt} = (P + U + I) - (E + T + D) \qquad (2.11)$$

Where

P = Rate of water supply from rainfall (cm/day).

U = Rate of upward (capillary) flow into the root zone (cm/day).

I = Rate of irrigation water supply (cm/day).

E = Rate of evaporation (cm/day).

T = Rate of transpiration (cm/day).

D = Drainage out of the root zone (cm/day).

Payne *et al.* (1991) indicated that where runon and runoff are negligible, the field water balance equation reduces to:

$$ds = R - (ET - CR + D) \qquad (2.12)$$

Where

ds = Change in soil water storage between measurements (mm).

R = Cumulative rainfall (mm).

ET = Evapotranspiration (mm).

CR = Capillary rise (mm).

D = Deep percolation (mm).

Figure 2.12 represents the various incoming and outgoing fluxes of water in a crop-soil-atmosphere system. The figure illustrates that supply of water at the upper root zone boundary is composed of rainfall (at a rate P, in cm/day); irrigation (at a rate I, in cm/day) and possibly water that was stored on top of the soil surface (at a rate DS, in cm/day). There is also loss of water from the soil surface, viz as evaporation (at a rate E, in cm/day). In accordance with the above, Driessen (1986) expressed the actual rate of water infiltration through the upper root zone boundary as: $IM = P = I - E + DS - SR$ while Lal (1991); Kessler and Oosterban (1980) expressed the water balance of the unsaturated soil zone as: $P + I - SR - ET - (D - CR) = dS_{sm};$

Where

DS = Rate of decline of surface storage (cm/day); defined positive if surface storage decreases and negative if the surface storage increases.

ET = Evapotranspiration rate (cm/day).

SR = Rate of surface runoff (cm/day).

Thus the net rate of water supply at the soil surface is (P + I + DS - E) cm/day. This net surface supply rate may exceed the maximum rate which water can infiltrate in that particular soil (IMmax.). In the first instance, the excess supply is stored on the surface. The maximum surface storage capacity (SSmax., in cm) depends on the soil surface properties and the slope angle of the land (Driessen, 1986). If excess supply exceeds the surplus storage capacity (SSmax. - SSt)/dt, the remaining water leaves the system as surface runoff (SR, in cm/day).

At the lower boundary of the root zone, (i.e. at depth RD), vertical flow of water between root zone and ground water may take place (Driessen, 1986). Water flux from the ground water into the root zone is termed capillary rise, while water loss from the root zone to the ground water is called downward percolation. Stone (1976) noted that water flux accumulation in the 120 to 150 cm layer could be used to estimate downward water loss using the soil matric suction versus soil water content relationship (i.e. pF curve).

Shanan *et al.* (1980) reported that evaporation from the soil surface is a function of the energy input; hence can be measured directly or evaluated from temperature, net radiation and/or pan evaporation data. Raats and Warrick (1983) reported that evaporation is a function of the soil surface wetness as well as crop cover and that it increases with soil surface wetness; with subsequent decrease roughly proportional to the square root of time. When the soil surface is wet, the rate of evaporation is governed by factors external to the soil. Shanan *et al.* (1980) further indicated that when the soil is dry and the vapour pressure at the soil surface boundary is nearly equal to that of the atmosphere, the rate of water movement to the surface limits the rate of evaporation. Dry soil conditions are therefore favourable for minimizing evaporation losses.

Kessler and De Ridder (1973) noted that upward movement of soil water resulting from evaporation at the soil surface would be a function of soil moisture content and that evaporation from the soil volume will have a peak value when the surface is saturated.

According to Raats and Warrick (1983) transpiration rate is closely related to the surface area of leaves; termed as the leaf area index and along with solar radiation and nutrients, water is a crucial input for successful crop production. As a result, the capacity of the soil to absorb and retain water in the root zone is often crucial as an excess supply can cause water loss through runoff; and leaching of nutrients out of the root zone as well as poor aeration and traficability.

2.7 Irrigation Efficiency

Phene *et al.* (1989) indicated that the availability of adequate food and fibre for future generations will depend greatly on our ability to manage and conserve our soil, water and air resources. To meet these responsibilities, it is necessary to improve our ability to accurately measure variables which affect the status of these resources.

Batchelor (1984) noted that drip irrigation offers small holders a practical method of improving irrigation efficiency and of increasing the yields of horticultural crops, orchards and field crops by matching frequent low volume water application to the uptake rate of the crop. Compared to other conventional irrigation methods, drip irrigation offers small holders many potential advantages; particularly where water and agricultural land are expensive and limited.

Howell *et al.* (1981) reviewed over fifty papers on crop response to drip irrigation and concluded that it compared favourably with other irrigation methods, both as regards crop yield and water conservation. But in terms of economic return over a number of years, the success of the irrigation system depends on the choice of appropriate equipment, proper maintenance and management. James (1988) indicated that crop yield experiments have shown wide differences varying from little to no difference, to as much as 50% increases with drip irrigation compared to other irrigation methods with some evidence that quality of some crops is improved.

The aim of irrigation practice is to ensure that the crop has an adequate supply of water in its root zone for the production of optimum yields. Irrigation design and management are concerned with two main problems of timing and quantity of water to apply. In soils capable of storing a limited amount of water; and of this only part is available to the crop, water must be applied before this portion is wholly depleted. Experimental findings by Stegman *et al.* (1983) indicate that yields of many crops tend to be near their maximum when root zone available water is not depleted by more than 40% of the maximum soil moisture deficit between irrigations.

Shmueli *et al.* (1973) emphasized that the practical objective in irrigation is the determination of the minimum water quantity and the proper irrigation interval needed to produce the highest yield. The problem of timing involves the computation of available moisture and rate at which this is depleted, while the problem of the amount of water to be applied is to determine the quantity which will restore the soil moisture to more favourable conditions for the crop which is usually the maximum the soil can store in the rooting zone (Withers and Vipond, 1974). Hansen *et al.* (1979) indicated that three major considerations influence the timing of irrigation and how much water is to be applied. These are:

1. Water use of the crop.
2. Availability of irrigation water.

3. Capacity of the crop rooting zone to store water.

In the production of irrigated horticultural crops, it is essential to base the timing of irrigation on observations of soil water potential. Any variations in soil physical properties of different soils, may change soil moisture percentage or content at permanent wilting point of any particular crop.

Because tensiometric measurements eliminate such variables as soil type, salinity, variations in rooting depth and activity, crop coefficients in terms of water use and measures the true effect of weather factors on actual evapotranspiration, it leads one to a solid base of information for proper irrigation scheduling (James, 1988; Levin *et al.*, 1973b). This shows the need of making soil water potential measurements at different depths (at least two) within the crop rooting zone in order to have a fair estimate of the soil water status (Michael, 1978).

Hanks and Ashcroft (1980) suggested that the upper tensiometer should be in the zone of maximum root activity and the lower one near the bottom of the active root zone. For most crops, it is time to irrigate when the top tensiometer reads -300 to -500 cm soil water potential and the lower one begins to show some drying. Drip irrigation systems have made it possible to make productive use of more marginal soils (Pogue and Pooley, 1985) and hence irrigation management should be based on an accurate and direct measurement of soil water.

Soil water is a necessary component of the soil environment in addition to adequate nutrient supply, good aeration, optimum temperature; jointly which make the varied life forms in the soil possible (Sessanga, 1982). Increased food production per unit water consumed could be achieved on existing irrigation projects by increasing water use efficiency. Jensen *et al.* (1983) emphasized the optimization approach to maximize the ratio of crop yield to irrigation water applied by maximizing the yield per unit area and at the same time reducing seasonal amount of irrigation water requirement. Escalating energy costs and limited energy supplies are creating rapid changes in operating costs of irrigation systems, and irrigation designers should use an energy escalating factor to determine realistic operating costs.

Drip irrigation systems use less water because of less deep percolation, runoff and evaporation (i.e. higher water application efficiency) and irrigate only a portion of the potential crop rooting zone. Drip irrigation systems generally have lower energy requirements than do sprinkler systems because of reduced water use and lower operating pressures. Soil water management practices aim at satisfactory rain or irrigation water acceptance by the soil, transmission through the soil matrix and finally sufficient soil life forms' usage.

The adequacy of irrigation is based on the percentage of the field receiving sufficient water to maintain the quantity and quality of crop production at a 'profitable' level (James, 1988); which requires crop, soil and market conditions to be specified.

Uniformity of water application is critical in drip irrigation and soil moisture content must be maintained at a fairly constant level. Field observations on irrigation scheduling can provide a continuous check on emission uniformity by looking at the general appearance of plants and size of surface wetting pattern (Hardee and Benjamin, 1977). Sammis *et al.* (1990) developed a trickle irrigation scheduling model based on a water balance approach to water flow and with increasing soil depth represented by an increasing ellipsoid.

Proper management of irrigation systems require some form of irrigation scheduling especially at locations where part of the water requirements of the crop can be supplied by other sources like ground water, rain, irrigation. Sammis *et al.* (1990) and Shao-hua Li *et al.* (1989) noted that irrigation scheduling on a commercial basis was economically feasible.

Irrigation efficiency shows how available water supply is efficiently used with different methods of irrigation.

The efficiency of irrigation is dependent upon the selection of appropriate irrigation method considering the soil, topography, soil infiltration rate, water supply and other management factors (Batchelor *et al.*, 1990 and Faul, 1989).

The design of an irrigation system, the degree of land preparation and the skills of the irrigator are the principle factors influencing irrigation efficiency. Karmeli and Keller (1975) gave the following as some of the design criteria that affect drip irrigation efficiency:

(i) Efficiency of water filtration.
(ii) Permitted variations of pressure used.
(iii) Base operating pressure used.
(iv) Degree of flow (or pressure) control used.
(v) Relationship between discharge and pressure at the pump or hydrant supplying the system.
(vi) Allowance for temperature correction for long path emitters.
(vii) Chemical treatment to dissolve mineral deposits.
(viii) Use of secondary safety screening.
(ix) Incorporation of flow monitoring.
(x) Allowance for reserve system capacity or pressure to compensate for reduced flow due to clogging.

Water use efficiency (crop yield/evapotranspiration of cropped area) is influenced by crop and soil management practices. Storage of water in the soil profile greatly increases the water use efficiency especially of grain crops grown under conditions of limited water supply.

Water use efficiency could be increased by:

1. Maximising absorption of rainfall into the ground (i.e. eliminate surface runoff and use of water harvesting techniques).
2. Decrease any loss of moisture (i.e. evaporation, consumption of water by weeds, losses by subsurface flow and deep percolation).
3. Increase moisture reserve of plants.

FAO (1973) listed the following factors as among those that affect efficiency of water distribution:

(i) The maximum discharge variation of 10% from the average between drippers controlled by one header.

(ii) A sufficient initial pressure at the header in order to meet the cumulative head losses in the elements of the system; due to topography, emitter type filter and across flow regulators.

(iii) Successful checking of leakages and clogging.

The gross depth of irrigation equals the net depth divided by the water application efficiency. The main factors that affect water application efficiency are the uniformity of application and the amount of water lost in the least watered areas.

A primary objective of good drip irrigation system design and management is to provide sufficient system flow capacity to adequately irrigate the least watered plant. Therefore the relationship between the minimum and average emitter discharge within the system is the most important factor of the uniformity of application. This relationship is called emission uniformity.

The emission uniformity EU gives an estimate of the percentage of the average depth of water application. Taking these factors into account:

$$EU = \frac{100 \times Id_n}{TR \times Id} \qquad (2.13)$$

Where

Id = Gross depth of irrigation (mm).

Id_n = Net depth of irrigation (mm).

TR = Ratio of transpiration to water application.

EU = Emission uniformity.

Under good management, one can reasonably expect that approximately 10% of irrigation water will be needed for leaching or could be lost through deep percolation and evaporation. Water application efficiency, E_a may be expressed as:

$$E_a = TR \times EU \qquad (2.14)$$

Some emitter characteristics that affect water application efficiency are:

(i) Variation in rate of discharge due to manufacturing tolerances.
(ii) Closeness of discharge-pressure relationship to design specifications.
(iii) Emitter discharge exponent, x.
(iv) Possible range of suitable operating pressures.
(v) Pressure loss on lateral lines caused by emitter connections to the lateral.
(vi) Susceptibility to clogging, siltation, or build up of chemical deposits.
(vii) Stability of discharge-pressure relationship over a long period.

Even a well designed system that has high quality emitters requires good management to achieve high efficiency in irrigation. Maintaining the design pressure, keeping the filters clean and the emitters unclogged and applying the proper depth of water are the principal requirements of good management. In arid areas, a design value of TR = 0.9 is a reasonable management expectation. Excellent management may achieve a TR value of 0.95 provided the percentage of the area wetted and the water quality are both high (Karmeli and Keller, 1975).

In drip irrigation, the uniformity of water application depends completely on the uniformity of emitter discharge throughout the system. The variation in discharge between emitters is a function of pressure and emitter differences within the system. Vermeiren and Jobling (1980) defined localized or drip irrigation application efficiency, E_a as:

$$E_a = K_s \times E_u \qquad (2.15)$$

Where

K_s = Coefficient of deep percolation, evaporation and other water losses.

E_u = Coefficient of uniformity of water distribution.

Since water is conveyed by pipe network to a point where it infiltrates into the soil, the uniformity of discharge of individual distributors within the system gives a good idea of the uniformity of application. Potential water application efficiencies range from 75% to 90% with 70-80% as practical efficiencies in drip irrigation (Kaul, 1989).

Emission uniformity EU is generally used to describe the emitter flow variation for a drip irrigation unit or subunit. Emission uniformity can be a function of: 1. Hydraulic variation caused by elevation changes and friction losses along water distribution lines and, 2. Emitter discharge rate variation at a given operating pressure caused by manufacturing variability, clogging, water temperature changes and aging of system equipment (Bucks *et al.*, 1982). Vermeiren and Jobling (1980); Karmeli (1977) defined emission uniformity as the manufacturer's discharge ratio, adjusted for the number of water distributors per plant and expressed as a percentage, multiplied by the ratio of absolute minimum discharge rate determined from the nominal discharge rate, q versus head h curve; to the average distributor discharge rate, i.e.:

$$100 = \frac{q_{\min}}{q} \times M_r \, f(e), \text{ with } f(e) = 1 - \frac{1.27\,CV_f}{\sqrt{e}} \quad (2.16)$$

Where

$q_{\min}$ = Minimum discharge rate of distributors determined with minimum pressure within the nominal relationship of q and h (l/hr).

q = Average discharge rate of all distributors (l/hr).

CV_f = Manufacturer's coefficient of variation.

M_r = Manufacturer's discharge ratio (average of the lowest 1/4 to the average discharge rate of a test sample of distributors operated at a reference pressure head and estimated from CV_f).

Hence the equation can be expressed as:

$$EU = 100(1 - \frac{1.27CV_f}{\sqrt{e}})\frac{q_{min}}{q} \qquad (2.17)$$

Karmeli (1977) also recommended values of emission uniformity of 94% or more as desirable and stated that in no case should the design value be below 90%; and also expressed the overall water application efficiency of a system as:

$$E_a = K_s \ x \ EU \quad \textbf{OR} \quad \frac{10,000}{K_s \ x \ EU} \qquad (2.18)$$

Karmeli and Keller (1975) defined an empirical design EU for trickle irrigation system as:

$$EU = (1 - 1.27(C_{vm})n^{-1.5})(\frac{q_n}{q})100 \qquad (2.19)$$

Where

C_{vm} = Manufacturer's coefficient of variation.

n = Number of emitters per plant (with a minimum of one).

q_n = Minimum emitter discharge rate computed from the minimum pressure (l/hr).

q = Mean emitter discharge rate (l/hr).

The emission uniformity is based on the ratio of q for the lowest 25% of the emitters to the average discharge rate and increases as more emitters are added to each plant. Nakaya and Bucks (1986) reported the development of a coefficient of design uniformity C_{ud} based on statistical analysis of the discharge rate deviations from the average rate as:

$$C_{ud} = (1 - 0.798(C_{vm})n^{-1.5})100 \qquad (2.20)$$

Both equations 2.16 and 2.17 stress the importance of manufacturing variability and the number of emitters per plant in influencing emission uniformity. Wu and Gitlin (1977) are reported to have proposed another parameter called emitter flow variation, q_{var}:

$$q_{var} = (1 - \frac{q_n}{q_m})100 \qquad (2.21)$$

Where, q_n and q_m are the minimum and maximum emitter discharge rates.

Bralts *et al.* (1981) illustrated that for a single chamber trickle irrigation tubing the hydraulic and manufacturing variabilities were independent and that the total coefficient of variation C_{vt} can be expressed as:

$$C_{vt} = (C_{vh}^2 + C_{vm}^2)^{1.5} \qquad (2.22)$$

Where, C_{vh} is the hydraulic coefficient of variation.

Since crop quality and productivity may be affected by both excess watering and underwatering, a uniformity of application parameter termed absolute emission uniformity EU_a has been developed (Karmeli and Keller, 1975). During field tests of emission uniformity, minimum four locations along four different lateral lines uniformly spaced throughout a representative block of laterals is selected. Field emission uniformity EU' is a ratio expressed as a percentage of the average emitter discharge rate from the lowest 1/4 of the field data to the average discharge of all emitters. The average of the lowest 1/4 was selected as a practical value for the minimum discharge rate (as recommended by the US Soil Conservation Service for field evaluation of irrigation systems). Expressed as an equation:

$$EU' = 100 \frac{q'_n}{q'_a} \qquad (2.23)$$

Where

EU' = Field test emission uniformity, %.

q'_n = Average of the lowest 1/4 of the field emission rates, l/hr.

q'_a = Average of all the field data on emitter discharge rate, l/hr.

The field EU'$_a$ is a concept of the overall uniformity of an operating system. It is a function of the minimum, average and maximum emitter discharge rate expressed as:

$$EU'_a = 100\ x\ 1.5\left(\frac{q'_n}{q'_a} + \frac{q'_a}{q'_x}\right) \qquad (2.24)$$

Where

EU'$_a$ = Absolute field emission uniformity, %.

q'$_a$ = Average emitter discharge rate of all the emitters, l/hr.

q'$_x$ = Average emitter discharge rate of the highest 1/8 of the field data, l/hr.

Generally, the installation of an irrigation system and the application thereof to the fields must be economically justified and at the same time should serve a social purpose. The production value of a specific crop per unit m^3 of water as compared with a non irrigated yield is termed as the economic efficiency of irrigation (Nugteren, 1970). Pande (1989) reported that experiments (conducted at Mpau Rahun) with drip irrigation method gave a 15.47% increase in yield of cabbage with a water saving of 46.12%. Kaul (1989) indicated that the same yields are obtained if only 30% of the crop rooting zone is wetted, and the water should wet the soil not more than 60 cm depth in most cases. This water fills pores of the soil that are not more than 40% of the total soil mass in the root zone.

Bos and Nugteren (1982) indicated that efficient management of irrigation water will become more important as the competition for good quality water grows with the world's increasing population. Reliable determination of irrigation water requirements is vital in preventing wastage and in the attainment of maximum beneficial use. The application efficiency defined as the relation between the quantity of water supplied to the field inlet and the quantity needed to maintain the soil moisture above a minimum level required by the crop without significant negative effect on yields should be maintained at relatively high levels.

An effective system of irrigation scheduling is possible in areas with reliable consumptive use and meteorological data. Here, only periodic checks on soil moisture need to be made to ensure that irrigation is done before the soil moisture reaches the predetermined value or wilting point and that the application is no more than the remaining water holding capacity within the crop rooting zone. Hanks and Ashcroft (1980) and Michael (1978) suggested that making soil moisture determination measurements at different depths (at least two) within the crop root zone gives a fair estimate of the soil moisture status. Measurements of soil water potential are useful because they indicate the potential the plant must overcome to remove water from the soil and also indicates the direction of movement of water (Richards and Marsh, 1961). For practical use in irrigation scheduling, a tensiometer is an important instrument as it meets the requirements of quick, easy and repeated measurement without excess soil disturbance (Ah Koon *et al.*, 1990 and Hillel, 1982a).

In practice, at the peak water use design period, emitters are operated so as to keep the central portion of the wetted soil volume well above field capacity on medium and fine textured soils. The water distribution uniformity of new installations may be close to 90%. The potential water application efficiency usually declines appreciably with continued use. A more typical value of about 80% should be considered (Howell *et al.*, 1983).

Walker (1989) and Bralts *et al.* (1981) emphasized the importance of irrigation systems evaluation to obtain information that will assist engineers in designing other systems; determine how efficiently the particular system can be operated and where it can be improved; determine the efficiency of the system as it is being used and to obtain information that would enable comparison of various irrigation methods.

3.0 EXPERIMENTAL MATERIALS AND METHODS

3.1 Characterization of Soils at Experimental Site

3.1.1 Soil Properties

Soil sampling was done randomly at three sites; upper, middle and lower plots at the Experimental Site at intervals of 30 cm to a maximum depth of 60 cm down the soil profile for the determination of the basic physico-chemical soil properties (i.e. texture, hydraulic conductivity and bulk density). This was meant to explore any extreme soil variability at the Experimental Site. The preliminary results indicated that the soil consists of alternate layers of sandy loam, loam sand, sandy clay loam confirming it to be a fluvisol (Typic Ustifluvents); includes fluviatile and colluvial sediments. The soil depth of 60 cm is considered as most important for soil water extraction by most field crops as it contains the highest density of roots; greater than 66% (Hillel, 1971; Michael, 1978; Landon, 1984; Dasberg and Bresler, 1985).

More soil sampling was done at depth intervals of 30 cm up to a maximum depth of 150 cm at the upper plot. This was meant for further detailed soil characterization of the whole rooting depth (effective rooting depth of citrus taken as 120 cm). These soil samples were examined in the laboratory for the following soil properties: texture, bulk density, hydraulic conductivity, pH, porosity, available moisture, organic matter content and water retention capacity.

3.1.2 Soil Infiltration Rate

Infiltration tests were carried out at three locations within the upper plot to establish the instantaneous infiltration rate of the soil. The soil was initially wetted (to bring the soil moisture conditions to field capacity) by sprinkling water for about half an hour. An infiltration test using a double ring infiltrometer was then conducted for at least five hours per site. The double ring infiltrometer used had rings put in the soil to a depth of 10 cm and changes in water level monitored in the inner ring after some fixed time intervals of 15 minutes.

Plate 3.1. Measurement of instantaneous infiltration rate at Experimental Site.

3.1.3 Saturated Hydraulic Conductivity

Insitu saturated hydraulic conductivity (below the ground water table) was determined using the auger hole method for a two layered soil as described by Kessler and Oosterbaan (1980). To determine the hydraulic conductivity K_1 of the upper soil layer extending to a depth of about 40 cm from the soil surface, a hole 8 cm in diameter was bored into the soil with an auger up to a depth of 60 cm. Water was allowed to settle in the auger hole and the water table depth from the soil surface determined. When the water table level had settled, water was bailed out (using a bottle tied to a string) hence lowering the water level to a height h_2 which was noted. The ground water then begins to seep into the hole establishing a new water level h_1. The rate at which the ground water seeped back into the hole was monitored using a stop watch. The hole was then deepened up to the impermeable layer (175 cm below soil surface) and the above procedure repeated to determine the saturated hydraulic conductivity K_2 for the lower soil layer extending to the impermeable layer. Three replicates of each test were conducted at the investigation site.

The saturated hydraulic conductivity K_1 for the upper soil layer was determined using the equation:

$$K_1 = C_1 \left(\frac{\Delta h}{\Delta t}\right)_1 \qquad (3.1)$$

For the lower soil layer, saturated hydraulic conductivity K_2 was determined using the equation:

$$K_2 = C_o \left(\frac{\Delta h}{\Delta t}\right)_2 - K_1 \qquad (3.2)$$

Values for the constants C_1, C_2 and C_o were obtained from Appendix 3.1 (a) and 3.1 (b) respectively; where the meaning of the symbols in the two equations is also given.

3.1.4 Unsaturated Hydraulic conductivity

The unsaturated hydraulic conductivity versus soil matric suction function was developed from the equation given by Hillel (1982b) as:

$$K = \frac{a}{[b + (\psi - \psi_a)^n]} \quad for \quad \psi \geq \psi_a \qquad (3.3)$$

Where

K = Unsaturated hydraulic conductivity (cm/sec.).

ψ = Suction head (cm water).

ψ_a = Air entry suction (cm water).

a, b, n are constants; with a/b representing the saturated soil hydraulic conductivity.

The exponential parameter n characterizes the steepness with which K decreases with increasing ψ. For a sandy soil a = 1, $b = 10^{-3}$, $\psi_1 = 10$ cm and n = 3 (as given by Hillel, 1982b.

3.2 Instrumentation of Experimental Site

3.2.1 Calibration of Tensiometers

The four major parts; the ceramic cup, bourdon dial gauge, the jet and the glass tube (of the jet fill tensiometers; see Figure 3.1) were assembled in position. The tensiometers were filled with distilled water and tested for any leakage using a hand operated vacuum pump. The non leaking tensiometers were dipped into a bucket of clean water ensuring that the cups were adequately covered with water and the dial reading noted after about five minutes. For dials indicating a reading greater than zero, the dial hand was set to zero by adjusting the setting screw using a screw driver.

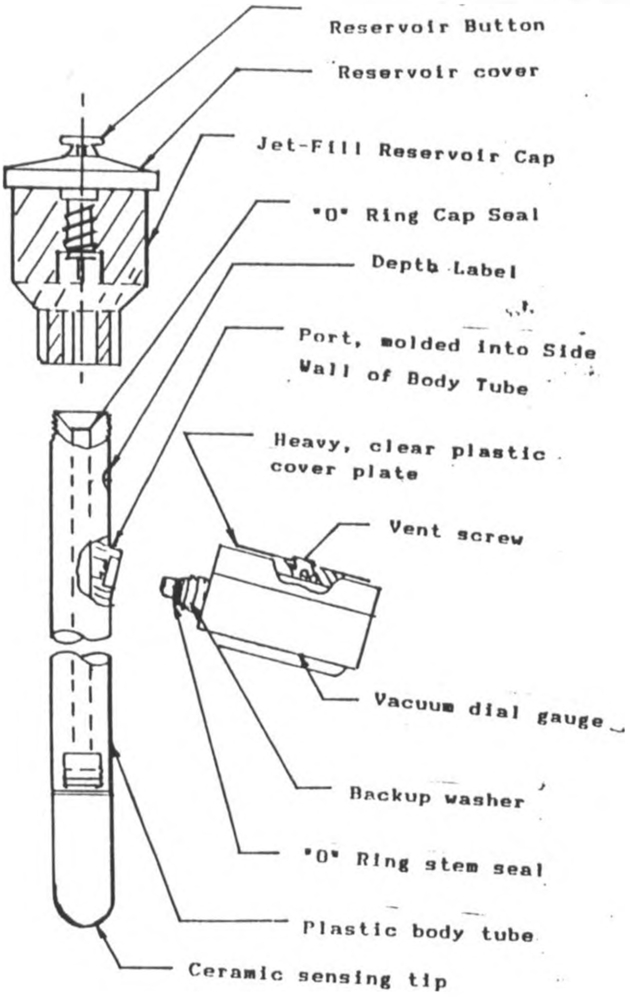

Figure 3.1. Jet Fill Tensiometer.

3.2.2 Installation of Instruments

Tensiometers

A hole was made upto the required installation depth by hammering a metal rod (of external diameter slightly larger than the tensiometer tube). The tensiometer was then filled with distilled water and checked against any possible leakage. The dial was also checked to ensure it was in good working order by dipping the ceramic cup in water (dial gauge reads zero) and then lifted out when the gauge registers a reading. The tensiometer was then dipped into the hole made just slightly deeper by about 2 cm; which was back filled to ensure some good hydraulic contact between the soil and the ceramic cup.

The hole was then back filled holding the tensiometer upright with some soil pressing to ensure the instrument was firm and in good contact with the soil. A few drops of soil moisture blue fluid were put into the tensiometer to curb any possible growth of algae and fungus on the ceramic cup; which also calls attention to accumulated air which should be released by pushing the reservoir button. The jet was then filled with distilled water and the tensiometer was ready for data recording. Regular inspection of the tensiometers was maintained throughout the data collection period adding more distilled water when necessary.

Rain gauge

A non recording rain gauge was used to record daily rainfall at the experimental site. To avoid splash rain water from the ground and plants getting into the gauge funnel, the rain gauge was installed at a height of about 1.0 m above the ground surface and supported on a firm, rigid metallic rod ensuring its rim was completely horizontal.

Drip Emitters

Button type, on-line, pressure compensating drippers were used. Four drip discharge rates of 2, 3, 4 and 8 l/hr were used in the experimentation.

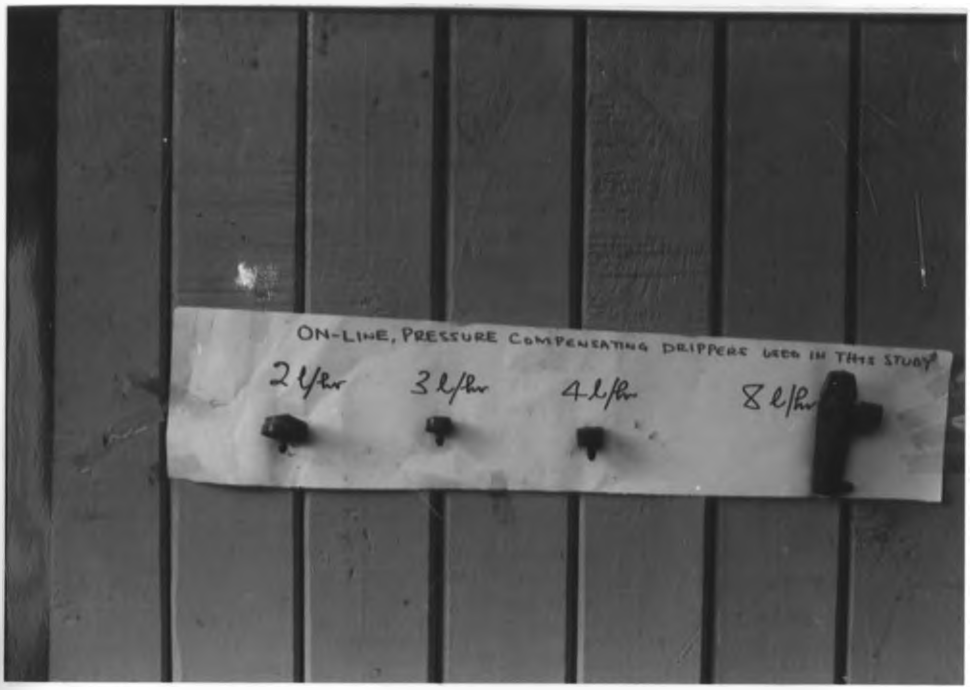

Plate 3.2. Four emission rate drippers installed at the Experimental Site.

Holes were made using a hand punch on a 16 mm (internal diameter) polyethylene tubing onto which the drippers were fixed. The tubing was connected to the water source via a 1" (2.54 cm) internal diameter pvc plastic pipe.

Observation Pits

Soil moisture pits of size 1.0 m by 1.5 m for observing the different drip wetting patterns were cut down the soil profile slightly beyond the maximum wetted depth. The wetted depth was marked with sticks at 5 cm intervals down the soil profile along the position of the dripper. At each of these 5 cm depths, the wetted radii (left and right of the centre line) were measured using a pocket measuring tape and data recorded for each test.

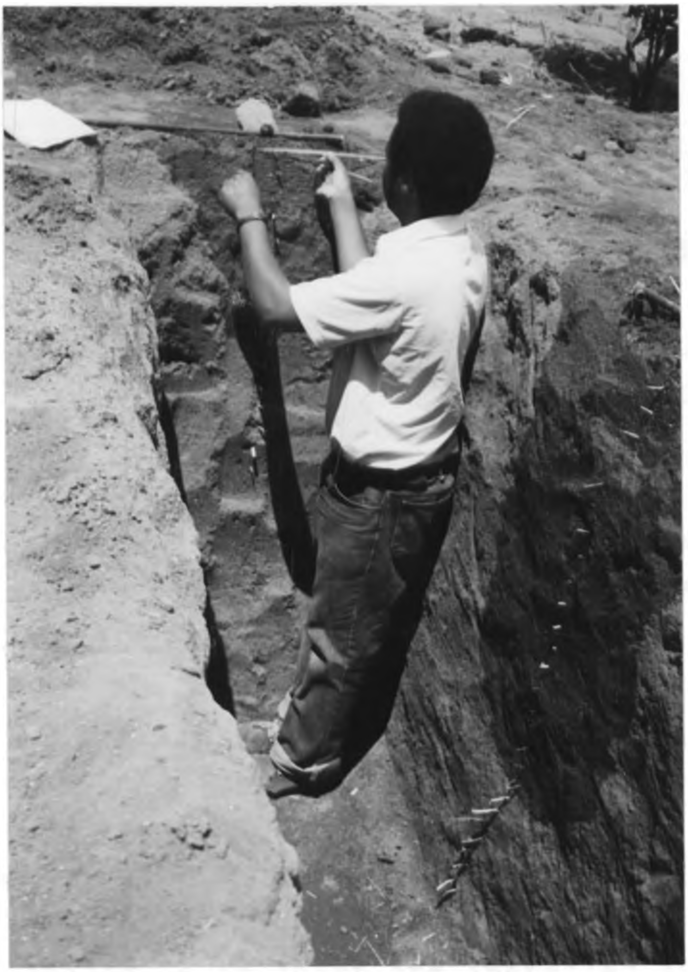

Plate 3.3. Soil Profile pit showing the wetted depth and graduations at 5 cm interval.

Double Ring Infiltrometer

The outer (buffer) ring was placed on a level ground at the test site. The inner ring was then placed inside and centred.

The top plate was placed on top and the rings fastened in position. Using a rubber hummer the rings were hammered down into the soil for about 10 cm. The top plate was then removed and the float measuring scale put in position. Water was put inside both rings at the same time and level.

3.3 Experimental Layout

3.3.1 Soil Wetting Pattern Plots

Experiments on monitoring the effect of drip discharge rates, emitter spacing, duration of water application and antecedent soil moisture on soil water flux and soil moisture distribution were conducted in the upper plot beside the soil sampling site.

The area was divided into six plots of about 5m by 4 m and experiments with the four drip discharge rates conducted in four of the plots. A tensiometer was installed at a soil depth of 60 cm to monitor the initial soil matric suction at each of the plots.

3.3.2 Soil water Potential Plots

To investigate the soil water potential distribution in the wetted soil volume due to drip water application, an array of tensiometers spaced 15 cm apart and installed at different soil depths of 15, 30, 45, 60, 90, 120 and 150 cm down the soil profile was used.

Plate 3.4. An array of tensiometers at point of drip discharge (2 l/hr) after 2 hours of water application.

These experiments were conducted in two of the six plots mentioned in Section 3.3.1.

3.3.3 Capillary Rise Plots

To monitor the upward soil water flux and soil matric potential as influenced by varying depths of shallow ground water table, three representative sites were selected at the lower part of the farm with a shallow ground water table (see Figure 3.2).

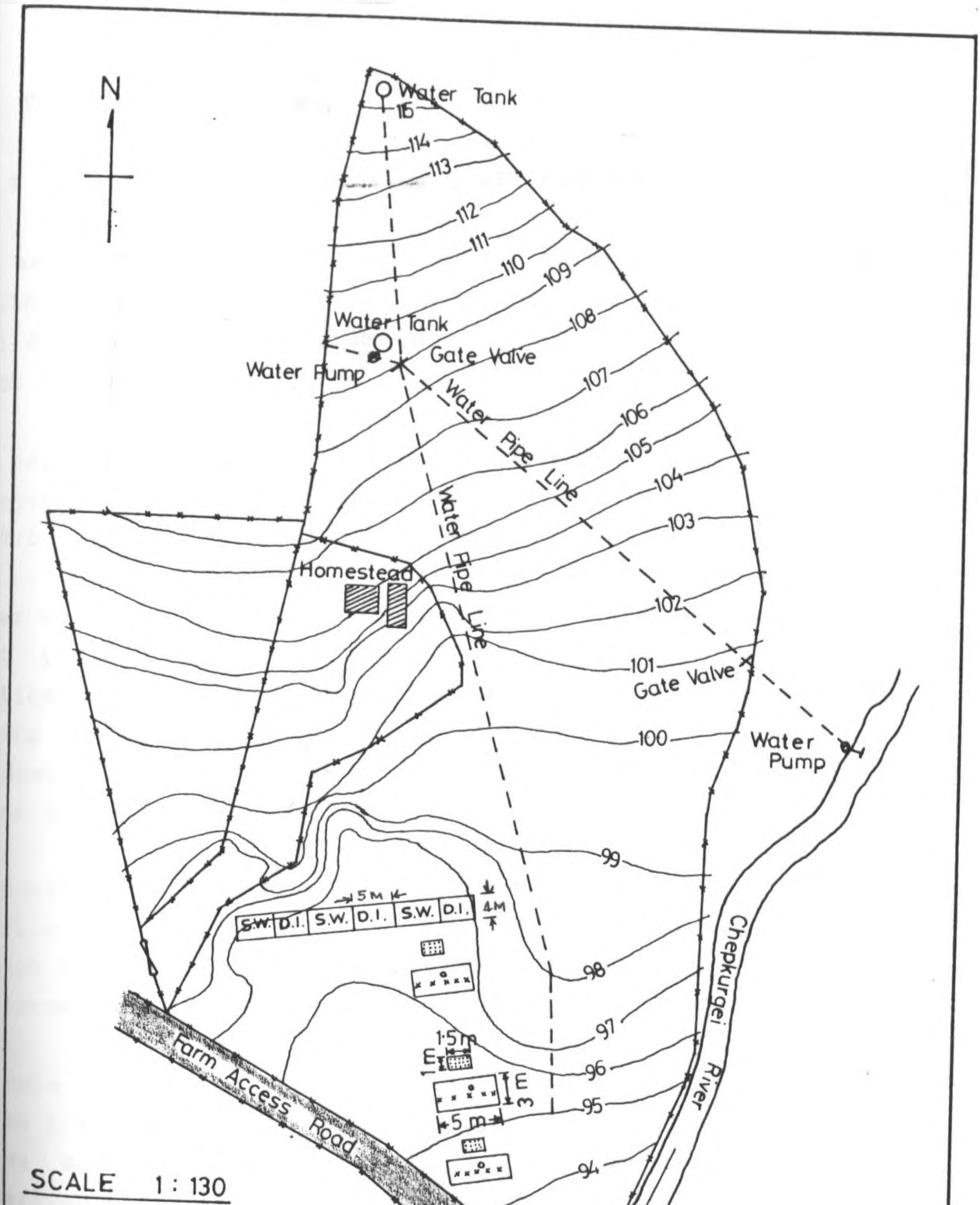

Fig. 3.2 LOCATION OF EXPERIMENTAL PLOTS AND SOIL SAMPLING SITES AT RUGUJU, KAPSENGERE, NANDI.

3.4 Experimental Methods

3.4.1 Downward Soil Water Flux (Infiltration)

For each drip discharge rate and at each initial soil matric suction value, drip water was applied continuously for different time durations ranging from one hour to at least a maximum of eight hours.

The experiments were conducted at three levels of initial soil moisture content as indicated by antecedent soil matric suctions of 0.2, 0.3, and 0.5 bars; measured at 60 cm soil depth.

After each time duration, water application was stopped and the soil profile cut symmetrically along the point of water application to expose the wetted soil which was then mapped by noting the wetted radii along the centre line; at intervals of 5 cm down the soil profile. The experiment was performed at the other two experimental sites.

Drip water application point was then moved next to the cut soil profile or observation pit (of dimensions 1.0 m by 1.5 m); making enough clearance to avoid the already wetted soil and experiment performed for the next duration of water application.

In case the soil profile was found to contain large cracks or holes (probably due to decaying tree roots, rodent and termite holes and other local variations in soil structure) the experiment was shifted to another site.

The above measurements were conducted using different emitter spacings (0.75 m and 1.0 m) and drip discharge rates (2, 3, 4, 8 l/hr) at about 0.3 bars antecedent soil matric suction. Starting with a 2 l/hr discharge rate and drippers spaced 0.75 m apart, the wetted zones were determined after 10 hours of water application.

With 3 and 4 l/hr emission rates and drippers spaced 0.75 m apart, the wetted zones were mapped after 8 hours of water application.

With 8 l/hr discharge rate and 0.75 m dripper spacing, the wetting patterns were measured after two periods of water application of 2 and 8 hours. This experiment was repeated with a 1.0 m dripper spacing and measurements of the wetting patterns done after 2, 6 and 8 hours of water application.

3.4.2 Soil water Potential

To monitor the soil water potential, soil matric suction readings were taken from an array of tensiometers which were installed in the sequence of 60, 90, 120, 150, 15, 30, 45 cm down the soil profile; with point of water application beside the 150 cm soil depth tensiometer. On installation, tensiometers were left overnight to stabilise before taking the readings. The experiments were conducted at about 0.3 bars initial soil matric suction (as indicated by the tensiometer installed at 60 cm soil depth) for all the four emitter discharge rates of 2, 3, 4, 8 l/hr.

For each emitter rate, water was applied upto a maximum period of 8 hours with tensiometer readings taken periodically after 1, 2, 4, 6 and 8 hours. After the maximum duration of water application of 8 hours, water flow was cut-off and water redistribution allowed overnight before taking the last tensiometer readings.

The tensiometers were then removed and installed at another site for experimentation with the next drip discharge rate.

3.4.3 Upward Soil Water Flux (Capillary Rise)

At each of these three sites, tensiometers at 50 cm spacing were installed at depths of 30, 60, 90, 120 and 150 cm to monitor soil matric suction changes. An observation well was dug adjacent (about 15 cm) to the tensiometers at each site for monitoring the ground water level fluctuations. Although the depth of the observation wells was about 2.0 m (limited by the length of available auger equipment) it served the purpose well throughout the data collection period since the water table depth was high. A water sample was collected from the observation well in the upper plot for laboratory analysis to check on the suitability of the ground water for irrigation of field crops.

Plate 3.5. Location of ground water observation well (covered with tin) next to tensiometers.

The sites were covered with plastic polythene sheets to prevent the direct effect of any rain water on the tensiometer readings. Readings of soil matric suctions and water table depth were recorded twice a week at three days interval.

Plate 3.6. Upward soil water flux monitoring site (middle plot).

Upward soil water flux (capillary rise) in the soil layer above the ground water table was determined using Equations 2.7 and 2.8 developed from the Darcy's equation:

$$v = -K\psi \times \frac{dH}{dL} \qquad (3.4)$$

Where

v = The average flow velocity (cm/day) or the volume flux per unit area per unit time.

$K\psi$ = Soil hydraulic conductivity at matric suction ψ (cm/day).

dh/dz = Potential gradient in the direction z (cm/cm).

H = Difference in hydraulic head (cm).

L = Flow distance (cm).

The minus sign indicates the flow direction from a high to a low soil water potential. The soil constants $K\theta$, α, a; in Equation 2.7 were obtained from Table 2.2 for fine sandy loam soil.

4.0 RESULTS AND DISCUSSION

4.1 Soil Characterization at Experimental Site

4.1.1 Soil Properties

Table 4.1 gives some physical soil attributes from analysis of soil samples collected at three sites to assess soil variability at the experimental site. The results indicate that the soil profile consists of alternate layers of sandy loam, sandy clay loam and loam sand. The percentage of sand is high throughout the soil profile. The soil bulk density and hydraulic conductivity vary irregularly down the soil profile. Higher values of bulk density at top layers could be attributed to less clay and organic matter content. Changes in bulk densities down the soil profile were also attributed to soil textural differences (see Table 4.1).

Table 4.1. Soil Physical Properties at Experimental Site.

Soil Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	Hydraulic Cond. (cm/hr)	Bulk Density (gm/cm^3)
0	78	6	16	SL	1.2	1.41
(UP) 30	74	10	16	SL	5.4	1.47
60	68	10	22	SCL	3.4	1.26
0	86	4	10	LS	3.8	1.48
(MP) 30	82	4	14	SL	4.4	1.34
60	84	6	10	LS	1.9	1.39
0	74	10	16	SL	7.1	1.37
(LP) 30	76	8	16	SL	3.4	1.38
60	76	8	16	SL	1.6	1.44

UP = Upper Plot, MP = Middle Plot, LP = Lower Plot
C = Clay L = Loam S = Sand

Soil particle size distribution down the soil profile up to 150 cm soil depth is shown in Table 4.2.

Table 4.2. Soil Particle size Distribution down the Soil Profile.

Soil Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture
0	76	8	16	SL
30	70	12	18	SL
60	67	11	22	SCL
90	60	12	28	SCL
120	60	14	26	SCL
150	66	12	22	SCL

Table 4.3 presents other soil physical properties of the soil profile up to 150 cm soil depth. The results show some irregular variation of soil pH, organic matter content and hydraulic conductivity down the soil profile. The soil pH is moderately acid and generally increases down the soil profile. These variations could be attributed to the nature of the soils which are classified as fluvisols (alluvial soils). Soil organic matter is generally low and decreases down the soil profile.

Table 4.3. Variation of some Physical Soil Properties down the Soil Profile.

Soil Depth (cm)	Bulk Density (g/cm^3)	Hydraulic Conductivity (cm/hr)	pH	Porosity (%volume)	Available Moisture (%v/v)	Organic Matter Content (%)	Texture
0	1.34	6.8	5.1	33.3	11.2	1.6	SL
30	1.49	0.1	5.4	35.1	10.2	1.3	SL
60	1.55	5.6	5.8	42.3	8.4	1.6	SCL
90	1.94	0.3	6.3	33.5	7.8	1.0	SCL
120	1.63	1.3	6.6	42.0	7.2	0.7	SCL
150	1.76	0.5	6.7	38.9	6.7	0.7	SCL

Soil porosity increases down the soil profile. This corresponds to decrease in percentage sand and higher silt and clay content resulting in a similar pattern in saturated hydraulic conductivity and available soil moisture.

The pH range (6.5-7.5) favours high microbial activity making most nutrients available to plants (Landon, 1984). The acidic nature of the soil makes it most suitable for growing citrus. Soil bulk density increases down the soil profile due to increased clay content with a corresponding decrease in sand.

High sand content at top soil layers results in high infiltration rates and less water retention capacity. The lower soil layers with more clay content have more water retention capacity. Thus the soil profile; 60-150 cm depth would be important in water storage and with the presence of a shallow ground water table would permit intensive upward soil water flux due to its high water diffusivity properties.

4.1.2 Soil water Intake Rate

From the soil infiltration test data, see Appendix 4.1 cumulative infiltration depths I_{cum} (cm) and the infiltration time t (min) were plotted on a log log scale and line of best fit determined. The equation of this line was obtained as $I_{cum} = 1.13\ t^{0.83}$. Differentiating this equation with respect to time gave the instantaneous infiltration rate (mm/hr) equation as $I_{rate} = 0.94\ t^{-0.17}$.

Results show that the cumulative infiltration does not reach equilibrium even after five hours of water application. This can be attributed to the sandy nature of the soil with a relatively high final infiltration rate. The final infiltration rate was obtained as 20 mm/hr (see Figure 4.1) which lies within the range obtained by Muniki (1989) of 12-20 mm/hr.

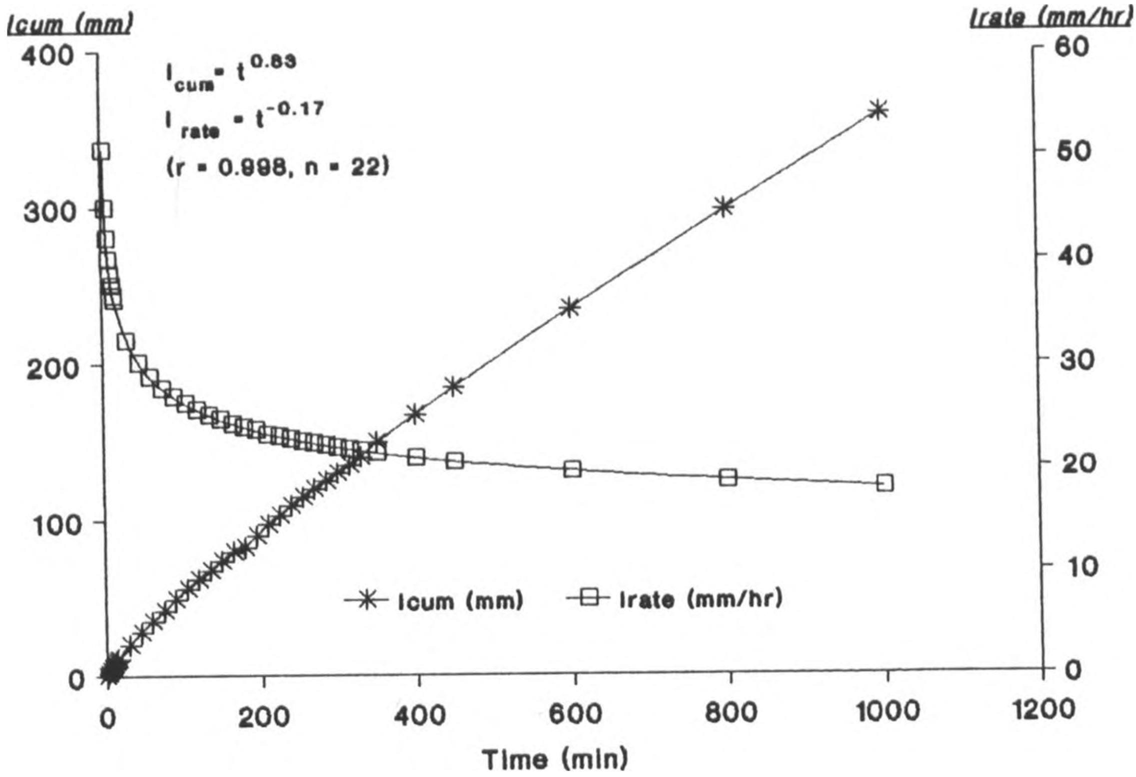

Figure 4.1. Cumulative and Instantaneous infiltration as functions of time.

With percentage sand being high in the top soil layers, the initial soil intake rate is high enhancing soil water intake and consequently reducing any possibilities of generating runoff.

4.1.3 Soil water Retention Capacity

The soil water retention capacity was determined considering both low and high pF values using the pressure plate apparatus (see Stakman, 1980). The results are presented in Table 4.4. For the sandy loam soil, the field capacity was taken at pF 2.0 (rather than 2.3) as due to its high sand content most water at field capacity is held in the macro-pores and requires much less energy to remove (see Landon, 1984).

Table 4.4. Soil Water Retention Capacity (% v/v) data.

	Upper Plot			Middle Plot			Lower Plot		
SD(cm)	0	30	60	0	30	60	0	30	60
pF									
0	41.0	44.2	42.5	39.5	42.7	38.7	46.2	46.8	43.9
2.0	22.7	26.2	23.8	19.3	18.4	19.0	23.1	26.0	28.2
2.3	17.7	22.8	21.0	15.1	14.8	16.0	19.0	22.1	24.3
2.5	17.2	22.4	20.1	14.7	14.5	15.6	18.9	21.0	23.8
3.0	15.5	21.0	17.4	12.8	13.2	13.9	16.6	19.7	21.6
4.2	14.1	19.6	16.0	11.3	11.8	12.5	15.1	18.3	20.2
5.0	11.7	17.1	13.6	8.9	9.4	10.1	12.7	15.9	17.8

SD = Soil Depth

Soil water retention capacity was in the range of 40-47% v/v on average. Moisture content at field capacity (pF 2.0) was in the range of 18-28% v/v and 9-18% v/v at permanent wilting point (pF 4.2).

The data is also presented in form of water retention curves as shown in Figure 4.2.

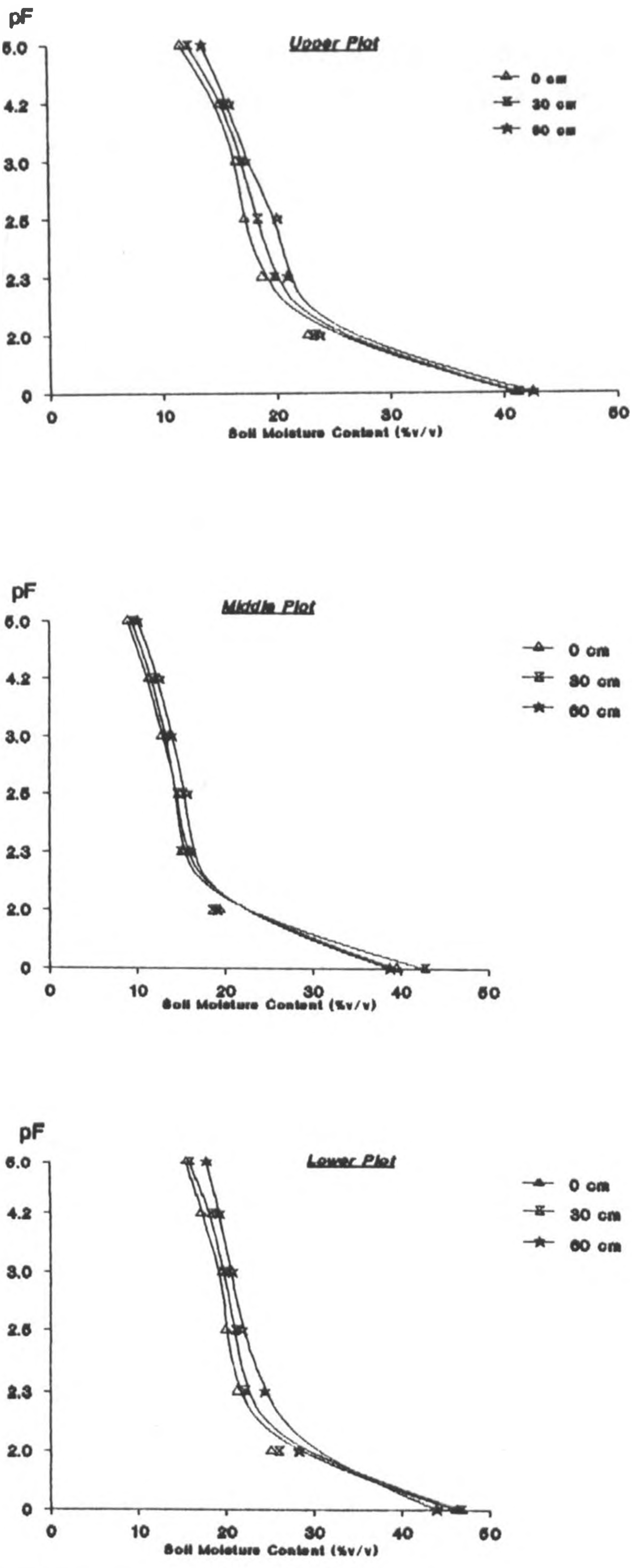

Figure. 4.2. Soil Moisture Characteristic curves.

Difference in water content of the sandy loam layer could be due to differences in bulk density and saturated hydraulic conductivity. The soil layer with low bulk density had high moisture content at any pF value and vice versa while that with high bulk density and low saturated hydraulic conductivity had low water retention capacity as compared to layers with low bulk density and high soil hydraulic conductivity.

Available soil moisture; taken as the soil moisture between pF 2.0 and pF 4.2 was determined (see Table 4.5).

Table 4.5. Available Moisture (AM % v/v).

Soil Depth (cm)	Upper Plot	Middle Plot	Lower Plot
0	8.6	8.0	8.0
30	6.6	6.6	7.7
60	7.8	6.5	8.0

The average available soil moisture (AM) was about 8% v/v. Considering a crop with an effective rooting depth of 120 cm (e.g oranges), the total available soil moisture (TRAM = AM x RD) was about 96 mm. Variations in available soil moisture in the soil profile can be attributed to difference in soil bulk density. Soil layers with high bulk density have low available moisture content while those with low values of soil bulk density and corresponding high clay content tend to have more water retention capacity.

4.1.4✓ Saturated Hydraulic Conductivity

Average saturated hydraulic conductivity values of the upper and lower soil layers were 0.96 and 0.44 m/day respectively.

High saturated hydraulic conductivity of the upper soil layers upto about 40 cm soil depth was associated with high percentage sand and high permeability resulting in relatively high soil intake rates. Soil permeability in the top layers was high thus allowing fast soil water intake, and hence reducing chances of water loss through runoff or evaporation. Low saturated hydraulic conductivity of the lower soil layers (beyond 40 cm soil depth) hinders fast downward water flow during drip water application and thus would enhance lateral spread. This could result in a soil wetting pattern that better wets the potential crop root zone by spreading laterally the soil water flow in the soil profile at 40-60 cm depth with high root density for most citrus crops e.g oranges.

4.1.5 Unsaturated Hydraulic Conductivity

Most soil water flow under drip irrigation or upward soil water flux from a shallow ground water table occurs in unsaturated soil conditions. The soil water redistribution under these soil conditions is important in availing soil water to crop roots. The rate at which the soil conducts the water determines the efficiency with which crop roots get the water and dissolved nutrients. This rate termed as the unsaturated hydraulic conductivity depends on the soil matric suction at various points in the soil profile.

The relationship between unsaturated hydraulic conductivity and soil matric suction at the Experimental Site is presented in Figure 4.3.

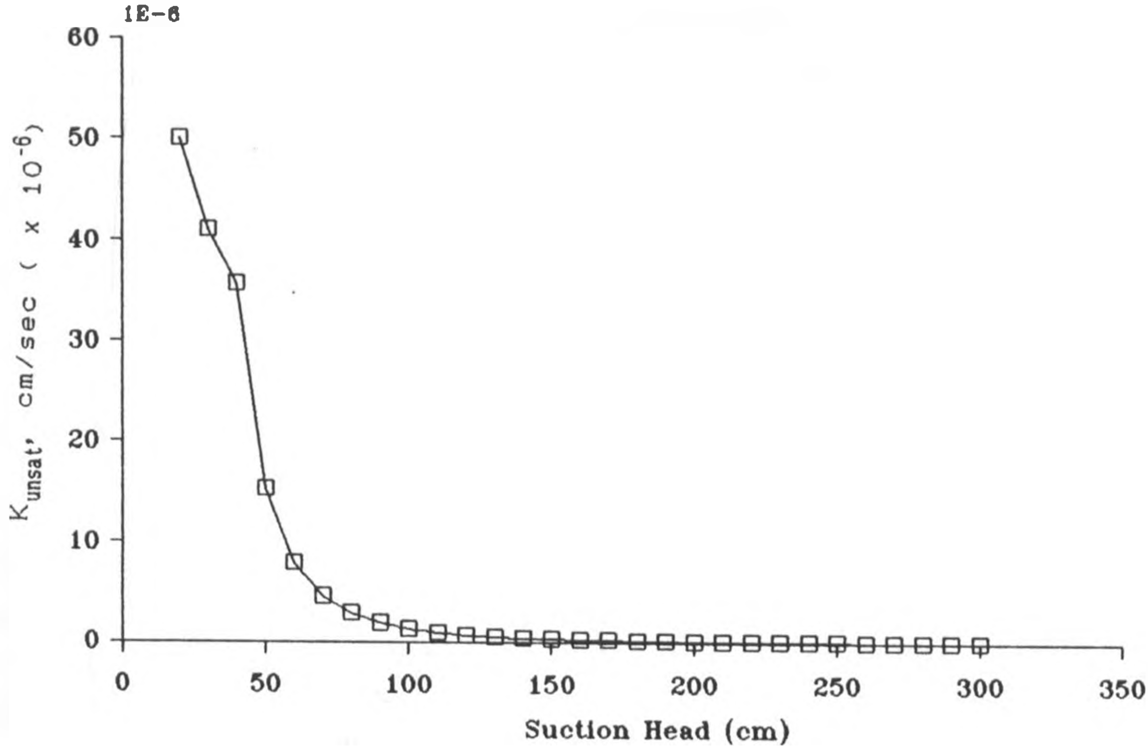

Figure 4.3. Variation of unsaturated hydraulic conductivity with soil matric suction.

The point of inflection on the curve corresponding to a suction head of 40 cm denotes the air bubbling pressure which indicates the transition from saturated to unsaturated conductivity.

4.2 Downward Soil Water flux (Infiltration)

4.2.1 Effects of Drip Discharge rates

Drip water flow in the soil profile was presented in form of soil wetting profiles (see Figures 4.4 to 4.7). The average values of the wetted radii measured at intervals of 5 cm down the soil profile for each test at the three experimental sites were used in plotting the soil wetting profiles.

Initially after a few hours (about 2 hours) of water application, for each emitter discharge rate, the wetted soil surface diameter and depth are larger at higher values of antecedent soil matric suction. However, continued water application reversed the trend resulting in larger wetted soil surface diameter and depth with lower values of antecedent soil matric suction. This could be attributed to the high soil permeability at higher values of initial soil matric suction (low initial soil moisture content). At lower initial soil matric suction (high soil moisture content), soil permeability was reduced but soil water conductivity increased towards saturated hydraulic conductivity with increased soil wetness.

With more water application, both the wetted surface diameter and soil depth increased steadily. After about six hours of continuous water application, the wetted soil surface diameter tended to stabilize as the wetted soil depth increased resulting in an elongated wetted pattern. With a drip discharge rate of 2 l/hr, the wetted soil surface diameter stabilized in the range of 60-70 cm; 70-80 cm for 3 l/hr; 75-80 cm for 4 l/hr and 100-120 cm for 8 l/hr.

The final wetted soil surface diameter and depth are shown in Table 4.6.

Table 4.6. Wetted soil surface diameter and depth with different drip discharge rates.

DDR	2			3			4			8		
ISMS	0.2	0.3	0.5	0.2	0.3	0.5	0.2	0.3	0.5	0.2	0.3	0.5
Wetted surface diameter (cm)	80	70	60	80	80	80	80	80	80	90	90	90
Wetted soil depth (cm)	70	90	60	80	90	100	120	120	110	150	130	130

DDR = Drip Discharge Rate (l/hr).
ISMS = Initial Soil Matric Suction (bars).

At the lower level of antecedent soil matric suction considered (about 0.2 bars), lateral soil water spread was more enhanced as compared to the vertical flow resulting in a larger wetted soil surface diameter than depth. At about 0.5 bars initial soil matric suction, both the wetted soil surface diameter and depth were lower than in the case considered above. In this case, the soil water storage capacity was high and most of the water applied went into filling the large pore volume available before any considerable soil wetting could occur. Hence the higher the initial soil matric suction the more the volume of water required to wet a given soil volume.

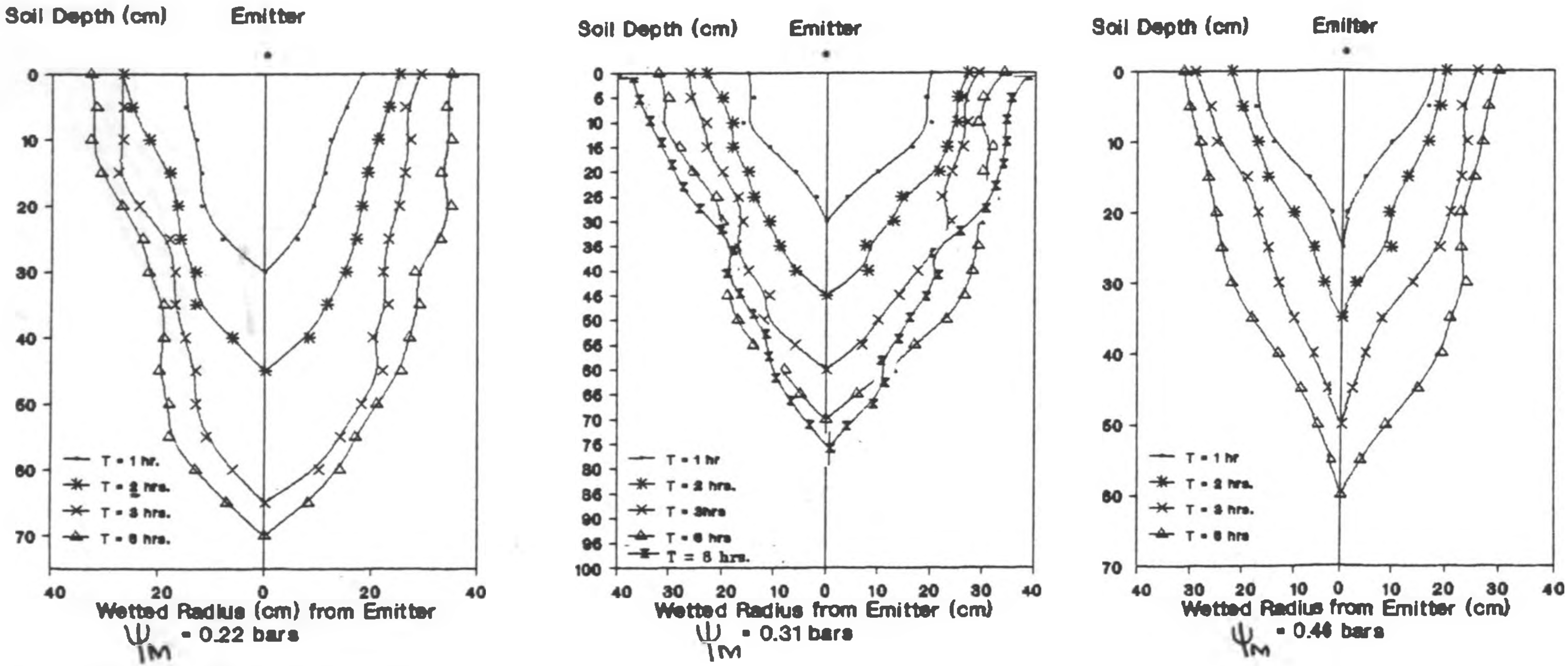

Fig. 4.4. Soil wetting Profiles of 2 l/hr emitter discharge rate.

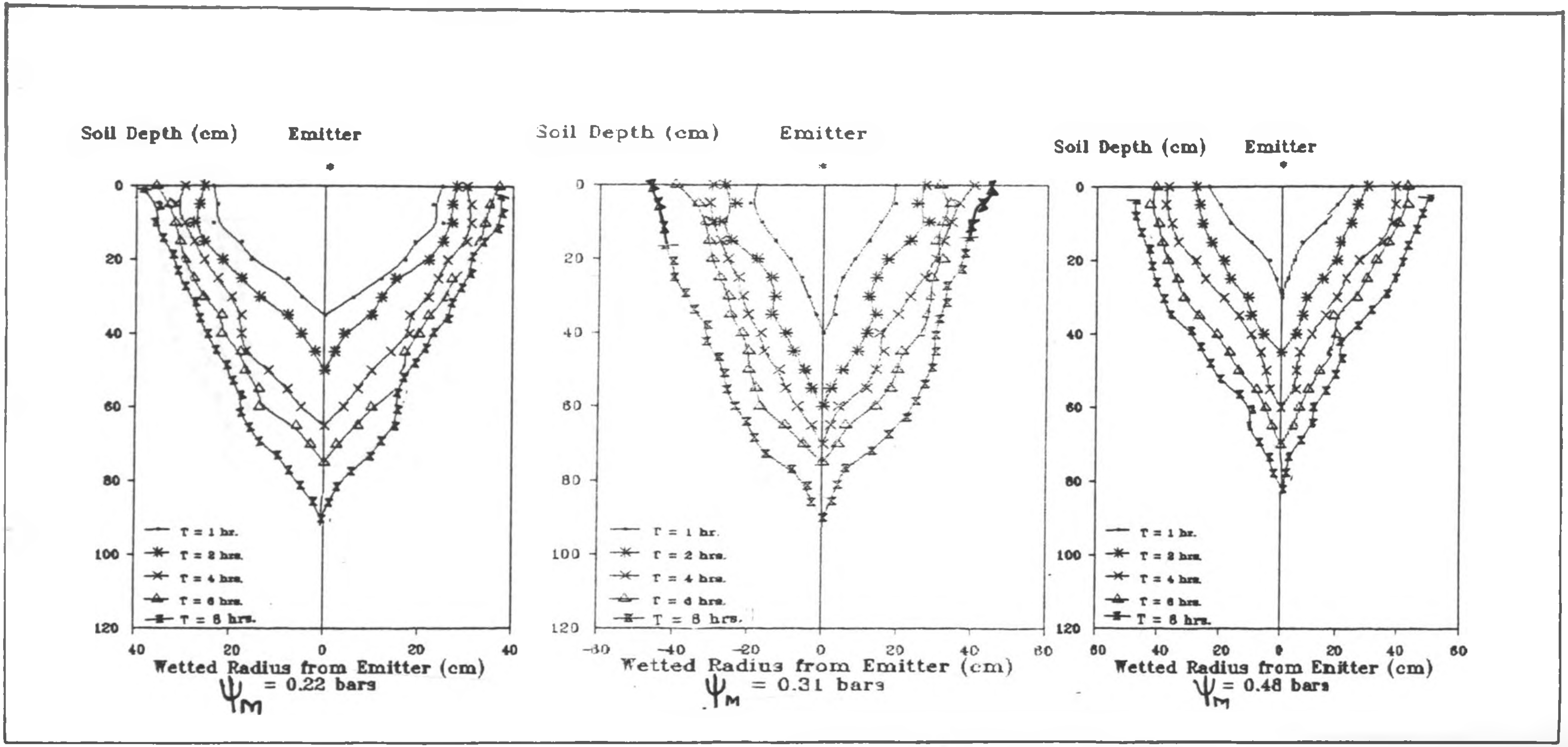

Fig. 4.5. Soil wetting Profiles of 3 l/hr emitter discharge rate.

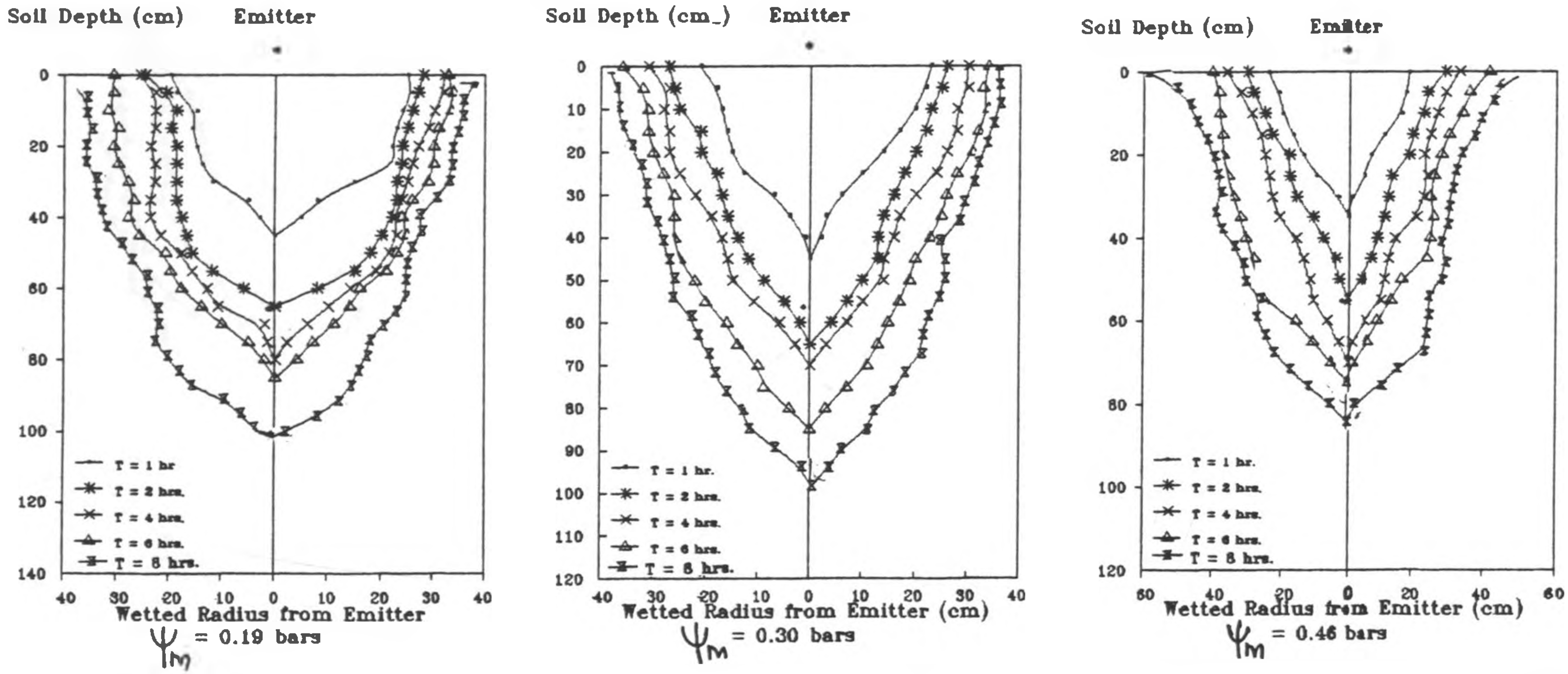

Fig. 4.6. Soil wetting Profiles of 4 l/hr emitter discharge rate.

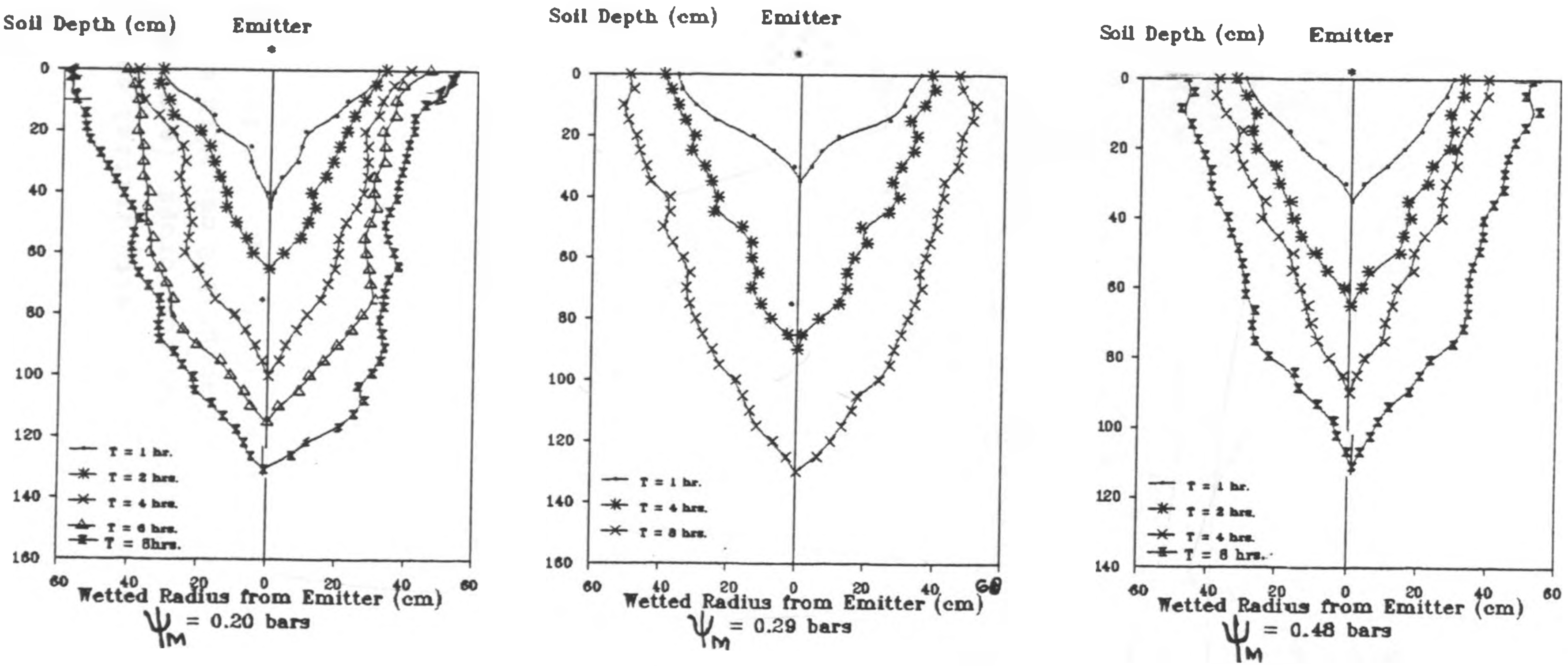

Fig. 4.7. Soil Wetting Profiles of 8 l/hr emitter discharge rate.

from the soil wetting profiles (with initial soil matric suction higher than 0.3 bars) and for crops (e.g oranges) with an effective rooting depth of about 120 cm; with a 2 l/hr and 3 l/hr drip discharge rate water must be applied for more than 8 hours to wet such a depth. Water application for 8 hours with a 4 l/hr drip discharge rate adequately covers this root depth while with l/hr drip discharge rate it is covered in a duration of about to 5 hours.

Plate 4.1. Soil wetting pattern of a 2 l/hr emitter after 8 hours of water application (showing the position of the emitter and drip line).

Plate 4.2. Soil wetting pattern of a 4 l/hr emitter after 8 hours of water application (showing the position of the drip line and the emitter).

The wetted soil volume $S_v(cm^3)$ for the conditions described above were determined by approximating the wetted zone(s) to cylindrical and conical sections. The results are given in Table 4.7.

Table 4.7. Wetted soil volume $S_v (m^3)$ at different emitter discharge rates.

Emitter discharge rate (l/hr)	2			3			4			8		
Matric suction (bars)	0.2	0.3	0.5	0.2	0.3	0.5	0.2	0.3	0.5	0.2	0.3	0.5
Time (hrs)												
1	0.020	0.014	0.009	0.028	0.012	0.016	0.054	0.039	0.019	0.056	0.059	0.035
2	0.039	0.042	0.027	0.045	0.040	0.035	0.086	0.088	0.048	0.106	0.089	0.078
3	0.066	0.060	0.041	-	-	-	-	-	-	-	-	-
4	-	-	-	0.085	0.098	0.109	0.104	0.115	0.062	0.183	0.141	0.115
6	0.019	0.071	0.080	0.088	0.101	0.145	0.188	0.121	0.078	0.399	0.330	0.312
8	0.098	0.080	0.084	0.197	0.130	0.187	0.256	0.185	0.140	0.447	0.438	0.348

For each drip discharge rate at a given level of antecedent soil matric suction, the wetted soil volume increased with an increase in the duration of water application. In general, the wetted soil volume was higher at lower values of antecedent soil matric suction for each emitter discharge rate.

4.2.2 Soil Water Potential

Soil water potential in the wetted soil volume for the different emitter discharge rates is shown in Appendix 4.2. The results show that the soil water potential was lowest near the point of water application and increased spatially away from the emitter position. For each emitter discharge rate, the soil water potential increased with depth down the soil profile. For all the four drip discharge rates, the soil water potential in the wetted soil volume ranged from 30-50 cm at 15 cm soil depth, and about 70-180 cm at 150 cm soil depth.

Immediately after stopping water application, the soil in the vicinity of the emitter was nearly saturated. Water then infiltrated into the surrounding soil mass and finally after allowing for overnight redistribution (of at least 12 hours) the soil matric suction ranged from about 30 to 180 cm (0.03-0.18

bars) over the soil depth of 0 - 150 cm with antecedent soil matric suction at 0.34 bars.

Soil water potential after allowing overnight soil water redistribution was plotted against soil depth (see Figure 4.8).

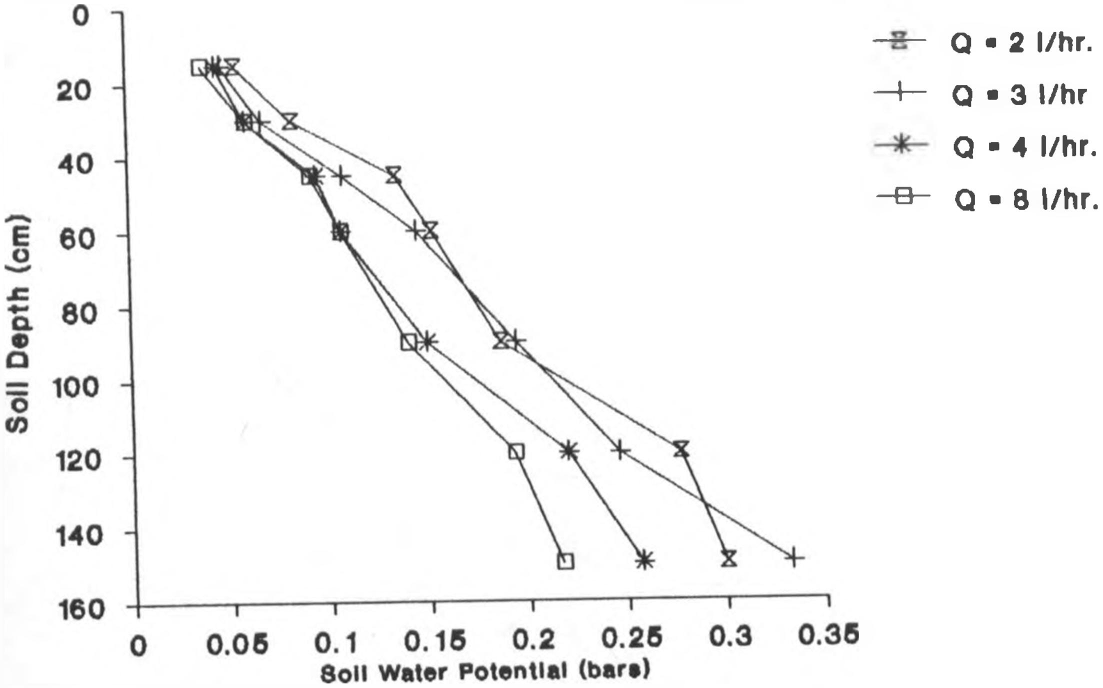

Fig. 4.8. Soil water potential within the wetted soil volume after 12 hours of redistribution.

For emitter discharge rates of 4 and 8 l/hr, lowering of soil matric suction enhances with duration of water application upto about six hours when the wetted zone is almost at saturation condition. With 2 and 3 l/hr emitter discharge rates, the wetted zone is almost at 0.1 bars (on average) after 8 hours of continuous drip water application. The soil matric suction distribution within the wetted soil volume (for the two discharge rates) was rather irregular.

At any given soil depth, the soil water potential decreased with an increase in drip discharge rate (see Figure 4.8). High up the soil profile (0-50 cm) the difference in soil water potential between the different drip discharge rates was low compared to soil layers down the soil profile (50-150 cm). This difference was more pronounced down the soil profile. This phenomena could be attributed to the soil texture variation. Upper soil layers with high percentage sand and high permeability were almost saturated after a short duration of drip water application. Lower soil profile layers having more clay content (with variations in percentage silt and loam) had different and low soil water hydraulic conductivity and bulk density values which resulted in the wide difference in soil water potential.

Plate 4.3. An array of tensiometers at point of drip discharge (4 l/hr) after an overnight's soil water redistribution following 8 hours of water application.

4.2.3 Effects of Emitter spacing

These experiments were conducted at an initial soil matric suction of 0.3 bars on average (as determined at 60 cm depth). The results showed that with a drip discharge rate of 2 l/hr and emitter spacing of 0.75 m, the wetted zones did not overlap even after 10 hours of water application. For prolonged water application exceeding six hours the horizontal spread approached a maximum value as vertical penetration steadily increased.

Plate 4.4. Soil profile pit showing soil wetting patterns of two; 2 l/hr drippers, spaced 0.75 m apart and after 10 hours of water application (showing position of the drip-line).

With the 3 and 4 l/hr emitter discharge rates and spacing of 0.75 m the wetted zones started to overlap after applying water continuously for about 8 hours (maximum duration of water application considered).

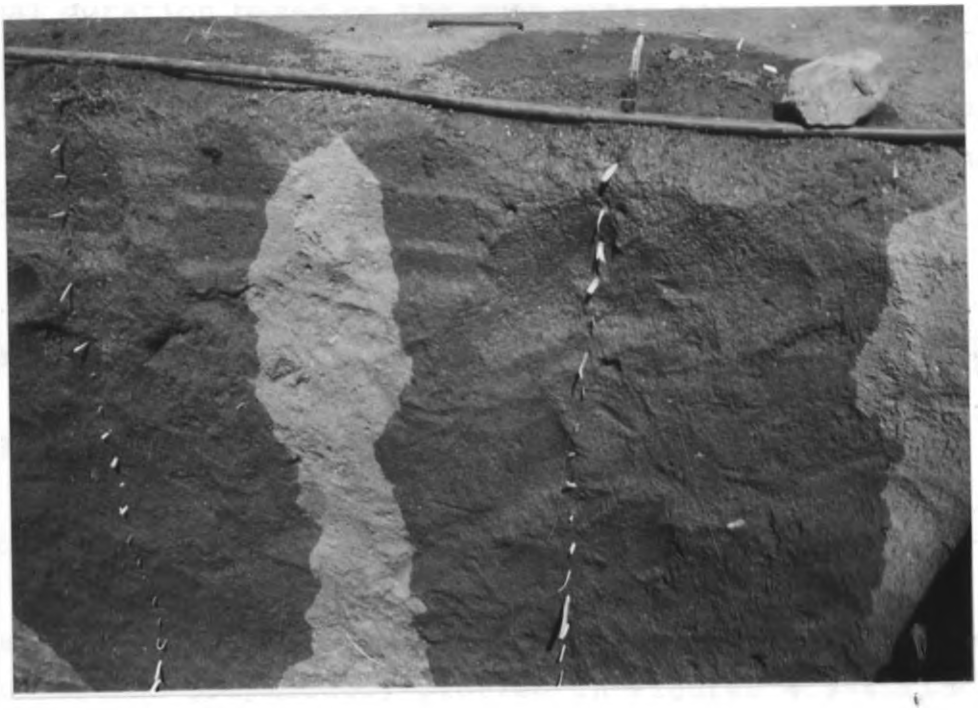

Plate 4.5. Soil profile pit showing soil wetting patterns of two 4 l/hr drippers and spaced 0.75 m apart after 8 hours of water application (showing position of drip-line).

With the 8 l/hr emitter discharge rate at 0.75 m emitter spacing, the wetted zones started to overlap after about two hours of water application. When the emitter spacing was increased to 1.0 m, the wetted areas overlapped after about six hours of water application. These wetting patterns are shown in Appendix 4.3.

For other spacings and duration of water application that could not result in overlapping of the wetted soil zones, any reference(s) should consider combination of the downward soil water flow patterns under a single source (emitter) as shown earlier in Section 4.2.1.

For mature orange trees, with an effective rooting depth of 1.2 m and an approximate effective rooting diameter of 3.0 m, an emitter spacing of 0.75 m across the tree could be most suitable. To adequately wet the root zone, then with a 2 l/hr emitter discharge rate water must be applied for more than eight hours. The actual duration based on the crop water requirements is about 14 hours. With 3, 4, 8 l/hr emitter discharge rates water should be applied for about 10, 8, 4 hours respectively to adequately wet the crop rooting zone while considering an average initial soil matric suction of about 0.3 bars.

4.3 Upward Soil Water flux (Capillary Rise)

4.3.1 Soil Matric Potential

Soil matric potential at soil depths of 30, 60, 90, 120, 150 cm and the corresponding water table depth measurements made over the experimental period of about seven months are presented in Appendix 4.4 and graphically plotted in Figures 4.9-4.11. Daily rainfall data for the same period are presented in Appendix 4.5.

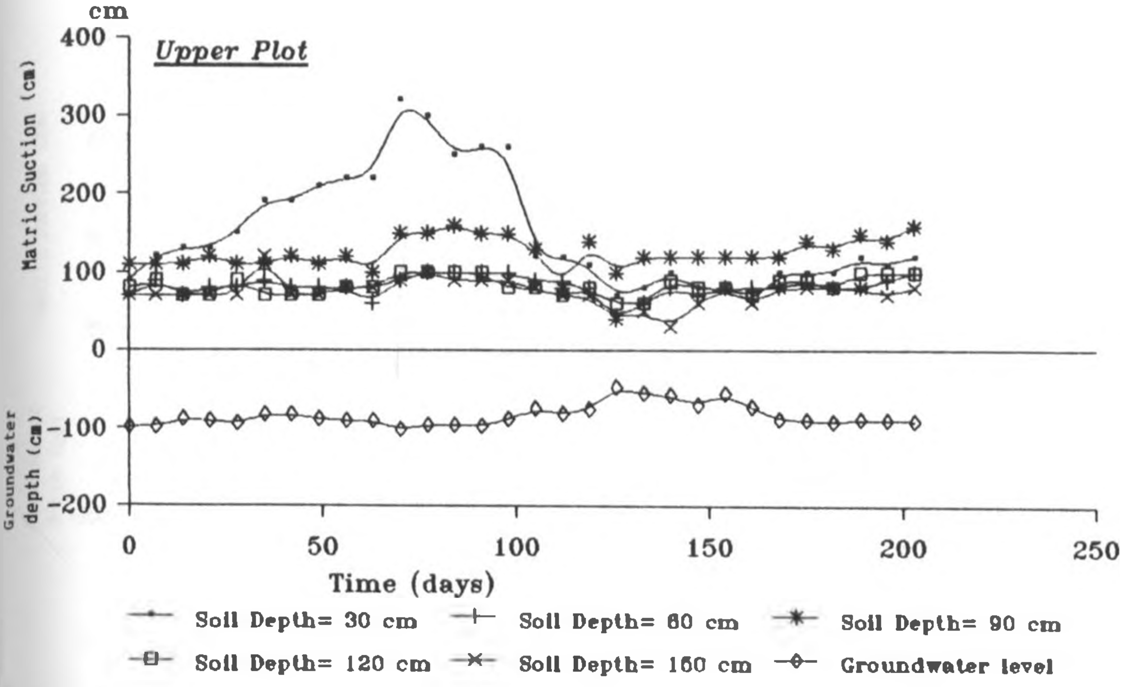

Fig. 4.9 (a). Variations in Soil Water Potential with Ground water depth at the Experimental Site.

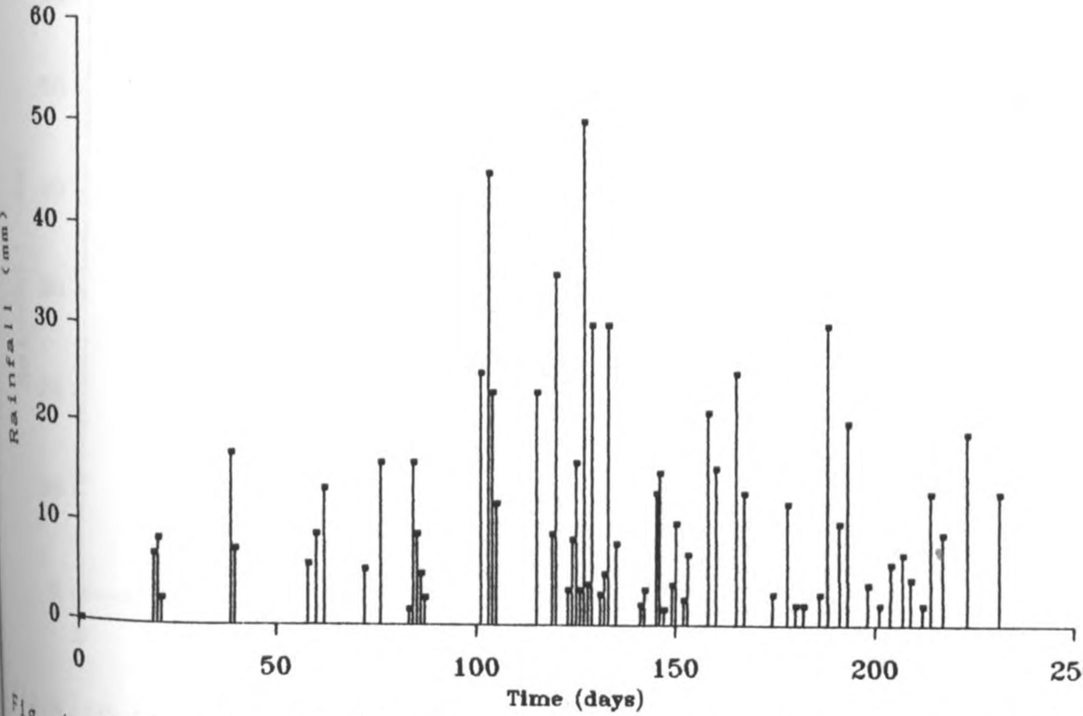

Fig. 4.9 (b). Rainfall distribution during the experimental period.

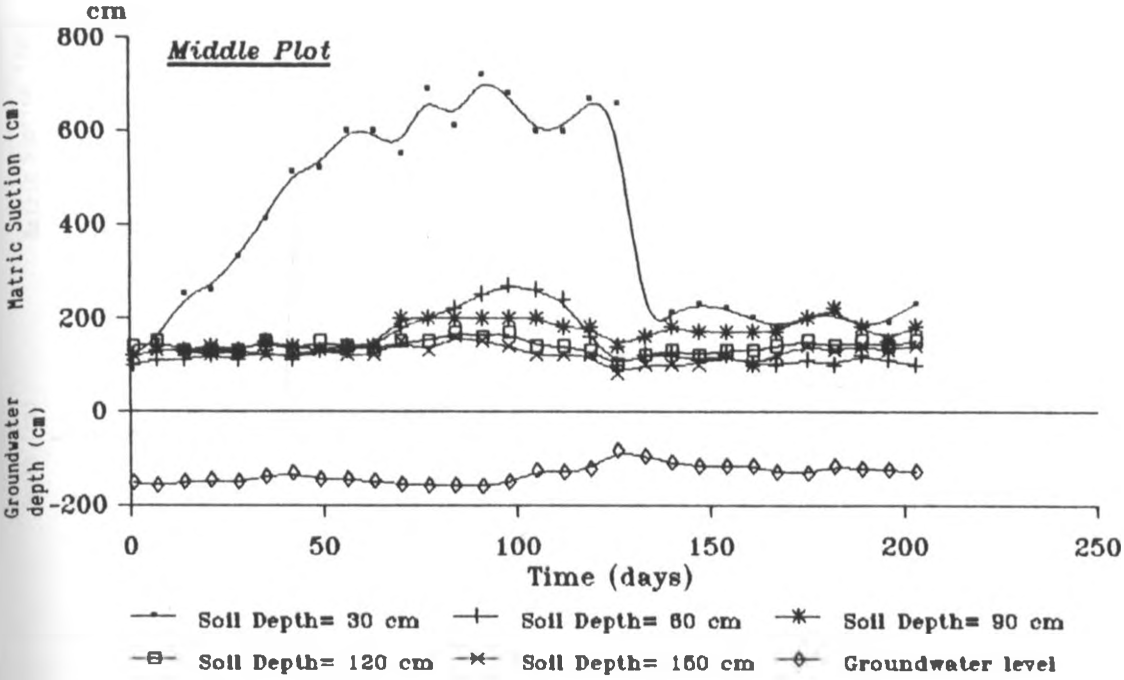

Fig. 4.10 (a). Variations in Soil Water Potential with Ground water depth at the Experimental Site.

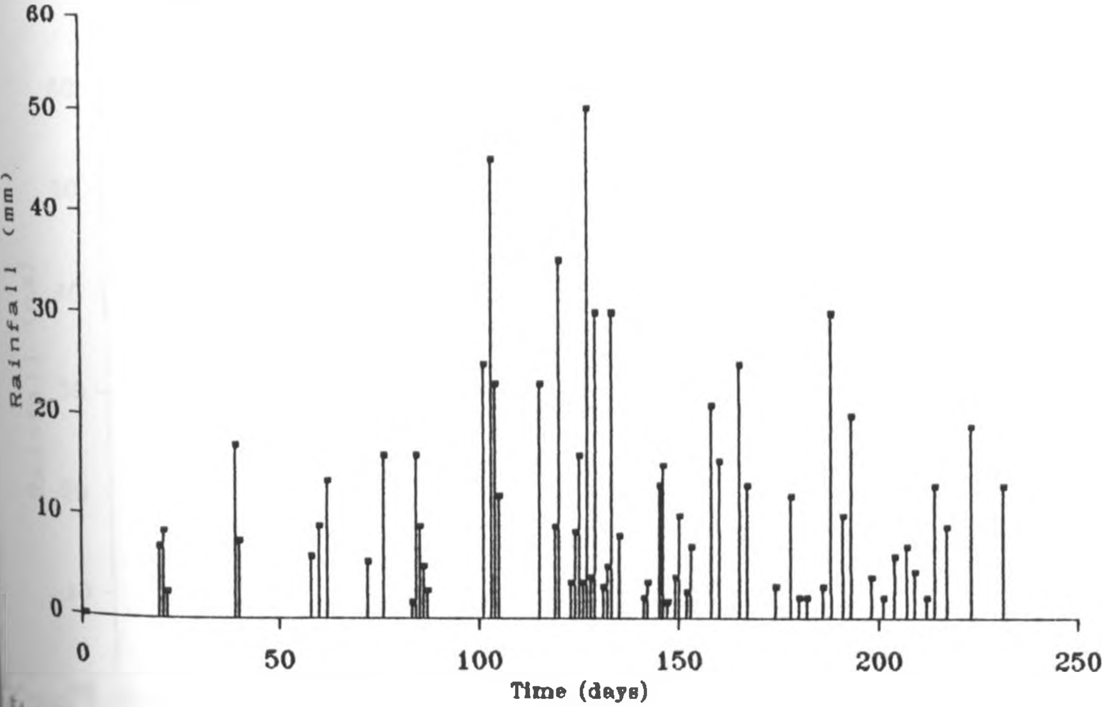

Fig.4.10 (b). Rainfall distribution during the experimental period.

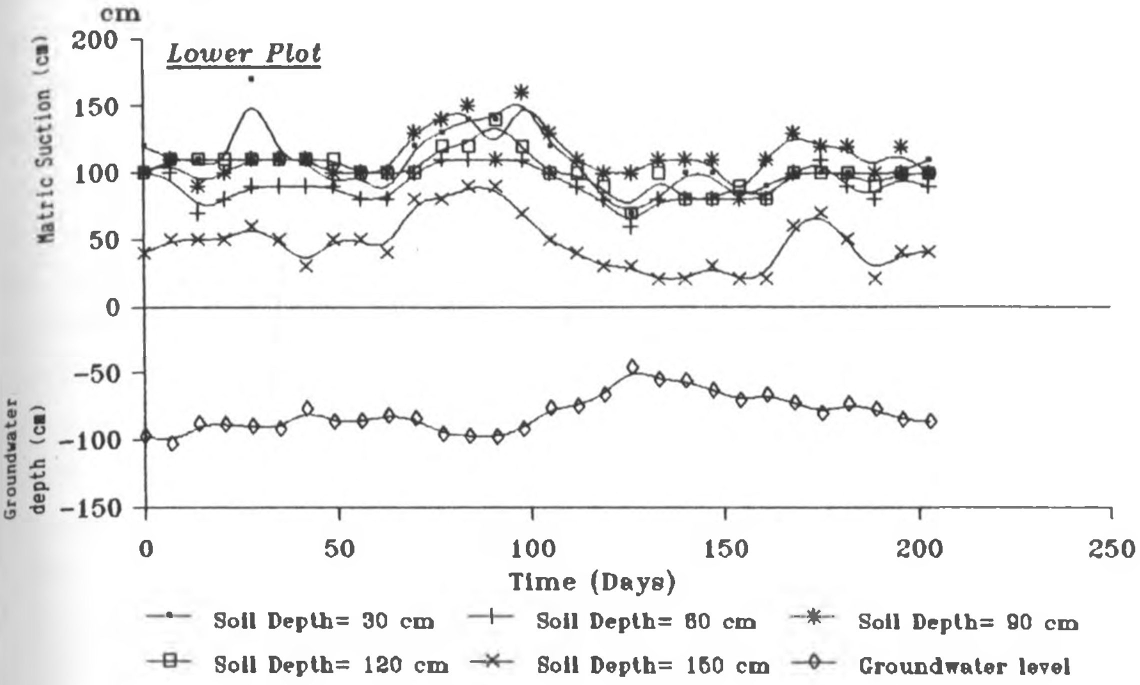

Fig. 4.11 (a). Variations in Soil Water Potential with Ground water depth at the Experimental Site.

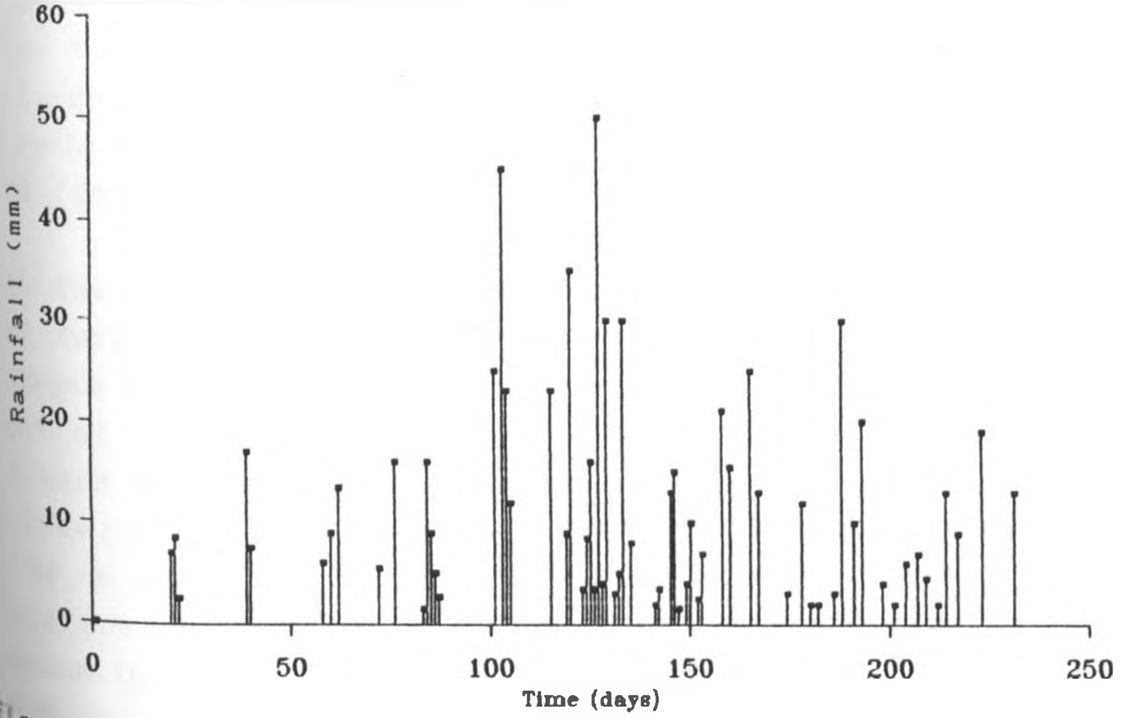

Fig.4.11 (b). Rainfall distribution during the experimental period.

At the start of the experimentation, the soil matric potential was low throughout the soil profile in the three plots. This was due to soil wetting from previous sprinkler irrigation just before setting up the experimental plots.

In all the three plots, the results obtained showed that matric suctions within the soil profile increased the with lowering of the water table. However the change in soil matric suction due to fluctuations in water table level was more pronounced within the upper soil layers (above 30 cm soil depth) than near the water table. This behaviour could be attributed to water losses from the upper soil zone through evaporation resulting in the formation of a thin air dry mulch layer. This increase in suction did influence capillary rise significantly and hence the increase in soil moisture within the capillary fringe.

When there was some ground water recharge e.g from rainfall, the results show that there was some lag before notable changes on soil matric suctions occurred. The lag represented the time it took recharge water to infiltrate through the soil profile and finally percolate through the zone of saturation into the ground water table. These changes started at the bottom going up the soil profile. The change in matric suction depended on the amount of recharge, antecedent soil moisture content and the evaporation rate (in case of a bare soil surface).

With the ground water level at approximately 80-90 cm below the soil surface, the matric suction within the soil profile 30-130 cm depth remained in the range 0.1-0.15 bars. At the ground water depth of 100 cm, this soil zone stayed below 0.3 bars and below 0.5 bars with water level at about 150 cm depth below the soil surface. Within a ground water depth of 150 cm, the soil volume at 30 cm depth and above had a matric suction of about 1.0 bar while the soil volume at 60 cm depth and below had a matric suction in the range of 0.2-1.0 bars. In general, a ground water depth range of 80-100 cm maintained the whole soil volume above the water table at an average soil matric suction range of 0.3-0.4 bars.

From about 130 days to the end of monitoring of upward soil water flux, results obtained (see Figures 4.9 to 4.11) showed that fluctuations in ground water level resulted in insignificant changes in soil matric potential throughout the soil profile. This is because continued recharge by rainfall occurring frequently (though with no effect on ground water level) gave rise to low soil matric potential in the upper soil layers.

When the soil was initially wet, light and frequent rainfall resulted in more lateral spread of soil water as compared to the vertical penetration mainly due to the high horizontal component of soil hydraulic conductivity expected in the top sandy layers. This resulted in the low soil matric potentials observed at depths of 30 cm and 60 cm as compared to 90 cm and 120 cm soil depth. This trend was more pronounced in the lower plot than in the other two plots. In this plot, the high water table observed throughout the observation period kept the soil profile above the water table constantly wet.

Upward soil water flux supplied soil moisture to the lower soil layers above the ground water level causing the lowering of the water table level without any significant changes in soil matric potential in the soil profile. Variations in soil moisture content (SMC) and available soil moisture (AM) with water table depth was established and the relationship graphically presented in Figure 4.12.

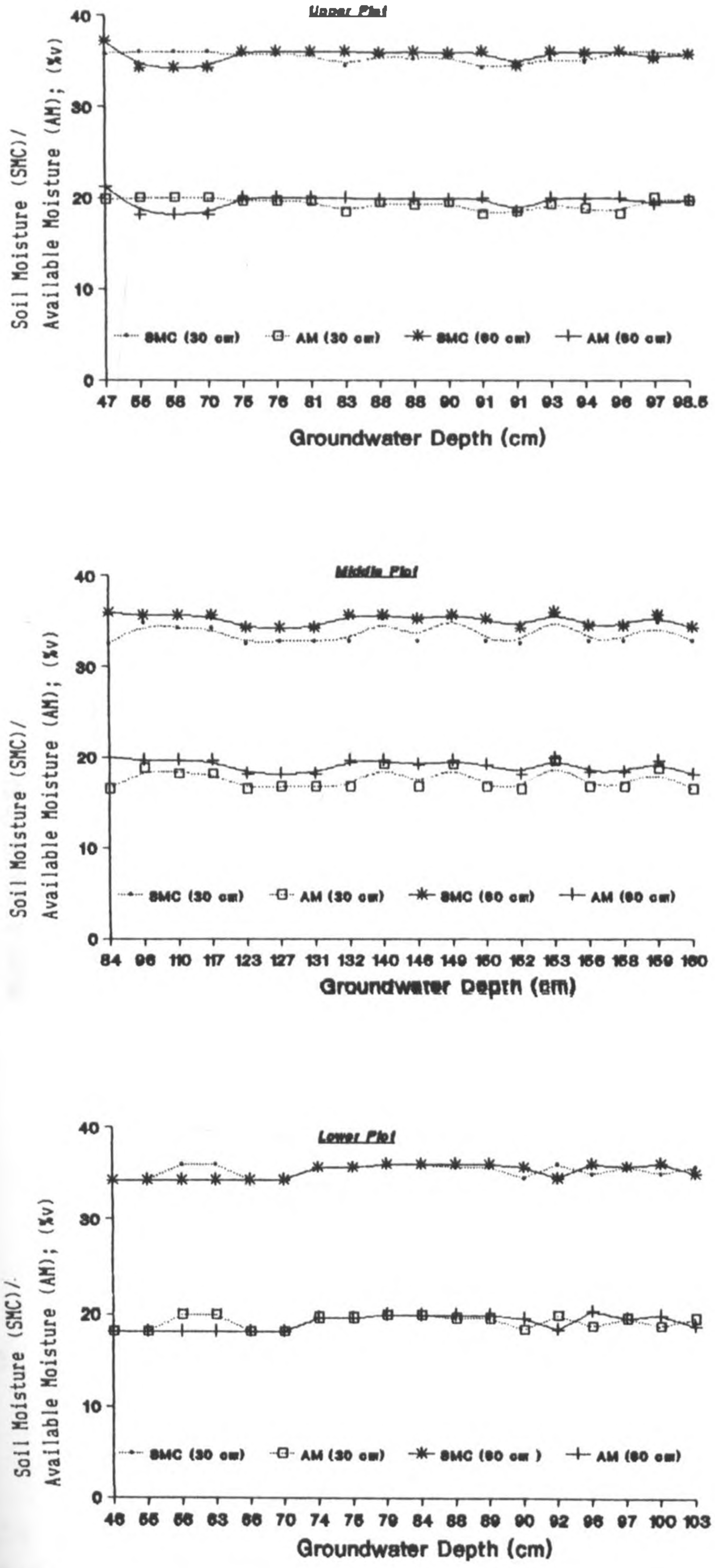

Figure. 4.12. Variations in Soil Moisture with Ground water Depth.

The high ground water level observed throughout the experimental period in the upper and lower plots resulted in no significant difference in soil moisture content and available moisture at 30 cm and 60 cm soil depth. The lower ground water level observed in the middle plot gave rise only to a small difference in both soil moisture content and available soil moisture at 30 cm and 60 cm soil depth. In all three plots, the soil moisture content and available soil moisture were on average about 35% and 20% respectively.

The soil moisture status in the soil profile (30-150 cm soil depth) due to capillary rise over the experimental period is shown in Figure 4.13.

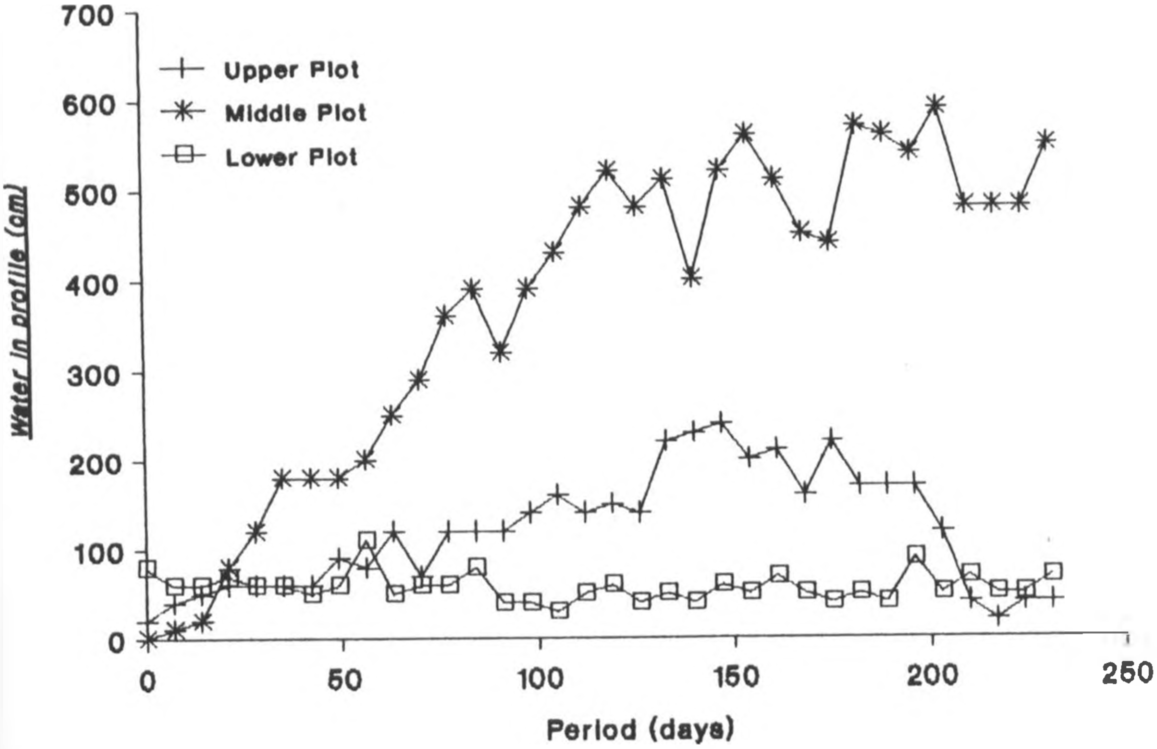

Fig. 4.13. Soil moisture status due to capillary rise over the experimental period.

The middle plot had a relatively high range of soil moisture status (0-600 cm) due to the low ground water level (85-160 cm) recorded throughout the experimental period. In the upper and lower plots, with ground water level in the range of 47-102 cm and 46-92 cm respectively, the range of soil moisture status was relatively low (below 200 cm).

These results show that with a ground water level of 150 cm below the soil surface, capillary rise can supply adequate soil moisture in the potential crop root zone of the soil profile above the water table level. Other research workers have indicated that a soil moisture status range of 300-500 cm is ideal for optimal growth of most crops (Goldberg *et al.*, 1976; El-Shafei, 1989; Bell *et al.*, 1990).

4.3.2 Capillary Rise

Upward soil water flux (capillary rise) arising from the ground water was determined at different soil depths for the three plots using the procedure described in Section 3.4.3 with tensiometric data mentioned in Section 4.3.1 and presented in Appendix 4.4. Values of capillary rise (cm/day) were then plotted against water table depth (cm) as shown in Figure 4.14.

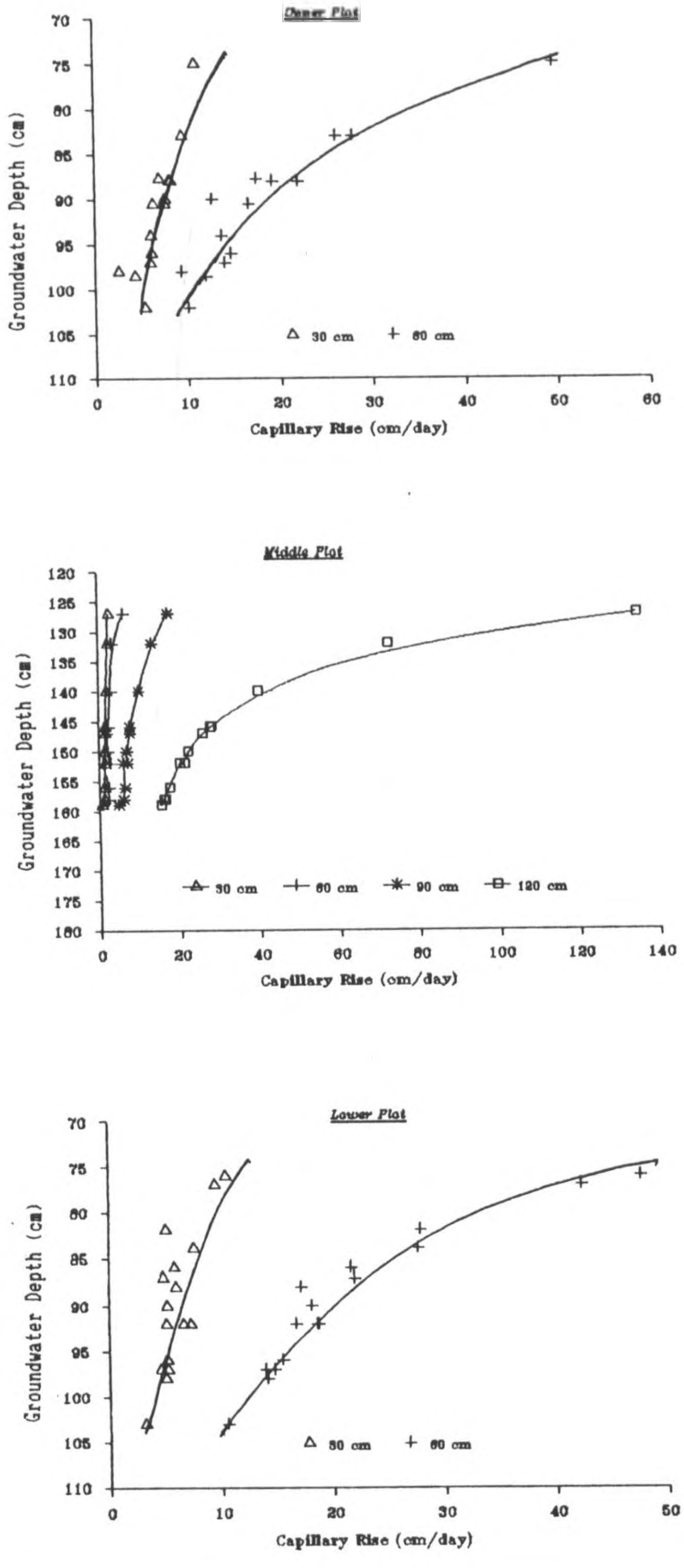

Figure. 4.14. Variations in Upward Soil Water Flux with Ground water Depth.

In terms of capillary rise, the soil profile can be divided into three zones: the upper zone (0-30 cm), middle zone (30-90 cm) and the lower zone (>90 cm).

Upper zone (0-30 cm).

The soil in this zone was sandy loam. In all three plots, the capillary rise was rather low; about 2.5-10.0 cm/day in the upper plot, 0.5-3.0 cm/day for the middle plot and 4.5-10.5 cm/day for the lower plot with ground water level in these plots being in the range of 83-102 cm, 127-160 cm, 76-103 cm respectively when there was upward soil water flux.

Middle zone (30-90 cm).

This zone consisted of sandy loam, loamy sand and sand clay loam layers which were associated with the relatively high capillary rise compared to the 0-30 cm upper soil profile zone. Capillary rise here varied from about 9-50 cm/day, 0.5-17 cm/day and 14-48 cm/day in the upper, middle and lower plots respectively.

Lower zone (>90 cm).

In the upper and lower plots, there was no capillary rise in this zone throughout the experimental period. This is attributed to the high ground water table level that persisted during the data collection period. The zero flux plane was hence between 90 cm and 120 cm soil depth.

In the middle plot where a much lower ground water table level was recorded, the capillary rise was quite high in this zone; in the range of 15-135 cm/day. Here, the zero flux plane was between 120 cm and 150 cm soil depth.

From the above observations, it is clear that capillary rise can supply adequate soil moisture for optimal crop growth and yield. Apart from a few days where the capillary rise was less than the potential evapotranspiration (ET_o) in the 0-30 cm soil profile zone, the rest of the soil profile had capillary rise exceeding the average potential evapotranspiration of 5.73 mm/day (highest being 6.7 mm/day and the lowest being 4.6 mm/day experienced in the months of February and June respectively).

Due to the clay content of the lower soil profile (lower zone >90 cm soil depth), soil water retention is high. Such stored soil moisture can then be utilized to replenish crop water requirements in days of water shortage and if not adequate then consideration of supplemental irrigation becomes vital. Laboratory analysis of the ground water sample (see Table 4.8) showed that the water was very suitable for irrigation purposes.

Table 4.8. Physical and Chemical properties of ground water sample.

pH	7.1
Electrical Conductivity (mhos/cm)	210
Sodium (me/l)	0.43
Potassium (me/l)	0.01
Calcium (me/l)	0.28
Magnesium (me/l)	0.65
Carbonates (me/l)	Trace
Bicarbonates (me/l)	0.06
Chlorides (me/l)	3.00
Sulphates (me/l)	2.63
Sodium Adsorption Ratio	0.60

Remarks: Water was very suitable for irrigation purpose on most soils for most crops.

Under high potential evapotranspiration conditions, a combination of drip irrigation with capillary rise in supplying soil moisture for crop growth should be recommended where feasible. Results obtained from this study showed that at a ground water depth of 130 cm, the capillary rise at the soil depth range of 30-90 cm ranged from 0 to 20 cm/day and was relatively high. At the ground water depth of 120 cm, capillary rise was about 130 cm/day. At any ground water depth, the capillary rise was highest nearer the water table level and decreased exponentially upwards in the soil profile as the soil wetness or soil moisture decreased.

From the relationship of capillary rise with ground water depth the following was observed:

(i) With a ground water depth of 130 cm or lower, the capillary rise is almost constant and below 20 cm/day for the 0-90 cm depth of soil volume.

(ii) In the upper soil profile (above 90 cm soil depth), the capillary rise decreased rapidly with increasing water table depth below the soil surface. This could be attributed to reduced soil moisture content; with larger pores emptying first and moisture flow taking place through increasingly smaller pores as soil water potential increased.

(iii) Higher up in the soil profile (at 30 cm soil depth and above) capillary rise ceases. This could be due to water transport as film flow along the outer surface of the soil particles due to great reduction in soil moisture and very high soil matric suction.

4.4 Soil Water Balance

A water balance study was undertaken over the seven months experimental period. Capillary rise and deep percolation components were evaluated at 60 cm (soil depth with maximum root activity) and the net soil water flux obtained per month. Actual crop evapotranspiration (ETc) was obtained by multiplying the average monthly potential evapotranspiration (ETo) values with a crop factor of 0.9 (taken as the average for most crops).

Noting that runoff was negligible due to the high soil infiltration rate and gentle topography of the experimental site, the water balance was evaluated using the procedure described by Equation 2.12 (Payne *et al.* 1991). On a monthly basis there was negligible deep percolation at 60 cm soil depth due to the shallow ground water table over the experimental period at the three sites. Values of the actual crop evapotranspiration and rainfall were similar for all three sites.

Values for the water balance components of the three Experimental Sites are given in Table 4.9 and their variation over the experimental period presented in Figure 4.15.

Table 4.9. Soil water balance components of the three Experimental Sites.

			Upper Plot		Middle Plot		Lower Plot	
Month	R	ET_c	CR	ds	CR	ds	CR	ds
Dec	100.0	161.1	170.0	0.1	15.1	-46.0	175.9	114.8
Jan	81.0	182.7	207.7	106.0	20.4	-81.3	176.3	74.6
Feb	114.0	170.1	226.2	170.1	28.1	-28.0	321.2	265.1
Mar	173.0	180.9	145.8	137.9	23.2	15.3	247.2	239.3
Apr	230.0	153.9	123.4	199.5	23.6	99.7	215.4	291.5
May	171.0	144.0	142.8	169.8	24.0	51.0	144.1	171.1
Jun	101.0	124.2	358.3	335.1	45.7	22.5	331.7	308.5

ds = Change in soil water storage (mm).
R = Cumulative rainfall (mm).
ET_c = Actual crop evapotranspiration (mm).
CR = Upward soil water flux or capillary rise (mm).

Upper Plot

Between the months of December and March, rainfall was low and crop evapotranspiration relatively high; giving rise to high capillary rise. The net change in soil moisture was then low. With the start of the long rains (accompanied by lower daily temperatures) around March, rainfall contribution to soil wetness increased resulting in the lowering of both capillary rise and crop evapotranspiration. This trend continued upto around end of May when rainfall started to decrease. Henceforth capillary rise contribution to soil moisture supply increased with some consequent increase in available soil moisture at the 60 cm soil depth.

Middle Plot

Due to the low ground water table observed at this site, there was some soil moisture deficit between the months of December and February; hence the negative soil moisture change (see Figure 4.15). Profile water distribution at this site indicated that in the rainy period (March-May), soil moisture increased mainly due to rainfall contribution as capillary rise was rather low (below 50 mm). With reduced rainfall towards the end of May, the capillary rise contribution to soil moisture supply started to increase.

Lower Plot

Due to high ground water table observed at this site throughout the experimental period, capillary rise contribution to soil moisture supply was quite high with a peak value of about 320 mm in February. During the rainy period (March-May) the capillary rise contribution lowered upto about 145 mm around mid April, rising again towards the end of May due to reduced rainfall contribution to soil wetting.

The soil water deficit; taken as the difference between the crop evapotranspiration and the available soil moisture (noted as soil moisture change) in the soil profile represents the amount of water that was supplied through drip irrigation. From Figure 4.15, this deficit was mostly between the months of December and February especially where the ground water table was equal to or below 150 cm depth from the soil surface. The results shown in Figure 4.15 also indicate that capillary rise of about 145 mm corresponding to a ground water table depth of about 1.0 m below the soil surface can adequately meet the crop water requirements.

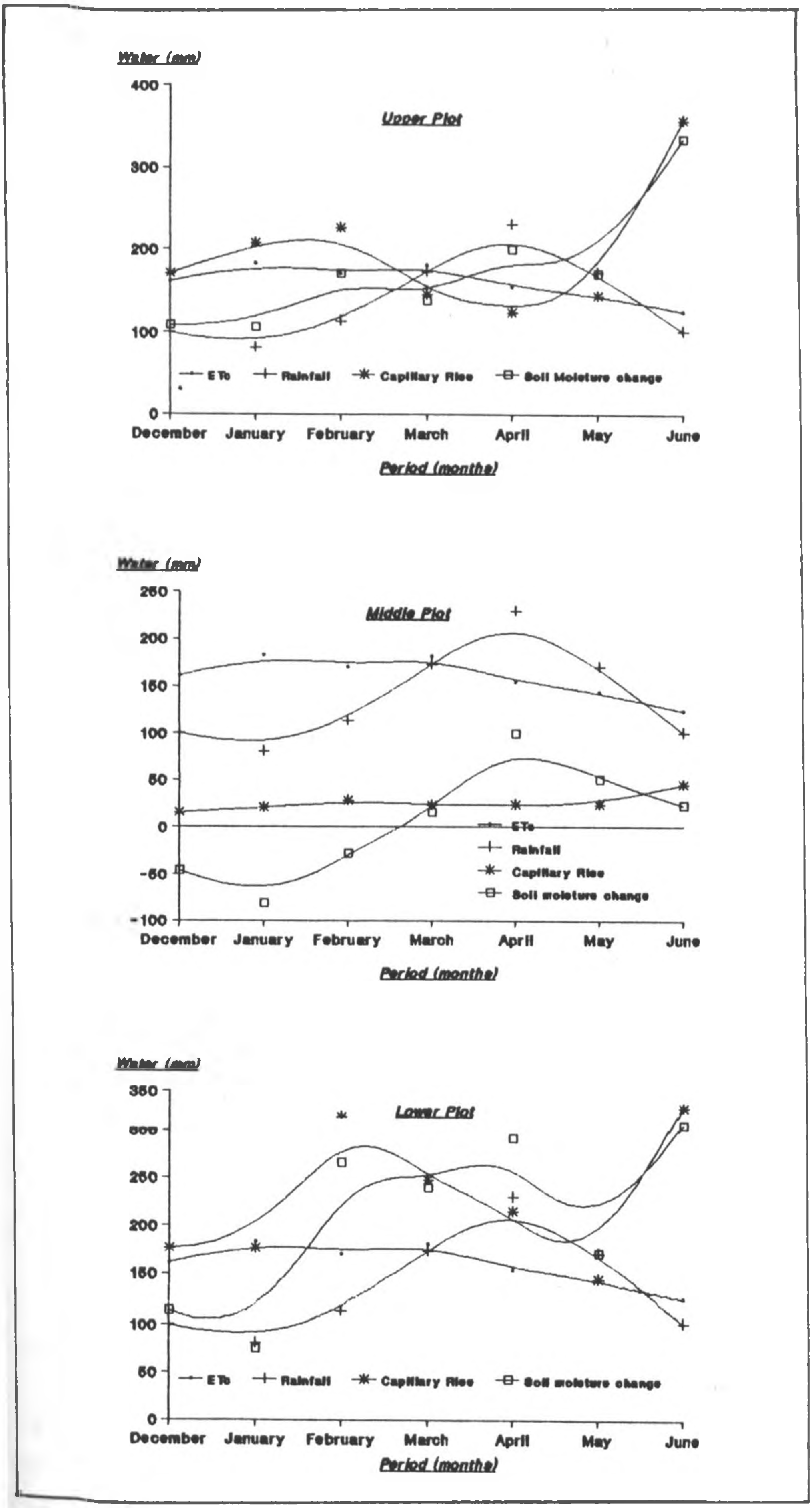

Figure. 4.15. Soil Water Balance components of three Experimental Sites.

5.0 SUMMARY AND CONCLUSIONS

5.1 Summary

Soils at the Experimental Site are fluvisols (Typic Ustifluvents) mainly characterized by alluvial deposits and varying organic matter content with soil depth. The top soil texture is predominantly sandy loam.

Due to stratification, other soil physical properties such as bulk density, porosity, pH, hydraulic conductivity, available soil moisture also vary down the soil profile. The moderately acidic nature of the soil makes it suitable for citrus farming as microbial activity is high resulting in availability of most nutrients to plants.

The final soil water infiltration rate of 20 mm/hr is high mainly due to the sandy nature of the soil especially the top soil layers. Though the sandy nature of the soil enhances soil water intake, it results in rather low soil water retention capacity, implying need for frequent water replenishment through irrigation for growing crops in areas with no other sources of water.

Hence the option of drip irrigation in growing tree crops (especially citrus) in such soils should be encouraged where continuous water application at low discharge rates is possible. With proper design considerations, the drip water application can be tailored to match the crop water requirements resulting in high irrigation efficiency and better crop yields in terms of quantity and quality.

In drip irrigation, soil water flow is influenced by both drip factors and the initial soil moisture conditions. Where ground water exists, upward soil water flux contribution in supplying soil moisture is significant and can greatly supplement the irrigation requirements. Monitoring the influence of drip factors, initial soil moisture conditions and ground water table on soil water flow was the gist of this research study.

Applied from a single source emitter, soil water flows in three dimensions. An almost stable wetted surface diameter is attained while the wetted depth steadily increases resulting in an elongated wetted soil volume. At any initial soil moisture conditions and same duration of water application, the wetted soil volume increases with an increase in emitter discharge rate. As the initial soil moisture decreases, the wetted soil volume for a particular drip discharge rate and duration of water application decreases. This is due to the fact that as the soil gets drier, more pore space is emptied hence becoming available for water storage.

In sandy loam soils, the capillary forces are relatively weak and gravity has relatively more influence on the resulting wetting pattern beyond six hours of continuous drip water application for 4 and 8 l/hr; and 8 hours for the 2 and 3 l/hr discharge rates. The extent of the vertical component of the soil water flow for these discharge rates is greater while the horizontal one is smaller; which enhances the elongation of the wetting pattern.

Field tests show that with the initial soil moisture conditions at about 0.3 bars moisture suction and with emitter discharge rates of 2 and 3 l/hr, the matric suction of the soil profile upto a total depth of 150 cm would be at or below 0.1 bars after 8 hours of continuous drip water application. With 4 and 8 l/hr emitter discharge rates, this condition occurs after about 5 to 6 hours of continuous water application.

Variation in soil matric suction throughout the soil profile observed after allowing for about 12 hours of soil water redistribution could be due to spatial variability in soil texture among other factors. Under drip water application, soil water potential increases with depth down the soil profile; with the lowest case near the emitter location or point of water application. The soil water potentials within the wetted zone for all drip discharge rates (upto 150 cm soil depth) ranged from 30 to 180 cm (0.03-0.18 bars) before substantial soil water redistribution took place.

The experimental results obtained from these sandy loam soils with a ground water table at 80-100 cm below the soil surface showed that the soil above it remains at about 0.3 bars soil matric suction on average. With a water table level at 150 cm depth, soil above 30 cm depth was at about 1.0 bar; soil at 60 cm depth and below was in the range of 0.2-1.0 bar; the soil matric suction decreased towards the water table due to soil moisture replenishment through capillary flux. The effect of evaporation on soil water withdrawal was most effective in the first 30 cm depth soil layer.

Any recharge that resulted in water table rise, led to the lowering of soil matric suction throughout the soil profile; the extent and spread within the soil profile depended mainly on the amount or depth of recharge, antecedent soil moisture content and any prevalent losses e.g through evaporation. The capillary rise of the Experimental Site soil is rather high probably due to the loam and clay loam component of the soil but also is enhanced by the high evaporative demand within the Study Area.

With the ground water depth within 100-150 cm, the soil volume above it can be maintained on average below 1.0 bar soil matric suction by the upward soil water flux (capillary rise). Thus capillary rise alone can adequately supply soil moisture for most crops with root zones extending throughout this soil depth. This makes such a situation suitable for growing oranges or citrus crops having an effective rooting depth of 120 cm.

5.2 Conclusions

From the foregoing results one can conclude that the information obtained from this study would prove useful on the interrelationships between drip factors, antecedent soil moisture content and the resulting water flow, and final wetting pattern. Thus knowing the crop rooting pattern, water requirements and the soil water retention characteristics, irrigation scheduling and the available capital for investment, one can chose a suitable drip irrigation system meeting the requirements especially of supplying crop water requirements at nearly the crop consumptive rate with high water application and irrigation efficiency.

Though developed only from a limited number of experiments, this information can be useful in the design of drip water application systems especially in sandy loam soils and even so where use of ground water contribution to crop soil moisture supply is possible.

In spite of the said information, it is very difficult to predict the wetting pattern until reliable and easier mathematical methods are developed.

Further considerations of drip irrigation application to specific crops, their rooting patterns, water requirements and probably considering water balance components as applied to different climatic zones, soils and tillage operations where irrigated agriculture is practised or has a high potential for future exploitation are recommended.

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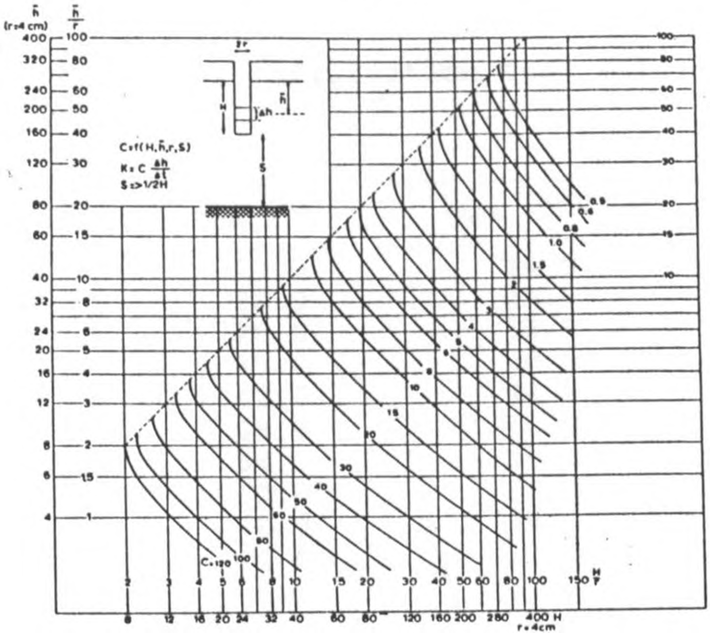
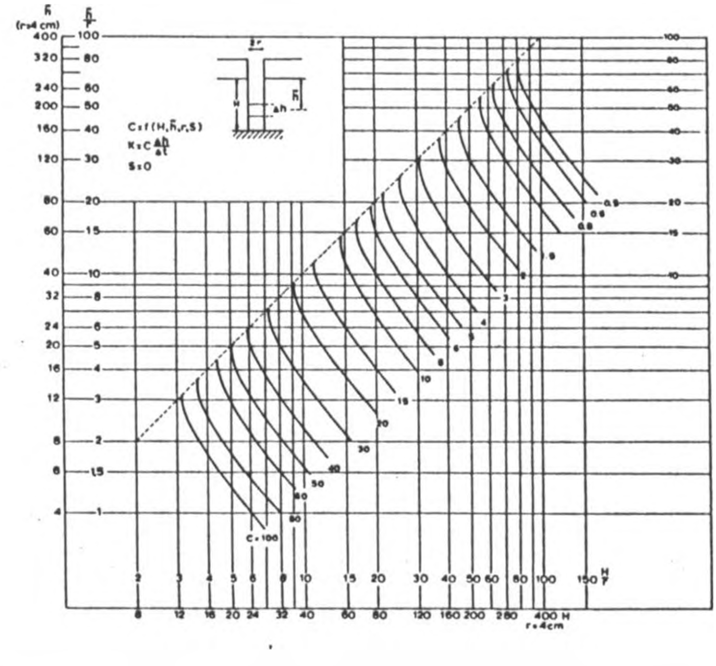


Appendix 3.1 (a) Nomograph for determination of C in auger-hole method (after Ernst, 1950).



Appendix 3.1 (b) Nomograph for determination of C in auger-hole method (after Ernst, 1950).

Appendix 4.1. Soil infiltration test data.

Time (min)	I_{cum} (mm)	I_{rate} (mm/hr
15.0	11.0	44.0
30.0	20.0	36.0
45.0	28.0	32.0
60.0	35.0	28.0
90.0	42.0	24.0
105.0	49.0	28.0
120.0	56.0	24.0
135.0	62.0	24.0
150.0	68.0	24.0
165.0	74.0	24.0
180.0	80.0	24.0
195.0	82.5	26.0
210.0	90.0	24.0
225.0	97.0	24.0
240.0	103.0	24.0
255.0	109.0	24.0
240.0	115.0	24.0
255.0	120.0	24.0
270.0	125.0	20.0
285.0	130.0	20.0
300.0	135.0	20.0
330.0	140.0	20.0

Appendix 4.2. Drip water flow patterns from a single source (measurements in cm).

ASMS = Antecedent Soil Matric Suction
L = Left wetted soil radius
R = Right wetted soil radius

1. Drip Discharge Rate = 2 l/hr

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
0.22	1.0	0.0	21.0	20.0	15.0	18.0	16.0	25.0
		5.0	18.0	16.5	15.0	15.0	15.0	25.0
		10.0	14.0	16.0	13.0	12.0	12.0	24.0
		15.0	11.0	14.0	12.0	11.0	11.0	22.0
		20.0	10.0	11.0	12.0	9.0	10.0	19.0
		25.0	4.0	2.0	8.0	6.0	12.0	15.0
		30.0	0.0	0.0	3.0	1.0	6.0	11.0
		35.0			0.0	0.0	2.0	4.0
		40.0					0.0	0.0
	2.0	0.0	21.0	28.0	17.0	28.0	27.0	25.0
		5.0	17.0	26.0	15.0	24.0	25.5	23.0
		10.0	15.0	25.0	15.0	22.0	22.0	21.0
		15.0	16.0	25.0	15.0	20.0	18.0	19.0
		20.0	15.0	24.0	15.0	18.0	16.5	18.0
		25.0	15.0	22.0	16.0	17.0	16.0	17.0
		30.0	14.0	20.0	13.0	17.0	13.0	15.0
		35.0	11.0	18.0	13.0	15.0	13.0	11.5
		40.0	8.0	18.0	7.0	11.0	6.0	8.0
		45.0	7.0	18.0	3.0	4.0	2.0	3.0
		50.0	7.0	11.0	0.0	0.0	0.0	0.0
		55.0	2.0	4.0				
		60.0	0.0	0.0				
	3.0	0.0	27.0	29.0	22.0	32.0	24.0	21.0
		5.0	27.0	26.0	16.0	30.0	22.0	22.0
		10.0	27.0	27.0	16.0	24.0	22.0	21.0
		15.0	28.0	26.0	17.0	22.0	20.0	21.0
		20.0	24.0	25.0	17.0	22.0	19.5	20.5
		25.0	18.0	23.0	20.0	21.0	19.0	19.5
		30.0	17.0	22.0	19.0	24.0	18.0	19.0
		35.0	17.0	23.0	20.0	23.0	17.0	16.0
		40.0	15.0	20.0	18.0	20.0	15.0	16.0
		45.0	13.0	22.0	17.0	20.0	12.5	14.5
		50.0	13.0	18.0	17.0	18.0	10.0	13.0
		55.0	11.0	14.0	14.0	13.0	4.0	6.0

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		60.0	6.0	6.0	10.0	7.0	0.0	0.0
		65.0	0.0	0.0	5.0	2.0		
		70.0			0.0	0.0		
	6.0	0.0	33.0	35.0	33.0	35.0	32.0	31.0
		5.0	27.0	33.0	32.0	34.0	32.0	30.0
		10.0	23.0	27.0	33.0	35.0	31.0	29.0
		15.0	21.0	22.0	31.0	33.0	29.0	25.0
		20.0	19.0	16.0	27.0	35.0	25.0	24.0
		25.0	18.0	20.0	23.0	33.0	23.0	24.0
		30.0	16.0	19.0	22.0	28.0	25.0	25.0
		35.0	16.0	18.0	19.0	29.0	23.0	24.0
		40.0	14.0	19.0	19.0	27.0	22.0	23.0
		45.0	13.0	10.0	20.0	25.5	20.0	27.0
		50.0	7.0	5.0	18.0	21.0	17.0	19.0
		55.0	0.0	0.0	18.0	14.0	19.0	9.0
		60.0			13.0	8.0	12.0	6.0
		65.0			7.0	3.0	6.0	1.0
		70.0			0.0	0.0	0.0	0.0
0.31	1.0	0.0	21.0	18.0	15.0	24.0	15.0	20.0
		5.0	17.0	16.0	14.0	22.0	14.0	19.0
		10.0	12.0	15.0	12.0	19.0	16.0	20.0
		15.0	9.0	13.0	10.0	16.0	11.0	16.5
		20.0	7.0	8.0	8.0	13.0	6.0	10.0
		25.0	3.0	2.0	2.0	6.0	2.0	4.0
		30.0	0.0	0.0	0.0	0.0	0.0	0.0
	2.0	0.0	20.0	28.0	16.0	27.0	23.0	27.0
		5.0	17.0	26.0	15.0	24.0	20.0	25.0
		10.0	15.0	25.0	15.0	21.0	18.0	25.0
		15.0	15.0	24.0	15.0	19.0	18.0	23.0
		20.0	14.0	23.0	14.0	17.0	15.0	21.5
		25.0	14.0	21.0	14.0	15.0	14.0	14.5
		30.0	10.0	23.0	11.0	14.0	11.0	13.0
		35.0	11.0	18.0	11.0	11.0	9.0	7.5
		40.0	8.0	10.0	4.0	3.0	6.0	8.0
		45.0	4.0	6.0	0.0	0.0	0.0	0.0
		50.0	0.0	0.0				
	3.0	0.0	26.0	29.0	21.0	32.0	32.0	21.0
		5.0	26.0	26.0	16.0	29.0	21.0	21.0
		10.0	23.0	27.0	16.0	24.0	20.0	21.0
		15.0	23.0	26.0	17.0	22.0	17.5	20.0
		20.0	20.0	24.0	17.0	20.0	18.0	19.0

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		25.0	17.0	22.0	18.0	19.5	18.0	18.0
		30.0	16.0	24.0	18.0	22.0	15.0	16.5
		35.0	17.5	22.0	19.0	19.0	14.0	13.5
		40.0	15.0	17.5	17.0	18.0	10.0	12.0
		45.0	11.0	14.0	12.0	18.0	7.0	8.0
		50.0	12.0	10.0	13.0	12.0	2.0	2.0
		55.0	6.0	7.0	12.0	12.0	0.0	0.0
		60.0	0.0	0.0	6.0	7.0		
		65.0			0.0	0.0		
	6.0	0.0	31.0	34.0	32.0	34.0	32.0	31.0
		5.0	26.0	31.0	30.0	30.0	31.0	29.0
		10.0	22.0	25.0	32.0	29.0	29.0	28.0
		15.0	20.0	22.0	28.0	32.0	25.0	23.0
		20.0	18.0	15.0	25.5	30.0	20.0	23.0
		25.0	15.0	16.0	21.0	32.0	21.0	21.0
		30.0	12.0	18.0	20.0	29.0	20.0	21.0
		35.0	12.0	18.0	20.0	29.0	21.0	19.0
		40.0	11.0	16.0	18.0	28.0	17.0	17.0
		45.0	10.0	18.0	19.0	26.5	13.0	16.0
		50.0	13.0	15.0	17.0	23.0	8.0	10.0
		55.0	12.0	10.0	14.0	17.0	2.0	4.0
		60.0	11.0	8.0	8.0	12.5	0.0	0.0
		65.0	10.0	7.0	5.0	6.0		
		70.0	6.0	3.5	0.0	0.0		
		75.0	0.0	0.0				
	8.0	0.0	31.0	33.0	34.0	36.0	30.0	30.0
		5.0	28.0	31.0	33.0	33.0	31.0	32.0
		10.0	25.0	25.0	31.0	32.0	30.0	31.0
		15.0	22.0	22.0	29.0	32.0	29.0	30.0
		20.0	18.0	20.0	27.0	31.5	30.0	29.0
		25.0	16.0	18.0	25.0	30.0	27.0	26.0
		30.0	15.0	19.0	22.0	28.0	24.5	23.0
		35.0	17.0	18.0	18.0	23.0	19.0	18.0
		40.0	17.0	17.0	16.0	17.5	16.0	17.0
		45.0	18.0	19.0	18.0	19.0	16.0	16.0
		50.0	16.0	15.0	16.0	17.0	16.0	16.0
		55.0	14.0	13.0	14.0	14.0	15.0	14.0
		60.0	13.0	13.0	12.0	12.0	13.0	14.0
		65.0	12.0	13.0	12.0	10.0	13.0	11.0
		70.0	11.0	12.0	11.0	9.0	11.0	10.0
		75.0	10.0	10.5	8.0	8.0	10.0	6.5
		80.0	7.0	8.0	4.0	3.0	7.0	5.0
		85.0	0.0	0.0	0.0	0.0	2.0	2.0

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		90.0					0.0	0.0
0.46	1.0	0.0	18.0	19.0	17.0	18.0	17.0	16.0
		5.0	18.0	17.5	17.5	17.0	14.0	13.0
		10.0	16.0	16.0	14.0	10.0	10.0	11.0
		15.0	10.0	12.5	7.0	5.0	6.0	5.0
		20.0	7.0	5.0	2.0	1.0	4.0	2.0
		25.0	0.0	0.0	0.0	0.0	0.0	0.0
	2.0	0.0	19.0	26.0	22.0	20.0	17.0	26.0
		5.0	17.0	24.0	20.0	19.0	15.0	23.0
		10.0	14.0	23.0	17.0	17.0	15.0	20.0
		15.0	14.0	22.0	15.0	13.0	15.0	18.0
		20.0	13.0	21.0	10.0	9.5	14.0	16.0
		25.0	13.0	19.0	6.0	10.0	14.0	14.0
		30.0	9.0	20.0	4.0	3.0	11.0	13.0
		35.0	10.0	16.0	0.0	0.0	4.0	3.0
		40.0	6.0	9.0		0.0	0.0	
		45.0	2.0	2.0				
		50.0	0.0	0.0				
	3.0	0.0	22.0	20.0	29.0	26.0	21.0	23.0
		5.0	20.0	20.0	26.0	23.0	22.0	22.0
		10.0	19.0	20.0	25.0	24.0	20.0	21.0
		15.0	16.5	19.0	19.0	23.0	18.0	20.0
		20.0	17.0	18.0	17.0	21.0	18.0	19.0
		25.0	17.0	17.0	15.0	19.0	17.0	17.0
		30.0	14.0	15.0	13.0	14.0	15.0	16.5
		35.0	13.0	12.5	10.0	8.0	14.0	13.0
		40.0	9.0	11.0	6.0	5.0	10.0	11.0
		45.0	6.0	7.0	3.0	2.5	7.0	8.0
		50.0	1.0	2.0	0.0	0.0	3.0	4.0
		55.0	0.0	0.0			0.0	0.0
	6.0	0.0	45.0	40.0	30.0	32.0	30.0	30.0
		5.0	40.0	42.0	25.0	29.0	30.0	29.0
		10.0	42.0	42.0	21.0	22.0	29.0	28.0
		15.0	40.0	38.0	19.0	20.0	27.0	24.0
		20.0	37.0	35.0	17.0	13.0	23.0	23.0
		25.0	36.0	36.0	14.0	14.0	21.0	23.0
		30.0	34.0	34.0	11.0	16.0	23.0	24.0
		35.0	26.0	26.5	11.0	16.0	21.0	23.0
		40.0	20.0	21.0	10.0	15.0	20.0	22.0
		45.0	18.0	17.0	9.0	16.0	18.0	26.0
		50.0	13.0	14.0	12.0	13.0	15.0	18.0

cont'd

Soil Depth (cm)	Site 1		Site 2		Site 3	
	L	R	L	R	L	R
55.0	10.0	8.0	11.0	7.0	17.0	10.0
60.0	7.0	4.0	4.0	2.0	8.0	4.0
65.0	3.0	2.0	0.0	0.0	0.0	0.0
70.0	0.0	0.0				

2. Drip Discharge Rate = 3 l/hr

ASMS = Antecedent Soil Matric Suction
L = Left wetted soil radius
R = Right wetted soil radius

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
0.22	1.0	0.0	20.0	26.0	24.0	25.0	24.0	23.0
		10.0	17.0	24.0	23.0	23.0	25.0	25.0
		15.0	15.0	23.0	24.0	25.0	26.0	27.0
		20.0	18.0	22.0	18.0	19.0	23.0	25.0
		25.0	18.0	18.0	16.0	17.0	18.0	20.0
		30.0	16.0	14.0	8.0	12.0	16.0	15.0
		35.0	12.0	12.0	5.0	6.0	12.0	12.0
		40.0	4.0	6.0	0.0	0.0	7.5	5.0
		45.0	0.0	0.0		3.0	3.0	4.0
		50.0					3.0	1.0
		55.0					0.0	0.0
	2.0	0.0	25.0	28.0	26.0	28.0	24.0	23.0
		5.0	28.0	32.0	27.0	27.0	25.0	25.0
		10.0	28.0	30.0	28.0	27.0	26.0	27.0
		15.0	25.0	27.0	26.0	25.0	23.0	25.0
		20.0	21.0	23.0	22.0	22.0	18.0	20.0
		25.0	17.0	16.0	18.0	15.0	16.0	15.0
		30.0	14.0	13.0	14.0	12.0	12.0	12.0
		35.0	11.0	8.0	8.0	10.0	7.5	5.0
		40.0	6.5	5.0	5.0	4.0	3.0	4.0
		45.0	3.0	4.0	2.0	2.0	3.0	1.0
		50.0	0.0	0.0	0.0	0.0	0.0	0.0
	4.0	0.0	32.0	26.0	30.0	30.0	33.0	32.0
		5.0	33.0	22.0	32.0	31.0	34.0	35.0

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		10.0	32.5	19.0	30.0	31.0	35.0	34.0
		15.0	29.0	18.0	28.0	30.0	31.5	30.0
		20.0	28.0	20.0	26.0	26.0	27.0	26.0
		25.0	27.0	19.0	23.0	24.0	24.0	21.0
		30.0	25.0	20.0	20.0	22.0	20.0	19.0
		35.0	30.0	20.0	18.0	18.0	17.0	16.0
		40.0	29.0	20.0	18.0	18.0	15.0	20.0
		45.0	28.0	21.0	17.0	14.0	14.0	17.0
		50.0	29.0	18.0	12.0	10.0	12.0	12.0
		55.0	22.0	17.0	8.0	7.0	7.5	6.0
		60.0	16.0	12.0	5.0	4.0	4.0	6.0
		65.0	8.0	6.0	0.0	0.0	3.0	6.0
		70.0	4.0	2.0			2.0	4.0
		75.0	0.0	0.0			0.0	0.0
	6.0	0.0	31.0	33.0	29.0	29.0	43.0	43.0
		5.0	28.0	30.0	30.0	30.0	33.0	35.0
		10.0	27.0	25.0	31.0	31.0	32.0	34.0
		15.0	26.0	24.0	29.0	28.0	31.0	33.0
		20.0	22.0	28.0	26.0	26.0	30.0	32.0
		25.0	23.0	33.0	24.0	23.0	28.0	27.0
		30.0	22.0	33.0	20.0	21.0	26.0	26.0
		35.0	21.0	32.0	17.5	16.0	22.0	22.0
		40.0	22.0	31.0	14.0	13.0	22.0	20.0
		45.0	24.0	30.0	11.0	11.0	18.0	17.0
		50.0	25.0	26.0	12.0	13.0	17.0	17.0
		55.0	18.0	25.0	10.0	11.0	14.0	16.0
		60.0	14.0	17.0	8.0	8.0	14.0	10.0
		65.0	11.0	13.0	7.0	7.0	6.0	7.0
		70.0	6.0	10.0	5.0	4.0	3.0	2.5
		75.0	4.0	5.0	3.0	2.0	0.0	0.0
		80.0	0.0	0.0	0.0	0.0		
	8.0	0.0	45.0	40.0	42.0	43.0	40.0	39.0
		5.0	40.0	42.0	44.0	46.0	41.0	40.0
		10.0	42.0	42.0	45.0	46.0	43.0	42.0
		15.0	40.0	38.0	41.0	40.0	40.0	40.0
		20.0	37.0	35.0	38.0	38.0	38.0	36.0
		25.0	36.0	36.0	36.0	37.0	35.0	35.0
		30.0	34.0	34.0	31.5	32.0	34.0	35.0
		35.0	31.0	32.0	30.0	30.0	30.0	31.0
		40.0	30.0	32.0	27.0	27.0	27.0	28.0
		45.0	28.0	28.0	25.0	25.0	29.0	28.0
		50.0	26.0	26.5	23.0	23.0	25.0	24.0
		55.0	23.0	24.0	20.0	19.0	21.0	20.0

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		60.0	22.0	21.0	17.0	18.0	18.0	18.0
		65.0	20.0	20.0	16.0	20.0	15.0	14.0
		70.0	22.0	21.0	18.0	20.0	11.0	11.5
		75.0	20.0	21.0	18.0	18.0	8.0	10.0
		80.0	18.0	17.0	14.0	12.0	10.0	10.0
		85.0	13.0	14.0	15.0	14.0	9.0	6.0
		90.0	10.0	8.0	8.0	10.0	4.0	2.5
		95.0	7.0	4.0	5.0	6.0	0.0	0.0
		100.0	3.0	2.0	4.0	2.0		
		105.0	0.0	0.0	0.0	0.0		
0.31	1.0	0.0	18.0	19.0	18.0	16.0	19.0	16.0
		5.0	20.0	19.0	18.0	18.0	20.0	19.0
		10.0	17.0	15.0	17.0	16.0	19.0	19.0
		15.0	13.0	12.0	14.0	14.0	16.0	15.0
		20.0	9.0	8.0	9.0	10.0	12.0	11.0
		25.0	6.0	5.0	6.0	4.0	8.0	6.0
		30.0	4.0	3.0	2.0	1.0	2.0	4.0
		35.0	2.0	3.0	0.0	0.0	0.0	0.0
		40.0	0.0	0.0				
	2.0	0.0	26.0	25.0	27.0	27.0	24.0	23.0
		5.0	26.0	26.0	24.0	25.0	26.0	27.0
		10.0	25.0	25.0	28.0	28.0	24.0	23.0
		15.0	23.0	24.0	25.0	23.0	20.0	18.0
		20.0	19.0	20.0	18.0	17.0	19.0	19.0
		25.0	20.0	13.0	14.0	14.0	17.0	15.0
		30.0	18.0	15.0	13.0	12.0	13.0	14.0
		35.0	12.0	14.0	14.0	14.0	12.0	12.0
		40.0	11.0	10.0	10.0	11.5	7.0	7.0
		45.0	8.0	6.0	8.0	9.0	6.0	4.0
		50.0	4.0	3.0	5.0	5.0	2.0	1.0
		55.0	2.0	2.0	3.0	2.0	0.0	0.0
		60.0	0.0	0.0	0.0	0.0		
	4.0	0.0	26.0	30.0	31.0	26.0	31.0	32.0
		5.0	23.0	27.0	31.0	22.0	32.0	33.0
		10.0	22.0	23.0	30.5	17.0	33.0	33.0
		15.0	20.5	20.0	27.0	18.0	30.0	30.0
		20.0	17.0	15.0	26.0	20.0	28.0	27.0
		25.0	16.0	16.0	25.0	20.0	26.0	25.0
		30.0	12.0	14.0	23.0	22.0	23.0	23.0
		35.0	10.0	11.5	20.0	18.0	21.0	21.0
		40.0	7.0	4.0	19.0	14.0	20.0	20.0
		45.0	3.0	2.0	12.0	8.0	17.0	16.0

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		50.0	0.0	0.0	6.0	2.0	15.0	14.0
		55.0			0.0	0.0	12.0	12.0
		60.0					9.0	9.0
		65.0					6.0	5.0
		70.0					0.0	0.0
	6.0	0.0	33.0	32.0	34.0	31.0	30.0	32.0
		5.0	34.0	35.0	34.0	33.0	28.0	29.0
		10.0	30.0	28.0	33.0	32.0	25.5	29.0
		15.0	28.0	28.0	30.0	29.0	25.0	28.0
		20.0	26.0	26.0	27.0	28.0	22.0	27.0
		25.0	24.0	23.0	26.0	26.0	20.0	21.0
		30.0	24.0	24.0	27.0	25.0	20.0	20.0
		35.0	20.0	18.0	25.0	25.0	18.0	18.0
		40.0	19.0	17.0	20.0	21.0	17.0	14.0
		45.0	16.0	15.0	17.0	18.0	10.0	6.0
		50.0	14.0	14.0	14.0	11.0	5.0	4.0
		60.0	10.0	12.0	10.0	7.0	0.0	0.0
		65.0	11.0	11.0	6.0	3.0		
		70.0	10.0	10.0	2.0	3.0		
		75.0	8.0	8.0	1.0	1.5		
		80.0	3.0	2.0	0.0	0.0		
		85.0	0.0	0.0				
	8.0	0.0	35.0	36.0	40.0	40.0		
		5.0	36.0	37.0	38.0	39.0		
		10.0	36.0	36.0	38.0	38.0		
		15.0	34.0	35.0	35.0	34.0		
		20.0	30.0	32.0	33.0	34.0		
		25.0	31.0	32.0	29.5	32.0		
		30.0	28.0	27.0	30.0	31.0		
		35.0	24.0	23.5	27.0	31.0		
		40.0	21.0	21.0	25.5	30.0		
		45.0	20.0	23.0	25.0	28.0		
		50.0	18.0	20.0	23.0	25.5		
		55.0	17.0	16.0	20.0	23.0		
		60.0	15.0	15.0	18.0	18.0		
		65.0	15.0	15.0	15.0	13.5		
		70.0	13.0	12.0	8.0	6.0		
		75.0	11.0	11.0	4.0	4.0		
		80.0	7.0	12.0	3.0	2.5		
		85.0	10.0	11.0	0.0	0.0		
		90.0	9.0	10.0				
		95.0	5.0	4.0				
		100.0	0.0	0.0				

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
0.48	1.0	0.0	24.0	25.0	21.0	23.0	24.0	25.0
		5.0	20.0	20.0	23.0	20.0	20.0	20.0
		10.0	17.0	14.5	17.0	14.0	17.0	14.5
		15.0	10.0	6.5	10.0	6.0	10.0	5.0
		20.0	4.0	4.0	4.0	2.0	4.0	3.0
		25.0	2.0	2.0	3.0	1.0	0.0	0.0
		30.0	0.0	0.0	0.0	0.0		
	2.0	0.0	30.0	29.0	28.0	30.0	20.0	21.5
		5.0	31.0	32.0	27.0	27.0	24.0	25.0
		10.0	26.0	28.0	26.0	25.0	20.0	19.0
		15.0	18.0	25.0	23.0	21.0	19.0	20.0
		20.0	13.5	17.0	19.0	20.0	16.0	15.0
		25.0	12.0	15.0	17.0	14.0	13.0	11.0
		30.0	8.0	11.0	11.0	8.0	7.0	6.0
		35.0	10.0	10.0	10.0	7.0	5.0	3.0
		40.0	7.0	10.0	6.0	5.0	2.0	2.0
		45.0	4.0	5.0	0.0	0.0	0.0	0.0
		50.0	0.0	0.0				
	4.0	0.0	36.0	38.0	39.0	40.0	37.0	39.0
		5.0	37.0	38.0	36.0	37.0	38.0	39.0
		10.0	36.0	36.0	30.0	27.0	36.0	38.0
		15.0	32.0	31.0	32.0	29.0	34.0	35.0
		20.0	33.0	30.0	28.0	26.0	28.0	27.5
		25.0	28.0	25.0	25.0	24.0	25.0	23.0
		30.0	21.0	20.0	18.0	14.0	19.0	20.0
		35.0	17.0	16.0	14.0	11.0	14.0	15.0
		40.0	14.0	11.0	11.0	8.0	10.0	10.0
		45.0	8.0	7.0	8.0	6.0	7.0	6.0
		50.0	6.0	4.0	4.0	3.0	5.0	5.0
		55.0	2.0	3.0	2.0	2.0	4.0	5.0
		60.0	1.0	1.5	0.0	0.0	0.0	0.0
		65.0	0.0	0.0				
	6.0	0.0	45.0	46.0	41.0	43.0		
		5.0	47.0	48.0	43.0	43.0		
		10.0	47.0	45.0	40.0	40.0		
		15.0	43.0	41.0	39.0	37.0		
		20.0	40.0	39.0	37.0	33.0		
		25.0	35.0	36.0	34.0	30.0		
		30.0	27.0	25.0	32.0	27.0		
		35.0	23.0	22.0	27.0	19.0		
		40.0	20.0	18.0	21.0	20.0		
		45.0	16.0	14.0	17.0	18.0		

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		50.0	10.0	8.0	14.0	13.0		
		55.0	6.0	7.0	8.0	9.0		
		60.0	3.0	2.0	5.0	6.0		
		65.0	0.0	0.0	3.0	4.5		
		70.0			0.0	0.0		
	8.0	0.0	46.0	45.0	44.0	44.0		
		5.0	46.0	43.0	46.0	46.0		
		10.0	44.0	41.5	45.0	45.0		
		15.0	41.0	39.0	43.0	43.0		
		20.0	40.0	37.5	40.0	37.0		
		25.0	38.5	35.5	39.0	39.0		
		30.0	36.0	33.0	33.0	31.0		
		35.0	34.0	28.0	30.0	28.0		
		40.0	27.0	24.0	25.0	23.5		
		45.0	24.0	18.0	18.0	17.0		
		50.0	21.0	19.0	15.0	14.0		
		55.0	18.0	17.0	10.0	10.0		
		60.0	12.0	14.0	8.0	7.0		
		65.0	8.0	10.0	6.0	6.0		
		70.0	10.0	10.0	4.0	4.0		
		75.0	7.0	6.0	2.0	2.0		
		80.0	4.0	2.0	2.0	2.5		
		85.0	3.0	1.0	1.0	1.0		
		90.0	0.0	0.0	0.0	0.0		

cont'd

3. Drip Discharge Rate = 4 l/hr

ASMS = Antecedent Soil Matric Suction
L = Left wetted soil radius
R = Right wetted soil radius

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
0.20	1.0	0.0	19.0	31.0	25.0	31.0	20.0	25.0
		5.0	16.0	31.0	28.0	20.0	19.0	26.0
		10.0	15.0	30.0	29.0	21.0	15.0	24.0
		15.0	16.0	27.0	19.0	22.0	16.0	23.0
		20.0	14.0	20.0	22.0	17.0	15.0	22.0
		25.0	11.0	18.0	17.0	17.0	14.0	23.0
		30.0	3.0	10.0	14.0	12.0	12.0	15.0
		35.0	2.0	5.0	14.0	8.0	5.0	8.0
		40.0	0.0	0.0	13.0	6.0	3.0	5.0
		45.0			6.0	2.0	0.0	0.0
		50.0			0.0	0.0		
	2.0	0.0	22.0	32.0	26.0	33.0	25.0	28.0
		5.0	20.0	34.0	31.0	26.0	21.0	27.0
		10.0	16.0	32.0	30.0	24.0	19.0	26.0
		15.0	17.0	28.0	27.0	25.0	20.0	25.0
		20.0	17.0	25.0	28.0	24.0	19.0	24.0
		25.0	13.0	19.0	25.0	25.0	19.0	24.0
		30.0	16.0	21.0	19.0	18.0	19.0	23.0
		35.0	15.0	23.0	20.0	18.0	19.0	23.0
		40.0	16.0	19.0	22.0	19.0	18.0	22.0
		45.0	14.0	18.0	21.0	19.0	17.0	20.0
		50.0	10.0	12.0	21.0	23.0	16.0	18.0
		55.0	6.0	7.0	17.0	18.0	12.0	15.0
		60.0	0.0	0.0	15.0	16.0	6.0	8.0
		65.0			7.5	11.0	0.0	0.0
		70.0			3.0	5.0		
		75.0			0.0	0.0		
	4.0	0.0	27.0	33.0	38.0	27.0	26.0	32.0
		5.0	23.0	34.0	32.0	29.0	23.0	32.0
		10.0	18.0	33.5	24.0	21.0	23.0	30.0
		15.0	19.0	30.0	24.0	21.0	23.0	29.0
		20.0	21.0	29.0	23.0	20.0	24.0	27.0
		25.0	21.0	28.0	20.0	17.0	23.0	26.0

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		30.0	23.0	26.0	23.0	16.0	23.0	25.0
		35.0	21.0	31.0	20.0	17.0	24.0	24.0
		40.0	26.0	30.0	20.0	16.0	24.0	22.5
		45.0	26.0	29.0	18.0	15.0	22.0	23.0
		50.0	22.0	30.0	17.0	13.0	18.0	21.5
		55.0	19.0	23.0	16.0	12.0	16.0	19.0
		60.0	16.0	24.0	14.0	14.0	13.0	14.0
		65.0	17.0	20.0	12.0	12.0	11.0	10.0
		70.0	11.0	12.0	8.0	10.0	2.0	6.0
		75.0	8.0	9.0	8.0	8.0	1.5	2.0
		80.0	3.0	6.0	2.0	5.0	0.0	0.0
		85.0	0.0	0.0	0.0	0.0		
	6.0	0.0	31.0	33.0	32.0	34.0	31.0	31.0
		5.0	31.0	34.0	27.0	31.0	33.0	28.0
		10.0	32.0	33.5	28.0	26.0	35.0	27.0
		15.0	30.0	31.0	27.0	25.0	34.0	24.0
		20.0	31.0	30.0	24.0	30.0	35.0	28.0
		25.0	30.0	30.0	24.0	34.0	34.0	27.0
		30.0	28.0	29.0	22.0	33.0	33.0	26.0
		35.0	27.0	26.0	22.0	33.0	32.0	18.0
		40.0	28.0	24.0	23.0	33.0	32.0	17.0
		45.0	26.0	25.0	26.0	30.0	32.0	21.0
		50.0	21.0	23.0	25.0	28.0	30.0	23.0
		55.0	20.0	21.0	24.0	27.0	30.0	24.0
		60.0	18.0	16.0	22.0	26.0	35.0	19.0
		65.0	14.0	14.0	22.0	24.0	30.0	25.0
		70.0	10.0	11.0	20.0	20.0	33.0	19.0
		75.0	5.0	7.0	18.0	19.0	33.0	20.0
		80.0	2.0	4.0	16.0	15.0	29.0	14.0
		85.0	0.0	0.0	14.0	8.0	26.0	13.0
		90.0			10.0	6.0	24.0	14.5
		95.0			4.0	2.0	20.0	14.0
		100.0			0.0	0.0	16.0	6.0
		105.0					8.0	5.0
		110.0					3.0	2.0
		115.0					0.0	0.0
	8.0	0.0	49.0	42.0	37.0	38.0	32.0	38.0
		5.0	40.0	33.0	33.0	36.0	34.0	34.0
		10.0	39.0	36.0	33.0	36.0	22.0	33.5
		15.0	33.0	35.0	32.0	35.0	24.0	32.0
		20.0	33.0	27.0	33.0	34.0	26.0	31.0
		25.0	35.0	27.0	33.0	34.0	26.0	32.0
		30.0	33.0	25.0	31.0	33.5	27.0	37.0

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		35.0	31.0	24.0	31.0	31.0	29.0	34.0
		40.0	34.0	26.0	30.0	27.5	30.0	33.0
		45.0	33.0	28.0	29.0	28.0	32.0	33.0
		50.0	30.0	24.0	26.0	26.0	31.0	34.0
		55.0	30.0	27.0	24.0	25.0	28.0	31.0
		60.0	28.0	26.0	21.0	25.0	28.0	31.0
		65.0	28.0	27.0	21.0	25.5	33.0	33.0
		70.0	28.0	23.0	19.0	24.0	32.0	32.0
		75.0	23.0	20.0	19.0	22.0	31.0	31.0
		80.0	18.0	15.0	20.0	20.0	29.0	30.0
		85.0	13.0	13.0	18.0	20.0	29.0	28.0
		90.0	6.0	7.0	16.0	19.0	26.0	24.0
		95.0	6.0	6.0	14.0	18.0	19.0	20.0
		100.0	4.0	5.0	8.0	16.0	14.0	11.0
		105.0	2.0	2.0	5.0	12.0	10.0	6.0
		110.0	1.0	3.0	3.0	6.0	5.0	3.0
		115.0	0.0	0.0	0.0	0.0	0.0	0.0
0.3	1.0	0.0	20.0	23.0	21.0	23.0	29.0	22.0
		5.0	19.0	20.0	18.0	22.0	29.0	21.0
		10.0	18.0	19.0	17.0	20.0	28.0	17.0
		15.0	13.0	16.0	16.0	17.0	25.0	18.0
		20.0	9.0	13.0	15.0	14.0	20.0	17.0
		25.0	7.0	9.0	13.0	10.0	21.0	21.0
		30.0	5.0	3.0	7.0	6.0	15.0	14.0
		35.0	2.0	2.0	4.0	3.0	14.0	7.0
		40.0	0.0	0.0	1.0	2.0	10.0	5.0
		45.0			0.0	0.0	3.0	2.0
		50.0					0.0	0.0
	2.0	0.0	29.0	30.0	28.0	30.0	27.0	26.0
		5.0	29.0	25.0	24.0	31.0	26.0	25.0
		10.0	28.0	24.0	20.0	30.0	25.0	23.0
		15.0	29.0	24.0	21.0	26.0	21.0	20.0
		20.0	30.0	23.0	22.0	24.0	21.0	18.0
		25.0	21.0	15.0	22.0	22.5	18.0	16.0
		30.0	15.0	13.0	22.0	21.0	17.0	14.0
		35.0	16.0	11.0	22.0	27.0	16.0	13.0
		40.0	11.0	10.0	26.0	22.0	14.0	13.0
		45.0	11.0	9.0	23.0	23.0	12.0	10.0
		50.0	9.0	9.0	22.0	15.0	9.0	7.0
		55.0	5.0	7.0	15.0	12.0	5.0	4.0
		60.0	0.0	0.0	8.0	6.0	0.0	0.0
		65.0			0.0	0.0		

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
	4.0	0.0	31.0	30.0	33.0	28.0	37.0	28.0
		5.0	27.0	30.0	33.0	24.0	31.0	30.0
		10.0	28.0	28.0	32.5	19.0	23.0	22.0
		15.0	27.0	28.0	29.0	20.0	23.0	22.0
		20.0	27.0	26.0	28.0	22.0	22.0	21.0
		25.0	25.0	24.0	27.0	22.0	19.0	18.0
		30.0	22.0	20.0	25.0	24.0	22.0	17.0
		35.0	19.0	17.0	30.0	22.0	19.0	18.0
		40.0	17.0	16.0	29.0	27.0	19.0	17.0
		45.0	16.0	14.0	30.0	25.0	17.0	16.0
		50.0	15.0	14.0	29.0	23.0	16.0	14.0
		55.0	11.0	10.0	22.0	20.0	15.0	13.0
		60.0	6.0	7.0	23.0	17.0	13.0	15.0
		65.0	3.0	3.0	19.0	18.0	12.0	12.0
		70.0	0.0	0.0	11.0	12.0	10.0	8.0
		75.0			3.0	5.0	4.0	3.0
		80.0			0.0	0.0	0.0	0.0
	6.0	0.0	36.0	34.0	32.0	33.0	33.0	36.0
		5.0	32.0	33.0	28.0	30.0	27.0	30.0
		10.0	31.0	34.0	28.0	26.0	28.0	31.0
		15.0	31.0	32.0	27.0	25.0	28.0	27.0
		20.0	30.0	31.0	24.0	30.0	24.0	23.0
		25.0	28.0	28.0	25.0	33.0	25.0	25.0
		30.0	26.0	26.0	22.0	33.0	24.0	22.0
		35.0	26.0	25.0	22.0	33.0	22.0	20.0
		40.0	26.0	23.0	23.0	33.0	20.0	19.0
		45.0	25.0	20.0	26.0	30.0	20.0	20.0
		50.0	22.0	19.0	25.0	28.0	18.0	17.0
		55.0	20.0	17.0	24.0	27.0	15.0	16.0
		60.0	16.0	15.0	23.0	25.0	14.0	13.0
		65.0	14.0	13.0	22.0	24.0	12.0	10.0
		70.0	10.0	11.0	15.0	14.0	7.0	5.0
		75.0	9.0	7.0	9.0	8.0	5.0	3.0
		80.0	4.0	3.0	6.0	3.0	2.0	1.0
		85.0	0.0	0.0	0.0	0.0	0.0	0.0
	8.0	0.0	42.0	37.0	36.0	42.0	38.0	36.0
		5.0	34.0	33.0	31.0	34.0	36.5	36.0
		10.0	36.0	30.0	28.0	31.0	36.0	34.5
		15.0	35.0	29.0	27.0	30.0	35.0	33.0
		20.0	27.0	33.0	24.0	28.0	33.0	31.0
		25.0	26.0	34.0	23.0	27.0	31.0	30.0
		30.0	25.0	32.0	23.0	27.0	30.0	28.0
		35.0	24.0	31.0	23.0	27.0	30.0	27.0

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1 L	Site 1 R	Site 2 L	Site 2 R	Site 3 L	Site 3 R
		40.0	26.0	30.0	23.0	30.0	28.0	23.0
		45.0	28.0	30.0	24.0	32.0	27.0	24.0
		50.0	24.0	28.0	23.0	29.0	26.0	24.0
		55.0	27.0	27.0	26.0	30.0	25.0	23.0
		60.0	26.0	26.0	26.0	26.0	25.5	21.0
		65.0	23.0	24.0	23.0	24.0	22.0	20.0
		70.0	20.0	21.0	24.0	24.0	21.0	20.0
		75.0	16.0	21.0	24.0	22.0	19.0	17.0
		80.0	13.0	19.0	24.0	18.0	18.0	15.0
		85.0	7.0	19.0	20.0	20.0	16.0	11.0
		90.0	7.0	20.0	19.0	17.0	13.0	10.0
		95.0	6.0	18.0	17.0	13.0	12.0	5.0
		100.0	4.0	14.0	9.0	6.0	7.0	3.0
		105.0	3.0	6.0	7.0	3.0	0.0	0.0
		110.0	0.0	0.0	0.0	0.0		
4.5	1.0	0.0	26.0	17.0	24.0	19.0	25.0	26.0
		5.0	20.0	15.0	21.0	18.0	28.0	18.0
		10.0	15.0	10.0	20.0	17.0	28.0	14.0
		15.0	9.0	6.0	17.0	12.0	16.0	12.5
		20.0	6.0	4.0	14.0	8.0	13.0	10.0
		25.0	2.0	1.0	10.0	6.0	8.0	6.0
		30.0	0.0	0.0	3.0	2.0	3.0	1.0
		35.0			0.0	0.0	0.0	0.0
	2.0	0.0	33.0	26.0	30.0	29.0	27.0	25.0
		5.0	31.0	18.0	28.5	24.0	27.0	24.0
		10.0	20.0	14.0	25.0	23.0	26.0	22.0
		15.0	18.0	13.0	23.0	20.0	26.0	21.0
		20.0	16.0	10.0	18.0	19.0	22.0	19.0
		25.0	5.0	6.0	18.0	14.0	21.0	17.0
		30.0	4.0	2.0	16.0	13.0	20.0	15.0
		35.0	2.0	1.0	11.0	12.0	19.0	13.0
		40.0	0.0	0.0	8.0	10.0	18.0	12.0
		45.0			4.0	8.0	16.0	12.0
		50.0			3.0	5.0	8.0	8.0
		55.0			0.0	0.0	4.0	2.0
		60.0					0.0	0.0
	5.0	0.0	49.0	30.0	40.0	42.0	38.0	32.0
		5.0	45.0	34.0	38.0	36.0	32.0	27.0
		10.0	28.0	16.0	38.0	34.0	31.0	22.0
		15.0	28.0	16.0	37.0	30.0	28.0	21.0
		20.0	28.0	16.0	37.0	28.0	24.0	17.0
		25.0	25.0	17.0	35.5	26.0	25.0	16.0

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		30.0	24.0	15.0	34.0	25.0	24.0	17.0
		35.0	22.0	13.0	32.0	26.0	27.0	17.0
		40.0	21.0	11.0	30.5	25.0	25.0	18.0
		45.0	17.0	10.0	28.0	24.0	23.0	14.0
		50.0	14.0	2.0	28.0	17.0	20.0	13.0
		55.0	7.0	0.0	25.0	14.0	18.0	10.0
		60.0	0.0	0.0	16.0	10.0	13.0	8.0
		65.0			11.0	7.0	10.0	9.0
		70.0			5.5	4.0	0.0	0.0
		75.0			0.0	0.0		
	8.0	0.0	44.0	42.0	42.0	33.0		
		5.0	36.0	30.0	33.0	28.0		
		10.0	33.0	29.0	32.0	24.0		
		15.0	32.0	26.0	30.0	23.0		
		20.0	30.0	25.0	29.0	20.0		
		25.0	29.0	22.0	26.0	19.0		
		30.0	29.0	21.0	26.0	20.0		
		35.0	29.0	21.0	29.0	19.0		
		40.0	32.0	21.0	28.0	19.0		
		45.0	31.0	22.0	28.0	19.0		
		50.0	28.0	21.0	28.0	9.0		
		55.0	26.0	24.0	24.0	18.0		
		60.0	26.0	24.0	19.0	15.0		
		65.0	22.0	21.0	16.0	17.0		
		70.0	24.0	22.0	11.0	12.0		
		75.0	22.0	22.0	9.5	8.0		
		80.0	20.0	22.0	6.0	4.0		
		90.0	16.0	14.0	2.0	2.0		
		95.0	11.0	10.0	0.0	0.0		
		100.0	5.0	2.0				
		105.0	0.0	0.0				

cont'd

4. Drip Discharge Rate = 8 l/hr

ASMS = Antecedent Soil Matric Suction
L = Left wetted soil radius
R = Right wetted soil radius

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
0.2	1.0	0.0	33.0	49.0	31.0	37.0	32.0	31.0
		5.0	31.0	48.0	28.0	29.0	31.0	30.5
		10.0	31.0	41.0	22.0	22.0	22.0	22.0
		15.0	28.0	41.0	17.0	7.0	17.0	19.0
		20.0	23.0	20.0	15.0	8.0	16.0	10.0
		25.0	18.0	6.0	6.0	2.0	6.0	9.0
		30.0	4.0	1.0	1.0	0.0	6.0	8.0
		35.0	0.0	0.0		0.0	4.0	3.0
		40.0					1.0	1.0
		45.0					0.0	0.0
	2.0	0.0	36.0	54.0	32.0	33.0	32.0	34.0
		5.0	34.0	53.0	33.0	30.0	25.0	30.0
		10.0	33.0	52.0	30.0	27.0	23.0	30.0
		15.0	34.0	48.0	29.0	24.0	22.0	30.0
		20.0	33.0	34.0	21.0	22.0	21.0	27.0
		25.0	32.0	25.0	18.0	20.0	21.0	28.0
		30.0	32.0	24.0	17.0	18.0	16.0	29.0
		35.0	32.0	16.0	15.0	16.0	14.0	26.0
		40.0	30.0	10.0	13.0	12.0	9.0	19.0
		45.0	29.0	8.0	13.0	13.0	9.0	14.0
		50.0	27.0	6.0	10.0	11.0	0.0	0.0
		55.0	29.0	3.0	7.0	9.0		
		60.0	21.0	5.0	5.0	4.0		
		65.0	11.0	6.5	0.0	0.0		
		70.0	0.0	0.0				
	4.0	0.0	39.0	40.0	44.0	43.0	36.0	45.0
		5.0	39.0	35.0	34.0	35.0	33.0	37.0
		10.0	37.0	32.0	29.0	36.0	32.0	32.0
		15.0	33.0	31.0	27.0	35.0	31.0	29.0
		20.0	29.0	27.0	26.0	35.0	30.0	26.0
		25.0	26.0	28.0	25.0	35.0	26.0	29.0
		30.0	25.0	28.0	23.0	38.0	31.0	30.0
		35.0	27.0	28.0	22.0	35.0	28.0	27.0

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		40.0	25.0	27.0	21.0	36.0	27.0	21.0
		45.0	24.0	25.0	21.0	34.0	26.0	21.0
		50.0	23.0	22.0	19.0	31.0	26.0	23.0
		55.0	24.0	20.0	14.0	23.0	25.0	20.0
		60.0	25.0	20.0	12.0	21.0	22.0	20.0
		65.0	21.0	19.0	8.0	20.0	24.0	27.0
		70.0	18.5	17.0	6.0	12.0	21.0	29.0
		75.0	16.0	15.0	4.0	14.0	20.0	20.0
		80.0	10.0	11.0	2.0	6.0	18.0	13.0
		85.0	7.0	8.0	0.0	0.0	15.0	14.0
		90.0	4.0	5.0			14.0	16.0
		95.0	2.0	3.0			10.0	14.0
		100.0	0.0	0.0			8.0	10.0
		105.0					0.0	0.0
	6.0	0.0	42.0	42.0	42.0	46.0	41.0	68.0
		5.0	39.0	39.0	40.0	38.0	40.0	64.0
		10.0	35.0	36.0	39.0	36.0	40.0	64.0
		15.0	30.0	34.0	38.0	36.0	40.0	64.0
		20.0	28.0	31.0	39.0	32.5	40.0	45.0
		25.0	28.0	31.0	37.0	33.0	37.0	38.0
		30.0	31.0	32.0	37.0	33.0	38.0	38.0
		35.0	32.0	31.0	37.0	30.0	41.0	36.0
		40.0	33.0	29.0	35.0	30.0	45.0	34.0
		45.0	33.0	33.0	36.0	31.0	41.0	30.0
		50.0	35.0	36.0	36.0	29.0	40.0	26.0
		55.0	38.0	38.0	34.0	27.5	41.0	28.0
		60.0	40.0	38.0	35.0	28.0	40.0	30.0
		65.0	36.0	40.0	32.0	29.0	39.0	31.0
		70.0	33.0	40.0	30.0	29.5	39.0	26.0
		75.0	32.0	35.0	28.0	31.0	40.0	19.0
		80.0	33.0	37.0	29.0	27.0	42.0	20.0
		85.0	35.0	35.0	25.0	24.0	39.0	20.0
		90.0	33.0	35.0	21.0	20.0	39.0	20.0
		95.0	31.0	33.0	14.0	16.0	38.0	19.0
		100.0	30.0	32.0	11.0	12.0	39.0	18.0
		105.0	29.0	31.0	7.0	9.0	34.0	18.0
		110.0	24.0	30.0	5.0	3.0	31.0	17.0
		115.0	23.0	26.0	0.0	0.0	31.0	16.0
		120.0	23.0	26.0			27.0	14.0
		125.0	19.0	22.0			23.0	8.0
		130.0	17.0	16.0			16.0	6.0
		135.0	16.0	13.0			11.0	5.0
		140.0	9.0	13.0			5.0	2.0
		145.0	4.0	8.0			0.0	0.0

cont'd

ASMS (bars)	Elapsed Time (hrs.	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		150.0	0.0	0.0				
	8.0	0.0	41.0	68.0	48.5	50.0	54.0	53.0
		5.0	40.0	66.0	46.0	42.0	56.0	54.0
		10.0	40.0	64.0	46.0	39.0	50.0	49.0
		15.0	41.0	64.0	45.0	39.0	49.0	48.0
		20.0	41.0	45.0	42.0	37.5	47.0	48.0
		25.0	38.0	38.0	40.0	37.0	47.0	47.0
		30.0	40.0	38.0	38.0	36.0	42.0	41.0
		35.0	41.0	36.0	36.0	35.0	38.0	37.0
		40.0	45.0	34.0	34.0	35.0	38.0	38.0
		45.0	42.0	31.0	32.0	33.0	39.0	40.0
		50.0	42.0	27.0	35.0	32.0	40.0	40.0
		55.0	42.0	30.0	35.0	33.0	38.0	37.0
		60.0	40.0	31.0	33.5	35.0	36.0	35.0
		65.0	40.0	31.0	31.0	37.0	34.0	36.0
		70.0	39.0	31.0	28.0	34.0	33.0	34.0
		75.0	42.0	26.0	28.0	33.0	33.0	33.0
		80.0	42.0	20.0	29.0	33.0	28.0	28.0
		85.0	42.0	21.0	29.0	32.0	26.0	25.0
		90.0	40.0	22.0	25.0	33.0	23.0	22.0
		95.0	39.0	22.0	23.0	34.0	22.0	21.0
		100.0	39.0	20.0	20.0	33.0	22.0	19.0
		105.0	39.0	21.0	20.0	31.0	20.0	20.0
		110.0	34.0	20.0	15.0	27.0	18.0	17.0
		115.0	31.0	18.0	12.0	29.0	18.0	18.0
		120.0	31.0	18.0	8.0	26.0	11.0	15.0
		125.0	27.0	15.0	6.0	22.0	16.0	8.0
		130.0	24.0	10.0	4.0	12.0	14.0	6.0
		135.0	8.0	2.0	0.0	0.0	10.0	4.0
		140.0	0.0	0.0			6.0	1.0
		145.0					0.0	0.0
0.3	1.0	0.0	42.0	32.0	36.0	35.0	42.0	40.0
		5.0	46.0	30.0	35.0	32.0	38.0	32.0
		10.0	42.0	31.0	31.0	30.0	29.0	24.0
		15.0	40.0	28.0	25.0	26.0	16.0	14.0
		20.0	36.0	23.0	14.0	11.0	8.0	6.0
		25.0	16.0	8.0	8.0	6.0	2.0	4.0
		30.0	4.0	3.0	2.0	3.0	0.0	0.0
		35.0	0.0	0.0	0.0	0.0		
	4.0	0.0	42.0	42.0	40.0	38.0		
		5.0	34.0	35.0	38.0	39.0		
		10.0	30.0	36.0	36.0	36.0		

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		15.0	27.0	36.0	34.0	32.0		
		20.0	26.0	32.0	31.0	34.0		
		25.0	24.0	30.0	32.0	33.0		
		30.0	22.0	28.0	28.0	29.5		
		35.0	21.0	27.0	26.0	27.0		
		40.0	20.0	25.0	24.0	29.0		
		45.0	18.0	22.5	25.0	26.0		
		50.0	18.0	23.0	17.0	18.0		
		55.0	16.0	22.0	14.0	20.0		
		60.0	17.0	20.0	14.0	16.0		
		65.0	16.0	16.0	12.0	14.0		
		70.0	17.0	16.0	14.0	14.0		
		75.0	15.0	13.0	11.0	12.0		
		80.0	8.0	7.0	8.0	6.0		
		85.0	5.0	4.0	3.0	1.0		
		90.0	2.0	2.0	0.0	0.0		
		95.0	0.0	0.0				
	8.0	0.0	40.0	46.0	38.0	42.0		
		5.0	39.0	46.0	38.0	40.0		
		10.0	39.0	45.0	40.0	40.0		
		15.0	38.0	43.0	37.0	38.0		
		20.0	39.0	42.0	34.0	37.0		
		25.0	38.0	40.0	32.0	35.0		
		30.0	38.0	40.0	33.0	36.0		
		35.0	36.0	40.0	32.0	34.0		
		40.0	35.5	39.0	30.0	32.0		
		45.0	34.0	37.0	28.0	30.0		
		50.0	30.0	36.0	25.0	28.0		
		55.0	31.0	36.0	23.0	27.0		
		60.0	33.0	32.0	18.0	24.0		
		65.0	29.0	28.0	16.0	17.5		
		70.0	27.0	28.0	14.0	16.0		
		75.0	27.0	29.0	12.0	13.0		
		80.0	30.0	27.0	7.0	10.0		
		85.0	26.0	25.0	3.0	6.0		
		90.0	24.0	22.5	0.0	0.0		
		95.0	20.0	18.0				
		100.0	21.0	20.0				
		105.0	16.0	14.0				
		110.0	12.0	11.0				
		115.0	8.0	10.0				
		120.0	9.0	8.0				
		125.0	6.0	4.0				
		130.0	2.0	3.0				

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
		135.0	0.0	0.0				
0.5	1.0	0.0	30.0	29.0	40.0	34.0	39.0	43.0
		5.0	28.0	27.0	45.0	31.0	36.0	34.0
		10.0	23.0	22.0	40.0	33.0	30.0	26.0
		15.0	17.0	20.0	36.0	23.0	18.0	14.0
		20.0	14.0	15.0	20.0	14.0	8.0	6.0
		25.0	8.0	10.0	6.0	4.0	4.0	2.0
		30.0	2.0	3.0	0.0	0.0	0.0	0.0
		35.0	0.0	0.0				
	2.0	0.0	33.0	31.0	33.0	32.0	40.0	38.0
		5.0	29.0	24.0	30.0	32.0	37.0	37.0
		10.0	29.0	22.0	27.0	28.0	34.0	33.0
		15.0	29.0	21.0	28.0	29.0	30.0	28.0
		20.0	26.0	20.0	27.0	28.0	26.0	25.0
		25.0	27.0	20.0	21.0	23.0	20.0	20.0
		30.0	28.0	15.0	20.0	22.0	17.0	17.0
		35.0	25.0	13.0	17.0	16.0	8.0	10.0
		40.0	18.0	8.0	16.0	17.0	6.0	10.0
		45.0	13.0	8.0	14.0	15.0	8.0	11.0
		50.0	8.0	5.0	10.0	14.0	9.0	10.0
		55.0	4.0	2.0	7.0	5.0	4.0	3.0
		60.0	0.0	0.0	2.0	3.0	0.0	0.0
		65.0			0.0	0.0		
	4.0	0.0	38.0	39.0	40.0	40.0	42.0	39.0
		5.0	39.0	39.0	32.0	33.0	38.0	37.0
		10.0	36.0	35.0	28.0	34.0	35.0	34.0
		15.0	31.0	33.0	25.0	34.0	32.0	30.0
		20.0	33.0	30.0	24.0	30.0	27.0	28.0
		25.0	31.0	30.0	22.0	28.0	28.0	28.0
		30.0	28.0	27.0	20.0	26.0	28.0	29.0
		35.0	24.0	26.0	19.0	25.0	26.0	25.0
		40.0	25.0	26.0	18.0	23.0	22.0	20.0
		45.0	20.0	21.0	18.0	22.5	18.0	19.0
		50.0	16.0	18.0	18.0	23.0	15.0	16.0
		55.0	16.0	18.0	16.0	22.0	13.0	11.0
		60.0	14.0	13.0	17.0	20.0	8.0	7.0
		65.0	12.0	12.0	16.0	16.0	8.0	6.0
		70.0	11.0	10.0	10.0	12.0	6.0	6.0
		75.0	9.5	10.0	6.0	7.0	5.0	4.0
		80.0	6.0	4.0	5.0	5.0	2.0	2.5
		85.0	2.0	2.0	3.0	1.0	0.0	0.0
		90.0	0.0	0.0	0.0	0.0		

cont'd

ASMS (bars)	Elapsed Time (hrs)	Soil Depth (cm)	Site 1		Site 2		Site 3	
			L	R	L	R	L	R
	6.0	0.0	45.0	48.0	42.0	41.0		
		5.0	41.0	39.0	39.0	40.0		
		10.0	38.0	34.0	36.0	40.0		
		15.0	37.0	30.0	34.0	40.0		
		20.0	36.0	28.0	31.0	40.0		
		25.0	36.0	29.0	32.0	37.0		
		30.0	34.0	28.0	32.0	38.0		
		35.0	33.0	24.0	31.0	41.0		
		40.0	32.0	36.0	29.0	45.0		
		45.0	31.0	28.0	33.0	41.0		
		50.0	31.0	25.0	36.0	40.0		
		55.0	32.0	25.0	38.0	41.0		
		60.0	30.0	24.0	38.0	40.0		
		65.0	27.0	21.0	40.0	39.0		
		70.0	25.0	23.0	40.0	39.0		
		75.0	22.0	21.0	35.0	40.0		
		80.0	20.0	23.0	37.0	42.0		
		85.0	24.0	21.0	35.0	39.0		
		90.0	24.0	17.0	33.0	38.0		
		95.0	20.0	15.0	18.0	16.0		
		100.0	16.0	14.0	11.0	10.0		
		105.0	8.0	8.0	6.0	5.0		
		110.0	0.0	0.0	0.0	0.0		
	8.0	0.0	45.0	40.0	50.0	51.0		
		5.0	45.0	39.0	48.0	49.0		
		10.0	43.0	39.0	52.0	53.0		
		15.0	42.0	38.0	49.0	49.0		
		20.0	40.0	38.0	47.0	46.0		
		25.0	40.0	36.0	45.0	44.0		
		30.0	39.0	35.0	43.0	43.0		
		35.0	37.0	34.0	43.0	43.0		
		40.0	36.0	30.0	41.0	40.0		
		45.0	36.0	31.0	38.0	37.0		
		50.0	32.0	33.0	37.0	37.0		
		55.0	28.0	29.0	35.0	36.0		
		60.0	27.0	29.0	34.0	34.0		
		65.0	30.0	31.0	33.0	33.0		
		70.0	30.0	30.0	33.0	33.0		
		75.0	29.0	28.0	30.0	33.0		
		80.0	26.0	25.0	31.0	32.0		
		85.0	23.0	23.0	30.0	29.0		
		90.0	20.0	20.0	26.0	22.0		
		95.0	18.0	16.5	18.0	19.0		
		100.0	14.0	13.0	17.0	16.0		

cont'd

Soil Depth (cm)	Site 1		Site 2		Site 3	
	L	R	L	R	L	R
105.0	16.0	15.0	11.0	10.0		
110.0	13.0	12.0	6.0	7.0		
115.0	10.0	9.0	5.0	5.0		
120.0	6.0	5.0	2.0	2.0		
125.0	2.0	1.0	0.0	0.0		
130.0	0.0	0.0				

Appendix 4.3. **Drip water flow patterns at different emitter spacings (measurements in cm).**

ASMS = Antecedent Soil Matric Suction
L = Left wetted soil radius
R = Right wetted soil radius

1. **Drip Discharge Rate = 2 l/hr**

Emitter Spacing = 0.75 m
ASMS = 0.32 bars

Soil Depth (cm)	L	R	L	R
0.0	29.0	23.0	35.0	32.0
5.0	28.0	22.5	33.0	31.0
10.0	27.0	24.5	32.0	30.0
15.0	26.0	24.0	30.0	29.0
20.0	24.0	24.5	27.0	27.0
25.0	21.0	23.0	27.0	27.0
30.0	22.0	25.0	29.0	28.0
35.0	24.0	28.0	28.0	28.0
40.0	25.0	28.0	26.0	29.0
45.0	27.0	27.0	25.0	30.0
50.0	29.0	23.0	24.0	30.0
55.0	28.0	18.0	24.0	27.0
60.0	27.0	19.0	23.0	22.0
65.0	22.0	17.0	18.0	20.0
70.0	20.0	16.0	11.0	12.0
75.0	14.0	13.0	3.0	7.0
80.0	8.0	3.0	0.0	0.0
85.0	0.0	0.0		

Measurements taken after 10 hrs of water application

cont'd

2. **Drip Discharge Rate = 3 l/hr**

Emitter Spacing = 0.75 m
ASMS = 0.31 bars

Soil Depth (cm)	L	R	L	R
0.0	36.0	36.0	38.0	36.0
5.0	39.0	37.0	38.0	38.5
10.0	38.0	36.0	36.0	36.0
15.0	35.5	35.0	33.0	36.0
20.0	32.0	32.0	33.0	34.0
25.0	29.0	32.0	31.0	33.0
30.0	29.0	27.0	28.0	31.0
35.0	27.0	24.0	28.0	29.0
40.0	26.0	24.0	26.5	28.0
45.0	18.0	21.0	26.0	26.0
50.0	15.5	17.0	25.0	23.0
55.0	16.0	16.0	17.5	16.0
60.0	16.0	12.0	14.0	16.0
65.0	14.0	14.0	13.0	13.0
70.0	11.0	11.0	10.0	9.0
75.0	9.0	10.5	8.0	9.0
80.0	9.0	7.0	8.0	10.0
85.0	7.0	7.0	6.0	8.0
90.0	7.0	7.0	6.0	7.0
95.0	5.0	5.0	6.0	4.0
100.0	5.0	3.0	0.0	0.0
105.0	3.0	2.0		
110.0	0.0	0.0		

Measurements taken after 8 hrs of water application

cont'd

3. **Drip Discharge Rate = 4 l/hr**

Emitter Spacing = 0.75 m
ASMS = 0.31 bars

Soil Depth (cm)	L	R	L	R
0.0	46.0	40.0	35.0	37.0
5.0	37.0	32.0	28.0	32.0
10.0	35.0	28.0	27.0	33.0
15.0	35.0	28.0	26.0	33.0
20.0	33.0	25.0	25.0	30.0
25.0	33.0	25.0	25.0	34.0
30.0	33.0	26.0	23.0	38.0
35.0	35.0	25.0	24.0	40.0
40.0	34.0	26.0	25.0	40.0
45.0	34.0	27.0	27.0	40.0
50.0	35.0	27.0	25.0	40.0
55.0	35.0	29.0	25.0	40.0
60.0	33.0	28.0	24.0	40.0
65.0	33.0	32.0	24.0	41.0
70.0	32.0	29.0	22.0	39.0
75.0	30.0	30.0	24.0	38.0
80.0	30.0	28.0	20.0	36.0
85.0	29.0	27.0	20.0	36.0
90.0	27.0	26.0	24.0	20.0
95.0	22.0	22.0	19.0	33.0
100.0	18.0	21.0	19.0	29.0
105.0	14.0	18.0	16.0	26.0
110.0	7.0	16.0	12.0	26.0
115.0	6.0	13.0	9.0	21.0
120.0	0.0	0.0	7.0	27.0
125.0			2.0	10.0
130.0			0.0	0.0

Measurements taken after 8 hrs of water application

cont'd

4 (a). Drip Discharge Rate = 8 l/hr

Emitter Spacing = 0.75 m
ASMS = 0.32 bars

Soil Depth (cm)	L	R	L	R
0.0	41.0	-	-	43.0
5.0	34.0	32.0	31.0	37.0
10.0	33.0	29.0	29.0	27.0
15.0	32.0	32.0	28.0	28.0
20.0	31.0	29.0	25.0	27.0
25.0	26.0	29.0	28.0	27.0
30.0	25.0	27.0	25.0	26.0
35.0	24.0	25.0	27.0	24.0
40.0	23.0	25.0	20.0	24.0
45.0	23.0	24.0	18.0	24.0
50.0	17.0	24.0	12.0	16.0
55.0	13.0	18.0	2.0	7.0
60.0	6.0	7.0	0.0	0.0
65.0	0.0	0.0		

Measurements taken after 2 hrs of water application

4 (b). Drip Discharge Rate = 8 l/hr

Emitter Spacing = 1.0 m
ASMS = 0.31 bars

Soil Depth (cm)	L	R	L	R
0.0	41.0	43.0	48.0	47.0
5.0	40.0	38.0	40.0	39.0
10.0	36.0	37.0	36.0	37.0
15.0	31.0	34.0	32.0	36.0
20.0	28.0	31.0	29.0	38.0
25.0	28.0	30.0	30.0	40.0
30.0	31.0	32.0	29.0	38.0
35.0	33.0	30.0	26.5	33.0
40.0	32.0	30.0	32.0	40.0
45.0	33.0	32.0	30.0	37.0
50.0	35.0	36.0	26.0	38.0

cont'd

Soil Depth (cm)	L	R	L	R
55.0	38.0	38.0	25.0	40.0
60.0	40.0	38.0	24.0	38.0
65.0	37.0	40.0	22.0	37.0
70.0	33.0	39.0	22.0	38.0
75.0	32.0	36.0	21.0	30.0
80.0	31.0	37.0	18.0	28.0
85.0	30.0	35.0	15.0	24.0
90.0	30.0	35.0	14.0	22.5
95.0	31.0	33.0	8.0	22.0
100.0	30.0	31.0	7.0	20.0
105.0	29.0	30.0	7.0	20.0
110.0	24.0	29.0	5.0	11.0
115.0	23.0	26.0	0.0	0.0
120.0	19.0	22.0		
125.0	16.0	15.0		
130.0	10.0	13.0		
135.0	6.0	7.0		
140.0	0.0	0.0		

Measurements taken after 8hrs of water application

Appendix 4.4. Soil matric suction under a fluctuating ground water table.

UPPER PLOT

Soil Depth (cm)		30.0	60.0	90.0	120.0	150.0	Water Depth (cm)
Date	Day	Soil Matric Suction ('x 10^{-3} bars)					
30.11.90	1	9.0	7.0	11.0	8.0	7.0	98.0
4.12.90	5	11.0	8.0	13.0	9.0	7.0	98.0
7.12.90	8	12.0	9.0	11.0	9.0	7.0	98.5
11.12.90	12	13.0	7.0	11.0	9.0	7.0	96.7
14.12.90	15	13.0	7.0	11.0	7.0	7.0	87.7
18.12.90	19	13.0	7.0	11.0	7.0	7.0	89.7
21.12.90	22	13.0	7.0	11.0	7.0	7.0	90.5
25.12.90	26	15.0	7.0	12.0	8.0	7.0	91.0
28.12.90	29	15.0	8.0	11.0	7.0	7.0	94.0
1.01.91	33	19.0	9.0	11.0	9.0	7.0	94.0
4.01.91	36	19.0	9.0	11.0	7.0	12.0	83.0
8.01.91	40	19.0	9.0	9.0	7.0	7.0	84.0
11.01.91	43	19.0	8.0	12.0	7.0	7.0	83.0
18.01.91	50	19.0	18.0	11.0	7.0	7.0	91.0
22.01.91	54	21.0	8.0	11.0	7.0	7.0	88.0
25.01.91	57	23.0	9.0	11.0	7.0	7.0	91.0
29.01.91	61	22.0	8.0	12.0	8.0	8.0	90.5
1.02.91	68	22.0	8.0	11.0	8.0	7.0	91.0
5.02.91	72	22.0	6.0	10.0	8.0	8.0	90.0
8.02.91	75	30.0	8.0	15.0	8.0	8.0	90.0
12.02.91	79	32.0	9.0	15.0	8.0	9.0	102.0
15.02.91	82	33.0	9.0	16.0	9.0	9.0	93.0
19.02.91	86	30.0	10.0	15.0	8.0	10.0	96.0
22.02.91	91	29.0	9.0	14.0	9.0	8.0	96.0
26.02.91	95	25.0	10.0	16.0	10.0	9.0	96.0
1.03.91	98	30.0	9.0	14.0	10.0	8.0	97.0
5.03.91	102	26.0	10.0	15.0	10.0	9.0	97.0
8.03.91	105	26.0	10.0	16.0	10.0	9.0	95.0
12.03.91	109	26.0	10.0	15.0	8.0	9.0	88.0
15.03.91	112	18.0	7.0	10.0	7.0	6.0	66.0
19.03.91	116	12.0	9.0	13.0	8.0	8.0	75.0
22.03.91	119	10.0	8.0	13.0	8.0	8.0	79.0
26.03.91	123	12.0	9.0	12.0	8.0	7.0	81.0
29.03.91	126	12.0	8.0	12.0	8.0	8.0	84.0
2.04.91	130	11.0	8.0	14.0	8.0	7.0	76.0
5.04.91	133	8.0	8.0	12.0	8.0	7.0	72.0
9.04.91	137	7.0	4.0	10.0	6.0	4.0	47.0
12.04.91	140	6.0	5.0	10.0	5.0	4.0	44.0

cont'd

Soil Depth (cm)		30.0	60.0	90.0	120.0	150 0	Water Depth (cm)
Date	Day	Soil Matric Suction ('x 10^{-3} bars)					
16.04.91	144	8.0	6.0	12.0	6.0	5.0	55.0
19.04.91	147	8.0	8.0	12.0	7.0	5.0	57.0
23.04.91	151	10.0	8.0	12.0	9.0	3.0	58.0
26.04.91	154	9.0	7.0	12.0	7.0	6.0	63.0
30.04.91	158	8.0	7.0	12.0	8.0	6.0	70.0
2.05.91	161	8.0	8.0	12.0	7.0	6.0	72.0
7.05.91	165	8.0	8.0	12.0	8.0	8.0	55.0
10.05.91	168	8.0	8.0	10.0	8.0	6.0	53.0
17.05.91	175	8.0	8.0	13.0	9.0	7.0	83.0
24.05.91	182	10.0	8.0	12.0	9.0	8.0	88.0
31.05.91	189	11.0	9.0	14.0	10.0	8.0	90.0
7.06.91	196	12.0	9.0	16.0	10.0	9.0	85.0
14.06.91	204	10.0	9.0	14.0	9.0	6.0	87.0
21.06.91	211	10.0	10.0	14.0	10.0	8.0	90.0
28.06.91	218	12.0	10.0	12.0	9.0	8.0	93.0

MIDDLE PLOT

Soil Depth (cm)		30.0	60.0	90.0	120.0	150 0	Water Depth (cm)
Date	Day	Soil Matric Suction ('x 10^{-3} bars)					
30.11.90	1	12.0	10.0	12.0	14.0	12.0	153.0
4.12.90	5	15.0	11.0	14.0	14.0	14.0	158.0
7.12.90	8	15.0	11.0	13.0	15.0	13.0	159.0
11.12.90	12	21.0	11.0	15.0	14.0	13.0	158.0
14.12.90	15	25.0	11.0	13.0	13.0	13.0	152.0
18.12.90	19	29.0	11.0	13.0	15.0	11.0	145.0
21.12.90	22	29.0	12.0	13.0	13.0	11.0	149.0
25.12.90	26	31.0	11.0	13.0	13.0	13.0	145.0
28.12.90	29	33.0	11.0	13.0	13.0	13.0	152.0
1.01.91	33	38.0	13.0	15.0	15.0	13.0	154.9
4.01.91	36	41.0	13.0	15.0	15.0	12.0	140.0
8.01.91	40	49.0	13.0	15.0	15.0	13.0	142.0
11.01.91	43	51.0	11.0	14.0	13.0	12.0	132.0
18.01.91	50	44.0	11.0	17.0	13.0	12.0	132.0
22.01.91	54	52.0	13.0	13.0	15.0	13.0	146.0
25.01.91	57	56.0	13.0	14.0	15.0	13.0	146.0
29.01.91	61	60.0	13.0	14.0	14.0	12.0	146.0

cont'd

Soil Depth (cm)		30.0	60.0	90.0	120.0	150.0	Water Depth (cm)
Date	Day	Soil Matric Suction ('x 10^{-3} bars)					
1.02.91	68	64.0	14.0	15.0	14.0	12.0	151.0
5.02.91	72	60.0	14.0	14.0	13.0	12.0	150.0
8.02.91	75	65.0	16.0	18.0	15.0	14.0	154.0
12.02.91	79	55.0	18.0	20.0	15.0	15.0	156.0
15.02.91	82	67.0	19.0	20.0	16.0	15.0	151.0
19.02.91	86	69.0	20.0	20.0	15.0	13.0	158.0
22.02.91	91	65.0	20.0	19.0	16.0	14.0	158.0
26.02.91	95	61.0	22.0	20.0	17.0	16.0	158.0
1.03.91	98	60.0	22.0	20.0	15.0	16.0	156.0
5.03.91	102	72.0	25.0	20.0	16.0	15.0	160.0
8.03.91	105	73.0	26.0	20.0	17.0	17.0	160.0
12.03.91	109	68.0	27.0	20.0	17.0	14.0	152.0
15.03.91	112	70.0	28.0	20.0	14.0	11.0	123.0
19.03.91	116	60.0	26.0	20.0	14.0	12.0	127.0
22.03.91	119	60.0	23.0	18.0	14.0	12.0	130.0
26.03.91	123	60.0	24.0	18.0	14.0	12.0	131.0
29.03.91	126	67.0	24.0	18.0	14.0	12.0	135.0
2.04.91	130	67.0	16.0	18.0	13.0	12.0	123.0
5.04.91	133	68.0	10.0	15.0	13.0	10.0	120.0
9.04.91	137	66.0	10.0	14.0	10.0	8.0	84.0
12.04.91	140	12.0	10.0	14.0	10.0	8.0	80.0
16.04.91	144	16.0	12.0	16.0	12.0	10.0	96.0
19.04.91	147	18.0	11.0	16.0	12.0	10.0	101.0
23.04.91	151	21.0	12.0	18.0	13.0	10.0	110.0
26.04.91	154	21.0	12.0	17.0	12.0	10.0	108.0
30.04.91	158	23.0	11.0	17.0	12.0	10.0	117.0
2.05.91	161	26.0	12.0	17.0	12.0	10.0	122.0
7.05.91	165	22.0	12.0	17.0	13.0	12.0	117.0
10.05.91	168	22.0	10.0	16.0	14.0	11.0	123.0
17.05.91	175	18.0	10.0	18.0	13.0	11.0	129.0
24.05.91	182	18.0	10.0	16.0	14.0	12.0	130.0
31.05.91	189	20.0	10.0	20.0	16.0	14.0	117.0
7.06.91	196	22.0	11.0	19.0	15.0	14.0	118.0
14.06.91	204	18.0	10.0	16.0	14.0	14.0	122.0
21.06.91	211	20.0	10.0	17.0	14.0	14.0	128.0
28.06.91	218	23.0	10.0	16.0	15.0	14.0	130.0

cont'd

LOWER PLOT

Soil Depth (cm)		30.0	60.0	90.0	120.0	150.0	Water Depth (cm)
Date	Day	Soil Matric Suction ('x 10^{-3} bars)					
30.11.90	1	12.0	10.0	10.0	10.0	4.0	97.0
4.12.90	5	11.0	9.0	11.0	10.0	5.0	98.0
7.12.90	8	11.0	10.0	11.0	11.0	5.0	103.0
11.12.90	12	12.0	9.0	11.0	11.0	5.0	97.0
14.12.90	15	11.0	7.0	9.0	11.0	5.0	88.0
18.12.90	19	11.0	7.0	9.0	11.0	5.0	91.0
21.12.90	22	10.0	8.0	10.0	11.0	5.0	89.0
25.12.90	26	11.0	9.0	11.0	11.0	5.0	87.0
28.12.90	29	17.0	9.0	11.0	11.0	6.0	90.0
1.01.91	33	12.0	9.0	9.0	11.0	7.0	92.0
4.01.91	36	11.0	9.0	11.0	11.0	5.0	92.0
8.01.91	40	11.0	7.0	10.0	11.0	5.0	74.0
11.01.91	43	11.0	9.0	11.0	11.0	3.0	77.0
18.01.91	50	9.0	9.0	9.0	11.0	5.0	84.0
22.01.91	54	9.0	9.0	10.0	11.0	5.0	87.0
25.01.91	57	9.0	9.0	9.0	11.0	6.0	92.0
29.01.91	61	10.0	8.0	10.0	10.0	5.0	86.0
1.02.91	68	10.0	8.0	10.0	10.0	4.0	88.0
5.02.91	72	8.0	8.0	10.0	10.0	4.0	82.0
8.02.91	75	12.0	10.0	14.0	11.0	7.0	92.0
12.02.91	79	12.0	10.0	13.0	11.0	8.0	84.0
15.02.91	82	14.0	11.0	15.0	12.0	8.0	96.0
19.02.91	86	13.0	11.0	14.0	12.0	8.0	96.0
22.02.91	91	15.0	11.0	13.0	11.0	8.0	97.0
26.02.91	95	14.0	11.0	15.0	12.0	9.0	97.0
1.03.91	98	13.0	11.0	14.0	13.0	9.0	97.0
5.03.91	102	14.0	11.0	11.0	14.0	9.0	98.0
8.03.91	105	15.0	12.0	16.0	12.0	11.0	100.0
12.03.91	109	16.0	11.0	16.0	12.0	7.0	92.0
15.03.91	112	9.0	8.0	12.0	10.0	4.0	70.0
19.03.91	116	12.0	10.0	13.0	10.0	5.0	76.0
22.03.91	119	10.0	10.0	12.0	10.0	5.0	79.0
26.03.91	123	11.0	9.0	12.0	11.0	6.0	76.0
29.03.91	126	11.0	9.0	11.0	10.0	4.0	75.0
2.04.91	130	10.0	10.0	12.0	10.0	4.0	70.0
5.04.91	133	8.0	8.0	10.0	9.0	3.0	66.0
9.04.91	137	8.0	7.0	10.0	8.0	2.0	52.0
12.04.91	140	7.0	6.0	10.0	7.0	3.0	46.0
16.04.91	144	10.0	8.0	12.0	9.0	3.0	56.0
19.04.91	147	8.0	8.0	11.0	10.0	2.0	55.0
23.04.91	151	8.0	6.0	12.0	8.0	7.0	60.0
26.04.91	154	10.0	8.0	11.0	8.0	2.0	56.0

cont'd

Soil Depth (cm)		30.0	60.0	90.0	120.0	150.0	Water Depth (cm)
Date	Day	Soil Matric Suction ('x 10^{-3} bars)					
30.04.91	158	9.0	8.0	10.0	9.0	2.0	60.0
2.05.91	160	10.0	8.0	11.0	8.0	3.0	63.0
7.05.91	165	9.0	8.0	12.0	9.0	7.0	52.0
10.05.91	168	8.0	8.0	8.0	9.0	2.0	70.0
17.05.91	175	9.0	8.0	11.0	8.0	2.0	66.0
24.05.91	182	10.0	10.0	13.0	10.0	6.0	72.0
31.05.91	189	10.0	11.0	12.0	10.0	7.0	80.0
7.06.91	296	10.0	9.0	12.0	10.0	5.0	73.0
14.06.91	204	10.0	8.0	10.0	9.0	2.0	77.0
21.06.91	211	10.0	10.0	12.0	10.0	4.0	85.0
28.06.91	218	11.0	9.0	10.0	10.0	4.0	86.0

Appendix 4.5. Daily rainfall data as recorded at the Experimental Site.

Date	Rainfall amount (mm)	Date	Rainfall amount (mm)
19.12.90	7.0	14.04.91	8.0
20.12.90	8.5	20.04.91	2.0
21.12.90	2.5	21.04.91	3.5
7.01.91	17.0	24.04.91	13.0
8.01.91	7.5	25.04.91	15.0
26.01.91	6.0	26.04.91	1.5
28.01.91	9.0	28.04.91	4.0
31.01.91	13.5	29.04.91	10.0
10.02.91	5.5	1.05.91	2.5
14.02.91	16.0	2.05.91	7.0
21.02.91	1.5	7.05.91	21.0
22.02.91	6.0	9.05.91	15.5
23.02.91	9.0	13.05.91	26.0
24.02.91	5.0	14.05.91	13.0
5.02.91	2.7	20.05.91	3.0
11.03.91	25.0	23.05.91	12.0
13.03.91	45.0	24.05.91	2.0
14.03.91	23.0	25.05.91	2.0
15.03.91	12.0	28.05.91	3.0
25.03.91	23.0	29.05.91	30.0
29.03.91	9.0	31.05.91	10.0
30.03.91	35.0	1.06.91	20.0
2.04.91	3.5	5.06.91	4.0
3.04.91	8.5	7.06.91	2.0
4.04.91	16.0	9.06.91	6.0
5.04.91	3.5	11.06.91	7.0
6.04.91	50.0	12.06.91	4.5
7.04.91	4.0	14.06.91	2.0
8.04.91	30.0	15.06.91	13.0
10.04.91	3.0	17.06.91	9.0
11.04.91	5.0	22.06.91	19.0
12.04.91	30.0	29.06.91	13.0