DEVELOPING A THEORETICAL BASIS FOR DEMAND IRRIGATION OF
ACER RUBRUM

DISSERTATION

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* * * * *

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ABSTRACT

A lysimeter study was conducted to determine evapotranspiration (ET) rates of Red Maple (*Acer Rubrum*) under field conditions in August and September, 1997. The average daily measured ET for the plant for two months was 998.75 g. This measured ET was compared against Fynn, Stanghellini and Penman’s evapotranspiration models which overestimated actual ET rates by 7.0, 10.16 and 25.70% respectively. Simple linear regression analysis showed that a solar radiation or a VPD based stochastic ET model could be successfully used to predict ET in terms of $R^2$ value of 0.875 and 0.684 respectively.

A tension-based, automatic irrigation system was scheduled by a Q-COM controller using a micro-irrigation technique. Plants were irrigated at a potting medium matric potential of 6-10 kPa. Comparison between tension-based irrigation and lysimeter experiments demonstrated the usefulness of the tension-based irrigation scheduling in nursery application. There was no drainage during the experimental periods of irrigation scheduling and average biomass production (wet basis) was approximately 2 kg per tree per month.
A closed-loop, feedback control system monitoring real-time medium tension in the pot was developed to schedule irrigation for nursery plants. The model performed the pot medium water balance and evaluated impacts of water stress on the plant by using reference set points. The calibration and validation of the model was done using experimental data collected between August 26 - September 6, 1997 and September 7 - September 22, 1997 respectively.

Multivariable, first and second order regression models with an $R^2$ of 0.883 and 0.899 respectively showed that the first order multiple linear regression model was adequate to demonstrate effects of climate factors on measured ET. The most important input climate factors affecting ET at the 90% confidence level were leaf temperature, media-water tension, and solar radiation based on the first order linear multiple regression model.

Single-factor, one-way analysis of variance (ANOVA) showed that plant growth medium tension was not highly correlated with ET at the 95% confidence level. Tensions above 12 kPa may have reduced transpiration rate and initiated plant stress as indicated by canopy leaf temperature which temporarily exceeded ambient air temperature during high radiation periods.
Dedicated

to my father and mother

&

in memory of my grandmother
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CHAPTER 1

INTRODUCTION

Intensive agricultural crop production requires a detailed understanding of environment, water, nutrient needs, and interactions among them throughout each growth stage. Correct estimation of fertilizer and irrigation needs during each plant growth stage is especially important in maintaining high agricultural productivity (Fynn et al., 1993).

The controlled feeding of nutrients with irrigation water, called fertigation, has especially been advantageous to high crop production in greenhouse operations. In the fertigation system, the accurate estimation of irrigation requirements is one of the most significant factors affecting the success of the system (Fynn et al., 1994).

One method of determining water requirements of plants is to predict evapotranspiration (ET) as the major parameter affecting water uptake in plants. The rate and amount of ET tend to be the core data required to design irrigation projects, and are also essential for managing environmental pollution. Application of excess water with nutrients to plants creates drainage, salinity and other environmental problems by leaching. Precise application of water to the plants not only prevents nutrient loss and
conserves water, but also reduces cost and protects the environment (Schwab et al., 1993; Singh, 1992; Linsley et al., 1986; Cuenca, 1989).

Since ET is a very important process for intensive crop production, environmental quality, cost, as well as water and nutrient conservation, many researchers have conducted studies to quantify ET including Stanghellini (1987), Fynn (1993), and Penman (1948). As a result, many complex methods have been developed to compute transpiration based on climatological parameters such as temperature, solar radiation, wind speed and relative humidity and also plant characteristics such as leaf area index, and stomatal resistance. However, all these models are criticized for being computationally difficult and data intensive allowing many opportunities for errors. So, it is desirable to develop reliable, simple, inexpensive and practical methods for the estimation of ET in proportion to vapor pressure deficit (VPD) or solar radiation inputs (Reicosky, 1983; Sadler and Evans, 1989).

Measurement of ET has been used almost entirely for research applications due to the required equipment complexity and cost. Therefore, the prediction of ET from meteorological data is potentially more useful since the measurement of weather parameters is much easier than the measurement of ET. Furthermore, recent advances in sensor and datalogger technology permit accurate and easy measurement of on-site weather data.

Growers generally tend to provide more nutrients and water to plants than required for optimum growth. This can lead to ground water pollution, which is a primary environmental concern of today. Intelligent nutrient and irrigation management requires accurate determination of plant needs based on the physiological requirements
of the plant and prevailing microclimatic conditions. In order to achieve this goal in intensive crop production, computer-controlled systems in agricultural production are required (Fynn et al., 1989; Fynn et al., 1994; Mankin and Fynn, 1992).

Computer-controlled irrigation systems have replaced traditional systems because they are reliable, and relatively maintenance free. But, they require experts to run and design the system properly. Main limitations of computer-controlled irrigation scheduling are measurement and data processing errors as well as spatial variations in the soil, crop and climate conditions (Clyma, 1996; Hansen, 1997).

In order to increase irrigation application efficiency (ratio of water stored within the root zone of the crop, and thus available for use by the crop, to the amount delivered by the irrigation system), a precise amount of water should be stored in the plant root zone. This can be achieved by measuring and controlling soil-moisture levels in the root zone during the entire growing season. High irrigation application efficiency means conserving water and nutrients and minimizing energy and costs (Clark et al., 1993; Hassan, 1995).

Automation of irrigation systems is very essential in nursery production because of high-frequency irrigations. Since soil-tension levels are widely used to schedule the irrigation, a feedback control system based on soil tension could easily advance irrigation scheduling in the nursery industry.

Champion and Suggs (1995) noted that automation was an important tool to reduce cost and risk while increasing performance in nursery production. In automation, a simple reliable method was preferred since the probability of failure of a simple reliable method was low according to others.
Red Maple (*Acer Rubrum*) is one of the most common trees grown in Ohio landscapes and nurseries. The primary focus of this research was to develop a theoretical basis for determining water requirement of Red Maple via a simple, but reliable ET prediction approach.
CHAPTER 2

OBJECTIVES

The overall objective of this research was to develop an accurate water delivery system for red maple based on demand irrigation which would potentially result in optimum growth. In order to accomplish the overall objective, the specific objectives were:

1- To determine the accuracy of the deterministic combination model for predicting ET in comparison to stochastic solar radiation and vapor pressure deficit models.

2- To compare the irrigation accuracy of different ET models with potting medium tension controlled sensors.

3- To determine a physical relationship between potting medium tension and measured transpiration rate.

4- To develop a theoretical method for scheduling irrigation using a closed-loop, feedback control system.
CHAPTER 3

LITERATURE REVIEW

3.1 Evapotranspiration Process

Evapotranspiration is the combined total amount of water lost via transpiration and evaporation from the soil and plant surfaces. Evaporation occurs from all open surfaces whenever there is sufficient energy for latent heat of vaporization. Transpiration involves movement of water from soil into plant roots, transport of the water through stems into leaves, and evaporation of the water from leaves into the atmosphere. Because it is difficult to determine each loss rate precisely and because larger plants lose water mostly by transpiration, they are generally grouped together as evapotranspiration (Burman and Pochop, 1994; Nokes, 1995; Keach, 1998). Figure 3.1 shows a schematic representation of the ET process.

Two essential components for ET to occur are latent heat of vaporization and a vapor pressure gradient (Vanderkimpen, 1991). Transpiration is generally favorable to plants since it aids in absorption and transport of mineral nutrients; it also cools the leaves during radiant periods due to latent heat of vaporization. Too much transpiration can result in stress and most plants have mechanisms for diminishing transpiration when necessary, including reduction in leaf area by rolling of leaves or by changing leaf
orientation (wilting) to reduce intercepted solar radiation (Nokes, 1995). Transpiration, however, is affected more by the meteorological conditions than by plant characteristics (Cline, 1997).

ET is a very complex process because there is always a dynamic interaction among the plant, the soil and the atmosphere, which in turn affect this process. The plant requires water for growth, the soil stores the water, and the atmosphere provides the energy required by the plant to withdraw water from the soil (James, 1993; Schwab et al., 1993; Allen, 1995).
Figure 3.1: Schematic representation of the evapotranspiration process.
3.2 Measurement of Evapotranspiration

ET is influenced primarily by micrometeorological, plant, and soil factors. Since the ET process is very complex, researchers simplified it by defining potential and actual evapotranspiration. Actual ET occurs under ambient environmental conditions and can be limited by low soil moisture availability. Potential ET, on the other hand, is the amount of ET that would occur if soil moisture is not a limiting factor (Jesen et al., 1990; Schwab et al., 1993; Singh, 1992).

In order to measure actual ET, many methods have been developed. These methods can be divided into two main categories. First, simple, inexpensive methods include soil water depletion and water balance methods. They are labor intensive and spatial and temporal variability of soil characteristics can create sampling errors. Second, a more precise, but also more expensive method is the lysimeter technique (Jensen et al., 1990; Nokes, 1995; Al-Shooshan, 1991; Abdel-Rahman, 1994).

The most common water balance method of predicting water loss from the plants has been pan evaporation approach. However, there are many concerns about the accuracy and relevance of the pan evaporation (Jensen et al., 1990). Lysimeters are valuable devices for directly measuring ET and calibrating ET equations. Although there are various types of lysimeters, weighing lysimeters measure the mass fluctuations of soil moisture within a mass of soil at precise time intervals. Mass changes in soil moisture content show the amount of water added to soil via rainfall or irrigation, or the amount lost through ET. Advances in electronic instrumentation and datalogging have allowed accurate, high resolution measurements in weighing lysimeters (Olmsted, 1990; Fisher, 1995; Kananto, 1993).
Allen et al. (1991) pointed out that an effective lysimeter should be a representative sample of the larger environment and larger group of plants. For instance, when lysimeters are used in container nurseries, conditions of the soil and plant should be the same for the lysimeter plant compared to other plants to diminish errors. Since lysimeters are used to measure ET directly, they are frequently used to evaluate the effect of different climatic factors on ET and to evaluate methods for estimating ET.

Under outdoor conditions, lysimeter-measured ET is a function of several measurements including soil moisture, surface runoff, precipitation and irrigation. Thus, even the lysimeter-computed ET is a function of several measurement uncertainties. In order to obtain an accurate ET from lysimeters, the relative measurement uncertainty of the lysimeter-computed ET should be smaller than 10% (Malone et al., 1998).

3.3 Estimation of Evapotranspiration

Besides direct measurement of ET, there are many different approaches to estimating ET indirectly from empirical or physically-based models using easily obtained meteorological data (Wright and Jensen, 1987).

The empirical approach uses statistics to identify correlations between input parameters and transpiration rate. The weakness of this approach is that empirical formulae developed for a specific region during a specific time period may not always be used accurately for other time periods and regions. Using energy balance, physically-based models typically provides a more comprehensive estimate of transpiration. The disadvantages of the physically-based models are that they have extensive data requirements that are often unavailable (Linacre, 1977).
Penman (1948) predicted the evaporation from wet surfaces by using a steady-state energy balance relationship. Use of Penman's equation requires continuous observation of temperature, humidity, wind speed and radiation. The Penman's equation subsequently was modified by considering aerodynamic and surface resistance by Monteith (1963). This modified ET equation was called the combination method.

3.4 Environmental Factors Affecting Evapotranspiration

When there is sufficient water in the soil and stomata are fully open, atmospheric conditions control the transpiration rate. The most important environmental factors affecting the transpiration rate are temperature, humidity, solar radiation, and wind speed (Hansen et al., 1979; Salisbury and Ross, 1992; James, 1993).

3.4.1 Solar Radiation

Pang (1992) and Oke (1987) summarized that solar radiation is one of the most significant environmental parameters affecting ET. Since ET is a thermodynamic process, it requires energy to convert water from liquid to vapor phase. Solar radiation is the primary source of energy for latent heat of vaporization and photosynthesis. And, most of the energy is absorbed as heat since photosynthesis is very inefficient using only approximately 3% of the spectrum between 0.4-0.7 μm, which is called photosynthetically active radiation (PAR). Green (1992) concluded that the total amount of radiation intercepted by a plant depends on density and distribution of the foliage.
According to Salisbury and Ross (1992), if a plant canopy absorbs more radiant energy than it radiates, leaf temperature will rise. To keep leaf temperature at or below air temperature, the excess heat energy is removed by convection or transpiration. They also noted that leaves often radiate more energy than they absorb during the night.

### 3.4.2 Temperature

Sumayao et al. (1980) stated that leaf-air temperature differential is a useful indicator of plant stress. The difference between air and leaf temperatures provides a gradient for sensible heat toward or away from the plants. This sensible heat flux is an important energy source during the ET process.

O’toole and Tomar (1982) studied the effect of microclimate factors on transpiration rate in field crops. They found that leaf temperatures were higher than air temperature in early morning and late afternoon hours, and concluded that transpiration rate was low in the early morning when solar radiation, VPD and wind speed were low. Transpiration rates were high in the afternoon when radiation, VPD and wind speed were also high. However, they also concluded that VPD was the driving force of transpiration in the afternoon.

### 3.4.3 Humidity

The interaction between temperature and relative humidity can appropriately be expressed in terms of VPD. Since VPD is a function of relative humidity and temperature, humidity has a significant effect on transpiration. Water vapor flux moves from high vapor pressure regions to low vapor pressure regions. So, the VPD between
the leaf and the surrounding atmosphere is a major driving force behind ET. Relative humidity inside leaf tissue is nearly 100% but may be lowered slightly when high solute concentration in the leaf water increases osmotic potential (Eagleman, 1963; Tee and Fleetwood, 1982).

James (1993) reported that if the humidity of the air surrounding the plant canopy increases while other factors remain constant, then vapor pressure difference between the leaf and the surrounding air will be reduced, as will transpiration rate. O'toole and Tomar (1982) showed that transpiration in field crops increased linearly with VPD and wind speed. Butler (1976) concluded that the dominant environmental factor governing transpiration in apple orchards was the VPD and that the effect of VPD became more dominant when the radiation was high.

Saha et al. (1986) found a negative linear relationship between canopy and air temperature differential and VPD under varied environmental conditions. Fynn et al. (1993) showed that the VPD and incoming solar radiation above the canopy were highly correlated to the ET with the combination equation, but that VPD was somewhat more highly correlated with ET than was solar radiation. They also found that the ET was primarily related to VPD on cloudy days and incoming solar radiation on sunny days, respectively.
3.4.4 Wind

There are opposing ideas about effects of wind on ET. Wind can either increase or decrease transpiration rate. If wind brings warmer or dryer air in contact with the leaf, transpiration increases. On the other hand, if the wind brings cooler or more humid air in contact with the leaf, transpiration decreases. Because wind affects VPD, stomatal and aerodynamic resistance, its influence on transpiration is complex. In general, however it is accepted that high wind speeds cause greater rates of transpiration and subsequent water stress (Dixon and Grace, 1984; James, 1993).

High wind speed may cause stomatal or cuticular damage resulting in high water loss. Dixon and Grace (1984) studied a nursery plant in a wind tunnel and showed that high wind speeds reduced transpiration rate. They concluded that increasing wind speed reduced aerodynamic resistance and the leaf-air temperature difference. Thofelt and Rufelt (1984) concluded that wind reduces leaf-air temperature differential. However, Dixon and Grace (1984) concluded that the effect of VPD on stomatal resistance is larger than the effect of wind.

The resistance to vapor flow through the air boundary layer around the leaf depends primarily on air movement. Higher windspeed tends to break up the boundary layer surrounding the leaves and reduces the air boundary layer resistance. The resistance to vapor flow through the stomata is proportional to the degree of stomatal closure. Stomata resistance increases to the maximum when stomata are closed (James, 1993).
3.5 Irrigation Scheduling and Automation

A rapidly growing population is placing increasing demands on the earth's limited resources. Of those resources, water is fundamentally important because it is essential for all life. A significant portion of the water consumed in the world is used for irrigation. Conservation of water resources is especially vital in arid and semi-arid regions.

Irrigation scheduling methods are generally based on either monitoring soil and/or plant water status or predicting water depletion in the root zone. In general, the success of agriculture is totally dependent on irrigation, even in humid areas. Water is a limited resource that has to be managed intelligently. Irrigation scheduling is a decision-making process to determine the timing and quantity of water applications based on soil, plant, and weather information. Control systems require devices for sensing, communicating, data processing, and actuating the system based on logical algorithms. The basic idea in irrigation control is to maintain the soil moisture content within a small range close to field capacity (Fereres, 1996; Riberio et al., 1998).

Improper scheduling of irrigation results in either under-irrigation or over-irrigation. Under-irrigation reduces growth and yield, whereas over-irrigation can cause root rot, salinization, leaching of nutrients and pesticides, and ground water degradation (Vanderkimpen, 1991; Wu and Kong, 1996).
Fynn et al. (1992) pointed out that efficient irrigation is the art of providing water to plants exactly when they need it and in the correct quantities. Efficient irrigation often requires a relatively high investment, but can offer a significant increase in net income for farmers. Efficient irrigation scheduling and optimum crop production requires the determination of soil moisture conditions in the root zone frequently.

Because drip irrigation systems can supply water to the plant root zone with high uniformity, they are especially adapted to use in fertigation. Fertigation systems can improve fertilizer application efficiency and reduce nutrient loss from the root zone. However, fertigation system sometimes reduce irrigation application efficiency. For example, if rainfall meets the ET requirement of the plant, the irrigation system should not be used. However, fertigation may still be necessary during this wet period since plants still need nutrients. Thus, the irrigation system is used sometimes only to transport nutrients to the plant (Clark et al., 1993).

One sensor for sampling soil water status is the tensiometer. Tensiometers are relatively cheap and practical. If the active root zone of the plant in an outdoor situation is less than 38 cm, it is only necessary to measure soil-moisture tension at one depth. However, it is better to measure the soil-tension at two depths if plants have active roots deeper than 38 cm. Tensiometers show soil-water matric potential not total soil-water potential. Summation of matric, gravitational, and osmotic potential gives the total soil-water potential (Harrison and Tyson, 1993; Hill, 1991).

A new sensor, time domain reflectometry (TDR), was developed to measure volumetric water content of soil directly. A TDR is based on measuring the dielectric constant of the soil media and measurement of the propagation time over a fixed length
of stainless steel probes. The dielectric constant of dry material is less than 12 whereas the dielectric constant of pure water is approximately 81. Therefore, there is a correlation between soil-water content and the dielectric constant of the media (Yoder et al., 1998).

Owino and Hamlett (1997) and Silva et al. (1998) tested TDR sensors in soilless medium. They concluded that a TDR predicts water content of the medium very accurately and it is more reliable than tensiometers. However, a TDR moisture measurement system is more expensive than tensiometers.

When soil water holding capacity decreases rapidly due to high ET rates, maintaining available water for the plant requires repeated brief irrigation events (high frequency irrigation). As irrigation frequency increases, the water holding capacity of the medium becomes less important since soil moisture is frequently replenished and plants easily extract necessary moisture from the medium. High-frequency irrigation systems can be controlled accurately by a solid state sensor that monitors the fluctuation of soil-matric potential within the root zone. When a desired threshold tension is reached, a logic circuit or software determines whether irrigation is necessary based on frequency-period-ET demand relationships (Phene and Howell, 1984).

According to Lorenzo et al. (1998), soilless irrigation management is different from field irrigation management. Soilless irrigation management requires more accurate control due to the low water holding capacity of the substrates and to their limited volume. Calado et al., (1990) stated that scheduling frequent irrigation can be accomplished with an automatic feedback control system based on measurements of soil matric potential.
In practice, irrigation is applied when available water reaches 60-70% or less of total water holding capacities (Olmsted, 1990). Sumayao et al. (1980) studied the effect of soil moisture on transpiration in field crops and, concluded that when available soil-water moisture was depleted to 35% of total water holding capacity, stomatal resistance increased and leaf temperature rose above air temperature due to the reduced transpiration rate.

Tensiometers are the most commonly used sensors for measuring soil-water matric potential. However, tensiometers cannot measure the full range of soil tension values. Tamari et al. (1993) concluded that ceramic porous cup tensiometers can measure values of soil water matric potential up to 80-85 kPa whereas dry soils can reach values up to 1500 kPa. According to Zazueta et al. (1995), use of the tensiometers for irrigation scheduling would be more useful in coarse textured soils than in fine textured soils since the coarse textured soils holds the water at a tension less than 80 kPa.

Before advanced electronic instrumentation was used in irrigation scheduling, field soil tensiometers were used to read soil-water potential manually with vacuum gauges. However, reading from field soil tensiometers is not precise, especially for research applications. Furthermore, manual reading is time consuming and awkward. Therefore, solid-state electronic tensiometers for measuring soil water tension were developed and subsequently tested in nursery production by many researchers (Long, 1981; Marvil et al., 1987; Hansen et al., 1996; Burger and Paul, 1987). These researchers confirmed that solid-state, electronic tensiometers can be used to precisely measure tension fluctuation in potting medium.
Hansen et al. (1996) used a Q-COM computer-controlled system along with tensiometers to monitor and control the tension for container-grown mini-roses, at three different levels: low (3-6 kPa), medium (9-12 kPa), and high (15-18 kPa) tension levels under winter and summer conditions. They concluded that moisture tension above 12 kPa could not be controlled consistently under either winter or summer conditions.

Smajstrla and Locascio (1996) used tensiometers for automated drip irrigation scheduling of tomato. They used three different threshold tension levels (10, 15 and 20 kPa) in order to see the effect of the tension levels on tomato yield. They concluded that tomato yield was largest with 10 kPa and yield declined linearly with higher tension levels.

Currently, computers can automatically control fertigation systems and environmental factors such as temperature and humidity in greenhouses. However, ET remains the most important factor that cannot be controlled effectively in the greenhouse system. In greenhouse systems, ET affects not only irrigation and fertilizer requirements of the crop, but also air temperature and humidity (Fynn et al., 1993).

Coulon et al. (1996) concluded that a good container-crop irrigation control system requires a good knowledge about climate, substrate and plants. These three factors should be managed simultaneously and in real time by the control system. They also mentioned that the matric water potential for container crops should be kept generally between 1 and 10 kPa.
In tensiometer based feedback control system, accuracy of the system depends on the hydraulic characteristics of the soil, installation depth of the tensiometer, the ET model used in the system, and the reference tension set-point (Ismail and Al-Shooshan, 1996).

3.5.1 Automatic Control System Components of an Irrigation System

An automatic control system for irrigation scheduling requires at least six main categories: (1) sensors; (2) transmitters; (3) controlled device/actuators; (4) reading devices; (5) computer hardware; and (6) computer software. The selection of the sensors is a very important step in the design of an automatic control system because they translate the required environmental variables into quantitative outputs. Transmitters convert the sensor signals into a proportional output signal of voltage or current. A typical example of an actuator in irrigation system can be either a pump or valve. Data loggers are the main recording devices used in the irrigation system design. Selection of the computer hardware and software depend on user’s choice (Lee, 1995).

3.5.2 Different Control Strategies in Automation

Control systems are mainly classified as open-loop and closed-loop systems. An open-loop control system is the simplest and least complex form of automatic control. The controlling action is independent of the output in the open-loop control and there is no measurement of the output in the open-loop systems. Therefore, it is very difficult to obtain a desired performance from an open-loop system.
One outstanding feature of open-loop control systems is that they usually have no instability problem. To obtain more accurate control system, closed-loop systems were developed (Distefano et al., 1995; Kuo, 1987).

Closed-loop control systems are more commonly called feedback control systems. Feedback is the distinguished characteristic of the closed-loop systems over open-loop systems. Feedback is the process of measuring the controlled variable such as soil tension and using that information to influence the value of the controlled variable. The closed-loop system measures output and adjusts input accordingly by using feedback (Franklin et al., 1994).

According to Menq (1998), overall characteristics of feedback control systems are increased accuracy, tendency toward oscillation or instability, diminished effect of disturbances, and noise. Basic control actions in the feedback control system are on-off control, proportional control (P), integral control (I), proportional and integral (PI) control, proportional and integral and derivative control (PID).

The corrective effort is the same for both small and large errors in on-off controllers. In proportional control, the output signal is in proportion to the error. The advantage of the proportional controller over an on-off controller is that they reduce the instability problem. A problem with proportional control, however, is that it tends to cause steady-state errors. Integral control is used to eliminate steady-state error. However, if the integral control is used alone, it also can create stability problem. Therefore, both integral and proportional controllers should be used together. Derivative action is used to increase speed of system response, and stability (Doebelin, 1962).
3.6 Plant-Soil Relationships

Treder et al. (1997) and Eagleman (1963) reported that evapotranspiration of potted plants is affected mainly by plant related factors (such as the stage of growth, distribution and length of roots, characteristics of growing medium and container size), and environmental conditions such as VPD and solar radiation.

3.6.1 Plant

James (1993) and Yang et al. (1990) stated that between 60 and 95% of living plant biomass is water. Although plants need water primarily for transpiration, it also require water for other processes including photosynthesis, transport of minerals and photosynthates, structural support, and growth.

Clark et al. (1993) and Yang et al. (1990) studied the effects of water stress on plant yield and concluded that water deficits created by evapotranspiration demand can induce water stress in plants which reduces growth and development, and may in turn affect crop yield and quality.

Reicosky et al. (1980) stated that plant-water stress can decrease the relative water content of the leaves from 85 to 60%, and also increase air-leaf temperature differentials up to 6 °C depending on the magnitude of water stress. The transpiration process usually accounts for about 99% of the water used by plants whereas only 1% of water taken up by the plant is used in metabolic activities.
James (1993) formulated the transpiration rate (the rate at which water vapor escapes from the leaf) as:

\[ T = \frac{e_{\text{leaf}} - e_{\text{air}}}{r_{\text{leaf}} + r_{\text{air}}} \]  

(3.1)

where

\[ T = \text{transpiration rate} \]
\[ e_{\text{leaf}} = \text{vapor pressure within the leaf} \]
\[ e_{\text{air}} = \text{vapor pressure of air} \]
\[ r_{\text{leaf}} = \text{resistance to vapor flow through the stomata} \]
\[ r_{\text{air}} = \text{resistance to vapor flow through the air boundary layer around the leaf} \]

Transpiration occurs whenever stomata are open because vapor pressure within the leaf usually exceeds vapor pressure of air. It is generally accepted that vapor pressure within the leaf equals the saturation vapor pressure for the temperature within the leaf. Choudhury (1983) proposed that leaf temperature alone can be used as an indicator of soil-water status. As available soil moisture decreases, leaf temperature increases.
The flow of water through the soil-plant-atmosphere system is controlled by water potential differences between the soil and leaves, as well as resistances to flow in the pathway (Choudhury and Idso, 1985). Plant roots extract moisture from the soil to replenish water lost by transpiration. Water moves through the soil into the leaves due to a water potential gradient that occurs between the leaf and the soil. This process is called passive absorption. Jones and Tardieu (1998), James (1993) defines this flow rate as:

\[ Q = \frac{\Psi_{\text{leaf}} - \Psi_{\text{soil}}}{r_{\text{plant}} + r_{\text{soil}}} \]  

(3.2)

\[ \Psi_{\text{leaf}} = \Psi_T + \Psi_\pi \]  

(3.3)

where

\( Q \) = flow rate

\( \Psi_{\text{leaf}} \) = total water potential in the leaf

\( \Psi_{\text{soil}} \) = total water potential in the soil

\( \Psi_T \) = turgor pressure within the leaf

\( \Psi_\pi \) = osmotic pressure within the plant

\( r_{\text{plant}} \) = resistance to water movement into the roots, through the xylem, and into the leaf

\( r_{\text{soil}} \) = resistance to water movement in the soil (inverse of the soil hydraulic conductivity)
One of the important characteristics of plant canopy structure is Leaf Area Index (LAI). It is a critical value to achieve an accurate estimation of the ET. LAI is defined as the ratio between total leaf area and horizontally projected plant canopy area (Chason et al., 1991). Al-Kaisi et al. (1989) concluded that there was a high correlation between LAI vs. ET and LAI vs. crop coefficient. Crop coefficient is a dimensionless ratio used to relate potential ET to actual ET for a specific plant at a specific time.

3.6.2 Soil

Physical properties of soil have a major influence on flow and storage of water, air movement, and nutrient supply to plants (Mii 1 and Shaykewich, 1994; Hillel, 1982). Brady (1990) stated that water is held in the soil by matric forces. The matric force is the total of adsorptive and capillary forces. Adsorptive forces tightly adsorb the water to soil particles, whereas capillary forces are responsible for holding water in soil pores. The plant has to overcome these matric forces to remove water from the soil. There is always an inverse relationship between the matric force and moisture content of the soil and the plant is not capable of extracting all the water held within the soil.

The portion of the water inside the soil that the plant can use is termed available water (AW). The available water content is the difference between the permanent wilting point (PWP) and field capacity (FC). In general, the matric potential of soil water at the PWP is 15 bars, and that of FC is 1/10-1/3 bars. In order to prevent plant water stress, the soil moisture content should never drop under PWP or increase above FC (Hill, 1982; Brady, 1990; Cassel and Nielsen, 1986).
Water holding capacity is affected by soil type. Coarse sandy soils hold less water than fine clay soils. Accordingly, required irrigation frequencies for coarse soils are greater than for fine soils. There is generally more water available for plants in fine soils, but they hold water very tightly (Heuser and Heuser, 1994; Jury et al., 1991).

In container nurseries, where plants are grown in a small volume of potting medium, root development is highly restricted and frequent irrigation is essential. Eagleman (1963) stated that the moisture level and hydraulic conductivity of the soil can limit ET. The soil tension represents how tightly water is held by soil particles. High-tension values mean that water is held very tightly, and low-tension values mean that water is held very loosely by soil. The hydraulic conductivity of the soil shows how easily water can be transported in a soil profile from one point to another. The effect of soil tension and hydraulic conductivity on ET can be negligible if there is sufficient water present throughout the growing season.

Kozlowski (1987) stated that low soil temperatures lessen absorption of water by directly reducing the permeability of roots to water, and indirectly by increasing the viscosity of water. Low soil temperature also limits the absorption of water by inhibiting root extension.

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CHAPTER 4

DEVELOPMENT OF AN IRRIGATION CONTROL MODEL

4.1 Development of a Simulation Model Considering the Potting Medium-Plant-Control System

To develop a control diagram for irrigation scheduling, a mathematical model or transfer function of irrigation scheduling was developed to relate system output response variables to changes in the system input variables (Raven, 1995; Doebelin, 1962).

Figure 4.1 is the block diagram for the potting medium-plant-control system. According to Figure 4.1, four primary climate variables of relative humidity, ambient temperature, solar radiation and atmospheric pressure were used to calculate ET. A fifth variable affecting moisture level as a perturbation was rainfall. In addition, blocks were designed representing: integration of medium water content; calculation of gravimetric medium moisture content; relationship between moisture content and tension; calculated error signal based on set points for tension; hysteresis effect, effective pumping rate, and lag time associated with water movement in the medium.
Fynn (1995) stated that movement of the water inside potting medium was relatively fast (30 seconds or less) so that the lag time was set to zero on the block diagram.

In this model, reference medium tension values were chosen to be between 6 - 10 kPa and the irrigation system was based on an on-off concept. The pump was assumed to give a constant irrigation rate when operating. The error signal (e) was the difference between the actual tension being sensed and the setpoint of tension.
Figure 4.1: Block diagram of a closed-loop, feedback irrigation control system based on medium tension measurements and ET models.
4.2 Hysteresis Characteristic of on-off Controller

The on-off controller was assumed to work as shown in Figure 4.2. The error signal, e, ranges from -20 cm to +20 cm and the irrigation was either on or off. The pump switch was designed to turn the irrigation off when medium tension falls to 20 below its setpoint of 80, and turns it on when it rises to 20 above its setpoint.

![Diagram of corrective effort](image)

Figure 4.2: Characteristic of the on-off controller used for the closed-loop, feedback irrigation control system in Figure 4.1.
4.3 Physical Modeling of Evapotranspiration for Potting Medium

Three different ET models were used in the simulation. Two of them were stochastic models based on VPD and solar radiation and the third one was the Fynn ET model based upon the combination equation. In the VPD based stochastic ET model, two climate data, ambient temperature and relative humidity, were used to determine plant water consumption. In the radiation based stochastic ET model, one climate variable, solar radiation was used to determine the ET requirement of the plant. In the Fynn ET model, all four climate variables (solar radiation, ambient temperature, relative humidity, and atmospheric pressure) shown in the block diagram were used to calculate ET. The atmospheric pressure was used to calculate the psychrometer constant and air density in the Fynn ET model. The Fynn ET model also required assumptions for aerodynamic and crop resistance.

In the modeling of the automatic irrigation system based on VPD and medium tension measurements, it was assumed that leaf temperature was equal to the ambient temperature. This assumption was reasonable because direct measurement of the leaf temperature is difficult and leaf temperature follows closely air temperature. Besides, correlation between leaf and ambient temperature (0.989) supported this assumption as explained in section 6.2. The equation for VPD was

\[ VPD = e^0 - e \] (4.3.1)
Where

\[ \text{VPD} = \text{vapor pressure deficit, kPa.} \]

\[ e^0 = \text{saturated vapor pressure, kPa,} \]

\[ e = \text{actual vapor pressure at ambient conditions, kPa,} \]

\[ e^0 = 0.6108 \times \exp \left( \frac{17.27 \times T}{(\text{T+237.3})} \right) \]  \hspace{1cm} (4.3.2)

where

\[ \text{T = ambient temperature, } ^\circ\text{C.} \]

\[ \text{RH} = \left( \frac{e}{e^0} \right) \times 100, \hspace{0.5cm} \text{Percent} \]  \hspace{1cm} (4.3.3)

Since Eq. (4.3.3) represents the definition of relative humidity, Eq. (4.3.4) can be obtained from Eq. (4.3.3) by mathematical manipulation.

\[ e = \left( \text{RH} \times e^0 \right) / 100 \]  \hspace{1cm} (4.3.4)

Using equation (4.3.1) and (4.3.4), VPD is defined as:

\[ \text{VPD} = e^0 \times (100-\text{RH}) / 100. \]  \hspace{1cm} (4.3.5)
Experimental results show that there was good correlation ($R^2 = 0.684$) between VPD and measured ET using the linear regression analysis. Based on statistical analysis, ET was determined as:

$$ET = -0.17 + 0.0898 \times VPD, \text{ g/hr.}$$  \hspace{1cm} (4.3.6)

To model ET based on solar radiation, equation (4.3.7) was developed from experimental data with $R^2 = 0.875$ and where:

$$ET = 4.05 + 0.207 \times \text{(solar radiation)}, \text{ g/hr} \hspace{1cm} (4.3.7)$$

To model ET based on Fynn model, equation (5.4) was used ($R^2 = 0.782$). The Fynn model will be explained in chapter 5.
4.4 Physical Modeling of Potting Medium System

In the physical modeling of the potting medium system, the soil-water balance concept was applied as shown on Figure 4.3. In this model, it was assumed that surface runoff and drainage were both equal to zero since the container represented an isolated environment and irrigation was applied based on medium matric potential measurements.

![Diagram of potting medium system](image)

**Figure 4.3:** Physical modeling of potting medium using $R=$ rainfall amount (g/hr), $I=$ irrigation (g/hr), $SR=$ surface runoff (g/hr), $D=$ drainage (g/hr), and $h=$ depth of medium in the container (cm).
Assuming no water storage in the plant, the water balance for a container medium was:

\[ \frac{dM_w}{dt} = M_{w(0)} + R(t) + I(t) - ET(t). \] (g/hr) \hspace{1cm} (4.4.1)

where

\[ M_{w(0)} = \text{initial weight of water in the container, (g)}. \]

Solving for \( M_w(t) \) gives:

\[ M_w(t) = \left[ \int_0^t (R(\tau) + I(\tau) - ET(\tau)) d\tau + M_{w(0)} \right] \] (g/hr) \hspace{1cm} (4.4.2)

Initial water content of the medium was set, assuming that irrigations were applied at the 60% of available water level of the medium. The available water capacity of the container medium was determined to be 10 kg from an experiment explained in Appendix A. Initial water content was determined as:

\[ M_{w(0)} = (0.60 \times 10^4) - (M_{w\text{pwp}}) \] (g) \hspace{1cm} (4.4.3)

Where:

\[ M_{w\text{pwp}} = \text{amount of water held at PWP}. \]
Mass of the medium was determined from dry bulk density and volume of the container. Therefore,

\[ M_{\text{medium}} = \rho_{\text{medium}} \times V_{\text{container}} \quad (g) \]  \hspace{1cm} (4.4.4)

where:

\( \rho_{\text{medium}} = \) dry bulk density, (g/cm\(^3\))

\( M_{\text{medium}} = \) mass of medium, (g)

\( V_{\text{container}} = \) container volume, (cm\(^3\)).

Dry bulk density of the medium was determined as 0.19 g/cm\(^3\) from the potting medium analysis. The volume of the pot was calculated using:

\[ V_{\text{container}} = \pi r^2 h \]  \hspace{1cm} (4.4.5)

where

\( h = \) depth of medium inside the pot, (20 cm)

\( r = \) radius of the pot, (17.5 cm)

The mass of medium was assumed to be constant in the analysis. Gravimetric water content of the medium was given as:
\[ w_{\text{medium}}(t) = \left( \frac{M_w}{M_{\text{medium}}} \right) \]  

(4.4.6)

where

- \( w_{\text{medium}}(t) \) = water content of the medium on a dry basis, (g/g)
- \( M_w \) = mass of water (g).

The importance of medium water content was in estimating medium tension since medium tension was a function of medium type and water content as explained in section 6.5. Medium tension was estimated using the equation:

\[ y = f_t(w_{\text{medium}}) \]  

(4.4.7)

The function \( f_t \) was derived from experimental data as shown in section 6.5.
CHAPTER 5

MATERIALS AND METHODS

5.1 Study Area, Experiment Plant and Potting Medium

This study was conducted at The Ohio Agricultural Research Development Center (OARDC), Wooster, Ohio (41° 48' N' latitude) in August and September 1997. A gravel bed covered the experiment area for weed control. The gravel bed was constructed by laying a weed mat over a soil surface which was graded to a 0.2% slope with drain tile placed 0.5 m below the surface. The general schematic drawing of the experimental station and experimental setup are shown in Figure 5.1 and Figure 5.2 respectively.

The trees used in this research were *Acer Rubrum* (Red Maple) acquired as 1.25 m tall “whips” and potted in 26.5 L containers. Red Maple is a tree very common to Ohio growers and considered somewhat difficult to grow. The experimental trees were part of a larger experiment shown in Figure 5.2. The trees were located on a 1.8 × 1.8 m spacing in the experiment area. The height and diameter of the container was 30 cm and 35 cm respectively and the medium depth of soil mix in the container was 20 cm.
Figure 5.1: Schematic drawing of top view of experimental landscape nursery and related data equipment.
Figure 5.2: Schematic drawing of top view of plant area shown in Figure 5.1.
The potting medium used in the experiment, Metro Mix 510 (The Scotts Company, Marysville, OH), was common to the nursery industry and recommended for its good physical and chemical characteristics. It was especially noted for excellent aeration and rapid water percolation. It was also compatible with drip emitters and microirrigation systems. The general ingredients of the growing medium were composted pine bark (20-45%), horticultural vermiculite (15-30%), Canadian sphagnum peat moss (25-35%), and processed bark ash (5-25%). The dry bulk density of the medium was estimated by the manufacturers to be 0.24 – 0.32 g/cm³. A slow release fertilizer called Osmocote (8-9 month) was used to fertilize half the plants and experimental formulations were injected into the fertigation system for the other plants (Figure 5.3). N-P-K ratio of the Osmocote was 18-6-12.

Since salinity levels of irrigation water and potting medium may affect ET, the nutrient content of the growing medium was analyzed and results are shown in Table 5.1. Results show that the salinity level of the medium is normal based on its pH (pH=7.2) and electrical conductivity (EC=3.0 mmho/cm). According to normally accepted standards, a normal soil must have a pH between 6.5 and 7.2 and an EC value less than 4 mmho/cm (Brady, 1990).
<table>
<thead>
<tr>
<th>TEST</th>
<th>VALUE</th>
<th>TEST</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soluble salts (mmho/cm)</td>
<td>3.0</td>
<td>Manganese (ppm)</td>
<td>3.6</td>
</tr>
<tr>
<td>Nitrate-Nitrogen (ppm)</td>
<td>96</td>
<td>Boron (ppm)</td>
<td>0.32</td>
</tr>
<tr>
<td>Phosphorus (ppm)</td>
<td>2</td>
<td>Zinc (ppm)</td>
<td>5.1</td>
</tr>
<tr>
<td>Potassium (ppm)</td>
<td>326</td>
<td>Iron (ppm)</td>
<td>8</td>
</tr>
<tr>
<td>Calcium (ppm)</td>
<td>383</td>
<td>Copper (ppm)</td>
<td>0.36</td>
</tr>
<tr>
<td>Magnesium (ppm)</td>
<td>85</td>
<td>pH</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Table 5.1: Result of growing medium analysis at the beginning of the experiment.

Figure 5.3: Fertigatör system developed at Wooster, OH.
5.2 Weather Station

Meteorological data (ambient temperature, wind speed, wind direction, relative humidity, barometric pressure, and radiation) were obtained from an automatic recording weather station located adjacent to the nursery growing area. All measurement sensors on the weather station were connected to the Q-COM control system and stored into GEM3V2 software at 15 minutes interval continuously. Rainfall was measured manually using rain gages located at three different places in the experimental area (Figure 5.4).

Figure 5.4: Automatic weather station located adjacent to the experimental area.
5.3 Irrigation System

A Q-COM Inc., Irvine, CA computer controlled micro-irrigation system with GEM3V2 software was used to irrigate the plants as illustrated in Figure 5.5. Two different irrigation experiments were conducted.

In the first experiment, the measurement of transpiration rate and effect of the potting medium tension on transpiration rate were investigated. Potting media tension was allowed to go up to 21 kPa in seven different tension increments (0-3, 3-6, 6-9, 9-12, 12-15, 15-18, and 18-21 kPa.). Irrigation was done manually by considering the tension levels and observing cumulative water loss with the weighing lysimeter. Sampling interval for medium tension was 15 minutes. Hourly average values were used to represent medium tensions in the statistical analysis. The water source for irrigation was local city water with a pH and soluble salts (electrical conductivity) of 7.2 and 0.53 mmhos/cm respectively. This range of pH and EC for the irrigation water was within acceptable water quality standards with a pH between 6.5 - 8.4 and an EC value less than 0.75 mmhos/cm (Hoffman, 1983). The full chemical analysis of the water source is shown in Table 5.2.

In the second irrigation experiment, the plants were irrigated automatically by only controlling the tension levels in the medium. The schematic drawing of the tension based controlled irrigation system is shown in Figure 5.6. For this computer-controlled, tension-based irrigation system, trees were irrigated based on one sensor in one of the tree. The other trees were used as observation trees in order to observe the differences in the potting medium moisture levels. One additional emitter was placed in an open container to measure the amount of water added to each plant.
Maximum and minimum potting medium tension values were chosen as 10 kPa and 6 kPa respectively and were based on a previous study conducted by Short et al. (1997).

<table>
<thead>
<tr>
<th>TEST</th>
<th>VALUE (PPM)</th>
<th>TEST</th>
<th>VALUE (PPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus (P)</td>
<td>&lt; 0.1</td>
<td>Molybdenum (Mo)</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>2.25</td>
<td>Strontium (Sr)</td>
<td>0.383</td>
</tr>
<tr>
<td>Calcium (Ca)</td>
<td>63.0</td>
<td>Barium (Ba)</td>
<td>0.02</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>27.8</td>
<td>Vanadium (V)</td>
<td>&lt; 0.003</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>39.1</td>
<td>Titanium (Ti)</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>&lt; 0.06</td>
<td>Beryllium (Be)</td>
<td>&lt; 0.0003</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>0.06</td>
<td>Tin (Sn)</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>&lt; 0.004</td>
<td>Cobalt (Co)</td>
<td>&lt; 0.007</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>&lt; 0.02</td>
<td>Mercury (Hg)</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>Boron (B)</td>
<td>0.09</td>
<td>Silicon (Si)</td>
<td>4.2</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>&lt; 0.003</td>
<td>Lithium (Li)</td>
<td>0.007</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>&lt; 0.007</td>
<td>Arsenic (As)</td>
<td>&lt; 0.007</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>&lt; 0.007</td>
<td>Sulfur (S)</td>
<td>15.05</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>&lt; 0.0007</td>
<td>Antimony (Sb)</td>
<td>0.034</td>
</tr>
<tr>
<td>Aluminum (Al)</td>
<td>&lt; 0.1</td>
<td>Nitrate-Nitrogen</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

Table 5.2: Chemical analysis of irrigation water supply.
A microirrigation system was chosen as the most convenient way of achieving precise irrigation or fertigation with computer control. The general layout of the microirrigation system and the plants is shown in Figure 5.7. The microirrigation system consisted of PVC lateral pipe and one spray stake emitter for each tree. Figure 5.8 shows the emitter and its placement in the medium. In order to verify water pressure, a pressure gauge was installed at the end of each irrigation line. The inside diameter of the lateral pipe was 13.5 mm.

A standard procedure explained by Rose (1997) and White and Mastalerz (1966) was used to define the container capacity of the Metro Mix 510 medium. Three replicates were used for this purpose and the average container capacity and air capacity were found to be 71.80 % and 24.10 % respectively. The procedure for this experiment is explained in the Appendix B.

Figure 5.9 shows the potting medium moisture capacities based on experimental results where the available water per container was arbitrarily found to be 10.0 L by ignoring the root volume. The water content at the permanent wilting point (1.75 L) was determined considering the experimental results of a medium-water release curve explained at Appendix A. The gravimetric moisture content at permanent wilting point (at 15 bars) was obtained from the medium-water release curve and multiplied times the mass of dry medium in the container to determine total mass of water at the permanent wilting point.
Figure 5.5: Schematic drawing of instrumental setup for Red Maple.
Figure 5.6: Schematic drawing of the computer-controlled, irrigation system.
The computer-controlled microirrigation system as shown in Figure 5.6 consisted of a soil tension sensor with a solid state pressure transducer attached, a spray stake emitter, a solenoid valve, an analog-to-digital converter (A/D), and a PC computer with GEM3V2 software.

Figure 5.7: General view of the experiment and microirrigation system.
Figure 5.8: Emitter (a) and placing of the emitter into the medium (b).
The tensiometer sensor consisted of a ceramic cup fastened to transparent tube with an airtight seal (Figure 5.10). A barb fitting was joined to the other end of the tube by an airtight seal to allow the tube to be coupled to a pressure transducer. The tube was filled with water until there was a small air column remaining at the top of the tube. The pressure transducer measured the vacuum in the air column and translated this vacuum pressure into an electrical signal. The signal was sent to a Q-COM soil tension controller; the controller forwarded the signal to an A/D converter called a Q-COM data link; and finally the signal was forwarded to the computer shown in Figure 5.11.
Figure 5.9: Physical classification of medium moisture based on procedure explained in Appendix B.
Figure 5.10: Porous cup tensiometer with an electronic pressure transducer at the top.
Figure 5.11: Remote control of irrigation system by Q-COM data link and its software.

There were four programmable parameters in GEM3V2 software. They were minimum tension, maximum tension, pulse time, and pause time. The minimum tension shows the highest level of soil moisture content to be allowed. When the soil moisture reached this level, the irrigation event was stopped automatically by closing a solenoid valve. The maximum tension related to the lowest level of controlled soil moisture. When the soil tension shows this value, the irrigation valve was opened. The pulse time was used to set the irrigation duration and the pause time was used to set the length of time which water was to be off during each irrigation event. As the water was
removed by the ET process, the soil tension increased. When the soil tension reached the maximum allowable tension, the irrigation was started by the computer. Irrigation continued until the minimum tension was reached. The main reason for the pause and pulse time cycling was to achieve a more uniform moisture distribution in the pot media and to avoid overwatering.

5.4 Analysis of Potting Medium for Moisture Content-Tension Relationship

Understanding the physical conditions (ratios among solid, air and water) around plant roots in a container required information about the water energy levels and moisture content of the medium. The relationship between soil tension and moisture content is a complex, nonlinear function (Hanks and Ashcroft, 1980; Rawlins and Campbell, 1986).

The relationship between tension and moisture content is called a soil moisture release curve or soil-water characteristic curve. In order to characterize the medium used in this study, samples were compacted by adding water before analyzing. The schematic display of this pre-setup is shown in Figure 5.12. In this pre-setup, dry bulk density of the medium was increased by reducing total volume.
Figure 5.12: Pre-experiment setup for potting medium analysis.

A tension table and pressure plate were used for low (<10 kPa or 100 cm) and high-tension values (<200 kPa or 2000 cm) respectively. In the determination of PWP, a thermocouple psychrometer was used. The experimental set up for a tension table, pressure plate, and thermocouple psychrometer are shown in Figures 5.13 and 5.14.

Soil moisture content can be expressed on either a weight or volume basis. Moisture percent by weight is based on dry weight of the sample and is given by
\[ P_w = \frac{W_w - W_d}{W_d} \times 100 \quad (5.1) \]

where

\( P_w \) = moisture percent by weight (\%),

\( W_w \) = wet weight of the soil (g),

\( W_d \) = dry weight of the soil (g).

Soil moisture content on a volumetric basis was calculated assuming that the specific gravity of the water in the soil was 1.0. The moisture percent by volume was given by:

\[ P_v = P_w \times \rho \quad (5.2) \]

where

\( P_v \) = moisture percent by volume,

\( \rho \) = dry bulk density of the soil (g/cm\(^2\)).

A thermocouple psychrometer assumes that there is a relationship between soil-water potential and vapor pressure of soil air that is in equilibrium with the soil water. Hanks and Ashcroft (1980) formulated this relationship as:

\[ \psi = \frac{R \times T}{V_m} \ln(e/e_0^\theta) \quad (5.3) \]
where

$\psi = \text{soil-water potential},$

$R = \text{universal gas constant},$

$T = \text{temperature},$

$V_m = \text{molar volume of the water},$

$E = \text{vapor pressure of the soil air},$

$e^0 = \text{vapor pressure of saturated air at the same temperature as the soil air}.$

A NaCl standard solution is used to obtain the psychrometric curves. Then, these standard curves are used to obtain the moisture content of the sample. The experimental procedure for the potting medium-water release curve is explained in Appendix A. The experimental data results and necessary calculations are shown in Table A.1, A.2, and A.3 in Appendix A.
Figure 5.13: Experimental setup of a tension table and pressure plate for obtaining potting medium-water release curves (a) and a temple-cell with a potting medium sample (b).
Figure 5.14: Experimental set-up of thermocouple psychrometer for obtaining potting medium-water release curve.
5.5 Instruments and Measurements

In order to measure ET, a SATORIUS F330S automatic weighing scale with an accuracy of ±1 g was placed beneath one of the tree containers. The lysimeter readings were recorded in print and cassette by using a Kaye DIGISTRIP III datalogger as shown in Figure 5.15. Instantaneous weight readings were also displayed digitally in grams by the Satorius A/D converter shown in Figure 5.16.

Figure 5.15: Datalogger for medium temperature, leaf temperature and weighing lysimeter data.
Figure 5.16: Digital weight display for the lysimeter.

One unique characteristic of the high resolution system was that the lysimeter printout had only a four-digit resolution and the data were stored as millivolts in the printer. The lysimeter printout had to be checked with the actual data shown in the digital weight display for each 5-6 hrs and then corrected.

While five climate parameters (ambient temperature, leaf temperature, wind speed, relative humidity, and radiation) and LAI were required to use the most complex theoretical ET estimation methods, soil temperature and potting medium tension were also collected to evaluate the potential effects of each on transpiration rates. The leaf temperature was measured from upper, middle and bottom parts of the plant and
averaged. Each leaf temperature was measured using type T thermocouples of 1 mm size inserted into the central veins at the underside of the leaf as shown in Figure 5.17. Since the thermocouples easily were taken out from the vein due to the effect of wind, an adhesive band was used for holding them in place. The datalogger recorded leaf and medium temperature readings in 15 minutes intervals.

Figure 5.17: Installation of the temperature probe & tension sensors into the medium, and leaf temperature sensors in the central vein.
The potting medium temperature was measured at two different depths within the root volume. Two potting medium temperature sensors were 9 ± 0.5 cm deep and 18 ± 0.5 cm deep and averaged. The soil temperature sensors were type T ungrounded, 1/8" stainless steel probes. These sensors were calibrated with ice in the lab before the experiment.

Each tensiometer was calibrated before use. The calibration was done by using a long plastic u-tube as shown in Figure 5.18. Each pressure transducer and u-tube were attached to a meter stick using a C-clamp. After the u-tube was filled with water, one end was attached securely to the pressure transducer in order to prevent leakage in the seal between the tube and the transducer. Then, the differential water head readings from u-tube and Q-COM controller were matched to each other. If there was no match between these two readings, adjustments were made on the Q-COM software.
Figure 5.18: Calibration of the tensiometer by aid of Q-COM controller.

5.5.1 Canopy Architecture

The leaf area index (LAI) is an input parameter for many ET equations. It is defined as the ratio of total leaf area of a plant to the projected horizontal ground area of the plant canopy. In this study, a total of 10 leaves were removed from different parts of the plant and then measured as a basis for determining the average leaf area. Since two
different sample plants were used in the lysimeter study, the LAI was calculated for each plant separately. An electronic areameter shown in Figure 5.19 was used to measure each sample leaf. The areameter was calibrated based on known areas of metal plates. The horizontally projected area of the plant was calculated assuming a rectangular shape.

Figure 5.19: Measurement of the leaf area of the plant using an electronic areameter.
The total leaf and canopy areas for the first plant were 0.64 m$^2$ and 0.44 m$^2$ respectively. Thus, the LAI was calculated to be approximately 1.45. The first plant was used at the beginning of the experiment only for a week. For the second plant, the total leaf and canopy areas were 1.25 m$^2$ and 0.79 m$^2$ respectively giving a LAI of 1.58.

Tree stem diameter and tree height were determined. Diameter was measured approximately 15 cm above the top of each pot. The height and radial orientation of the measurements were marked so that later measurements for determining growth could be made at the same location and orientation. Average canopy height and stem diameter for trees used in this study were approximately 1.62 m and 15.15 mm respectively. At the end of a two months experimental period, these values were approximately 1.88 m and 19.80 mm respectively. Figure 5.20 shows the canopy architecture measurements for Red Maple.
Figure 5.20: Measurement of the plant stem diameter using a caliper (a) and measurement of maximum plant height (b).
5.6 Deterministic Transpiration Calculation Methods

The combination method for estimating evapotranspiration combines aerodynamic and energy balance principles into one (Oke, 1987). Equations based on the combination of one-dimensional aerodynamic and energy-balance theory were useful in analyzing the interrelations between transpiration and evaporation, canopy properties, and meteorological conditions for both agricultural crops and forest crops (McNaughton and Jarvis, 1983).

The combination method was investigated for greenhouse and nursery applications by Stanglelani (1987) in the Netherlands, Yang et al. (1990), Pang et al. (1992), and Fynn et al. (1993) in Ohio. This method was used successfully to model evapotranspiration for tomato and cucumber and compared to lysimeter data.

In ET calculation methods, internal and external resistances for the canopy were chosen to be 70 sm\(^{-1}\), 50 sm\(^{-1}\) respectively and radiation resistance used in Stanglelani model was assumed to be 200 sm\(^{-1}\) (Short et al., 1997). Hourly ET was determined as the difference between lysimeter mass losses by considering the irrigation and precipitation. Then, these results were compared Penman, Fynn, and Stanglelani deterministic ET methods:
5.6.1 Penman Combination Method

Penman (1948) first derived the combination equation for computing the ET by considering the aerodynamic and energy budget equations that are required for evaporation and removing the vapor. The main advantage of the Penman equation is that the measurement of the leaf temperature is eliminated. Penman derived the equation below by using well-watered grass as a reference crop. The Penman combination equation is as follow:

\[
\lambda E = \frac{\Delta}{\Delta + \gamma} (R_n - G) + \frac{\gamma}{\Delta + \gamma} 6.43(1.0 + 0.53U_2)(e^*- e_s) \tag{5.6.1}
\]

where

\( \lambda E = \text{Latent heat flux density (MJ m}^{-2} \text{ d}^{-1}) \)

\( \Delta = \text{Slope of the saturation vapor pressure curve versus air temperature (kPa/C)} \)

\( R_n = \text{Net radiation (MJ m}^{-2} \text{ d}^{-1}) \)

\( G = \text{Soil heat flux (MJ m}^{-2} \text{ d}^{-1}). \)

\[
G = 4.2 \frac{(T_{i+1} - T_{i-1})}{\Delta t} \tag{5.6.2}
\]
where

\[ T = \text{Mean air temperature (C)} \]

\[ \Delta t = \text{Time period} \]

\[ \gamma = \text{Psychometric constant (kPa/C)} \]

\[ E_a = \text{Aerodynamic term or} \]

\[ E_a = (0.2625 + 0.1409 \, U_z)(e_z^o - e_z) \] \hspace{1cm} (5.6.3)

where

\[ U_z = \text{Wind velocity at 2 meter (m/s)} \]

\[ e_z^o = \text{Saturation vapor pressure at mean air temperature (kPa)} \]

\[ e_z = \text{Vapor pressure of the air (kPa).} \]

\[ e_a = (e_z^o \times RH) / 100 \] \hspace{1cm} (5.6.4)

where

\[ RH = \text{Relative humidity (\%)} \]

Wind speed at 2m can be approximated from measurements at other elevations using the power law.

\[ U_z = U_x(2/z)^{0.2} \] \hspace{1cm} (5.6.5)
where

\[ z = \text{Elevation in m at which } U \text{ is measured} \]
\[ U_z = \text{Wind speed at 2m above.} \]

### 5.6.2 Fynn Method

Fynn (1993) established an ET method under the greenhouse conditions by considering the energy balance for the plant canopy where:

\[
ET = \frac{2LAI \cdot \rho \cdot C_p \left[ e_s(T_a) - e(T_a) \right]/r_w + \delta(Q_{RAD} - Q_G)}{L_v \gamma_e} \tag{5.6.6}
\]

where

- \( ET \) = ET rate (Kg.m\(^{-2}\).s\(^{-1}\))
- \( L_v \) = Latent heat of vaporization of water (J.kg\(^{-1}\))
- \( Q_G \) = Rate that energy is stored in the canopy (J/m\(^2\).s)
- \( Q_{RAD} \) = Irradiance absorption rate by the canopy (J/m\(^2\).s)
- \( \rho \) = Air density (kg/m\(^3\))
- \( C_p \) = Specific heat of air at constant pressure (J/kg °C)
- \( e(T_a) \) = Vapor pressure at air temperature (Pa)
- \( r_w \) = Air resistance for water vapor transfer (s/m)
\( e_s(T_a) = \text{Saturation vapor pressure at air temperature (Pa)} \)

\( \text{LAI} = \text{Leaf area index} \)

\( \gamma = \text{Psychometric constant (Pa/C)} \)

\( r_e = \text{Crop resistance for water vapor transfer (s/m)} \)

\( \delta = \text{Slope of saturated vapor pressure curve with temperature (Pa/C).} \)

### 5.6.3 Stanghelline Method

Stanghelline (1987) used the combination equation as defined below to calculate transpiration under the greenhouse conditions. Stanghelline (1987) conducted research under greenhouse conditions by using equation (5.6.7) and concluded that this equation estimates the transpiration rate well. However, because climatic factors at the outside conditions, especially wind, solar radiation, and precipitation, may be more different than the conditions inside the greenhouse, the accuracy of the Fynn and Stanghelline equations for outdoor was evaluated.

\[
LE = \frac{2 \cdot \text{LAI} \cdot \rho_a \cdot c_p}{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e}} \left[ 0.07 \frac{\delta}{\gamma} \frac{I_s}{\rho_a c_p} + 0.16 \frac{\delta}{\lambda} \frac{T_h - T_a}{r_k} + \frac{1}{r_e} \frac{e_a^* - e_a}{\gamma} \right] \tag{5.6.7}
\]
where

\[ LE = \text{Latent heat flux (Wm}^{-2}) \]

\[ C_p = \text{Air specific heat at constant pressure (J Kg}^{-1} \text{ C}^{-1}) \]

\[ \rho_a = \text{Air density (Kg m}^{-3}) \]

\[ \delta = \text{Slope of saturated vapor pressure curve with temperature (PaC}^{-1}) \]

\[ \gamma = \text{Thermodynamic psychrometric constant (PaC}^{-1}) \]

\[ r_e = \text{Transfer resistance of external heat (sm}^{-1}) \]

\[ r_R = \text{Radiation heat transfer resistance (sm}^{-1}) \]

\[ r_l = \text{Transfer resistance of internal heat (sm}^{-1}) \]

\[ I_s = \text{Shortwave irradiance (Wm}^{-2}) \]

\[ T_h = \text{Ambient temperature (C}^{\circ}) \]

\[ T_o = \text{Temperature at the external surface (C}^{\circ}) \]

\[ e^*_{s} = \text{Saturation air vapor pressure (Pa)} \]

\[ e_a = \text{Air vapor pressure (Pa)} \]

\[ \text{LAI} = \text{Leaf area index (m}^2 \text{m}^{-2}). \]
CHAPTER 6

RESULTS AND DISCUSSION

6.1 Dynamic Evapotranspiration of Red Maple

In order to evaluate the ET rate of Acer Rubrum, all necessary climate and canopy data were collected as discussed in Chapter 5. Hourly ET rate of the plant was calculated using a written program in a Microsoft Excel spreadsheet. Leaf and air temperature, wind speed along with solar radiation, and measured transpiration were plotted for 24 hour periods in Figures 6.1-6.5. Each day was chosen because it was either sunny, cloudy or combination of both. For all cases, the trees were subjected to the highest transpiration stress during the mid-day because air and leaf temperature and radiation were all at the maximum levels.

The average difference between leaf temperature and air temperature was 2-2.5 °C. This temperature difference was due to the evaporative cooling during high transpiration rates for mid-day conditions. Leaf temperature variations among bottom, top and middle levels of the canopy were about 5-6°C. Figure 6.6 shows leaf temperature variations for these three levels of the canopy.
Figure 6.1: Air temperature, wind speed, measured transpiration and solar radiation for Red Maple on a sunny day (8/14/97) under 0-5 kPa medium tension.
Figure 6.2: Air temperature, wind speed, measured transpiration and solar radiation for Red Maple on a cloudy day (8/22/97) under 0-5 kPa medium tension.
Figure 6.3: Air temperature, wind speed, measured transpiration and solar radiation for Red Maple on a sunny day (8/23/97) under 0-5 kPa medium tension.
Figure 6.4: Air temperature, wind speed, measured transpiration and solar radiation for Red Maple on a sunny day (9/1/97) under 0-5 kPa medium tension.
Figure 6.5: Air temperature, wind speed, measured transpiration and solar radiation for Red Maple on a cloudy day (9/12/97) under 0-5 kPa medium tension.
Temperature differences on sunny days were higher than the cloudy days during the highest transpiration period. Figure 6.6 shows the top leaves being the coolest during the highest radiation periods. Evaporative cooling of middle and bottom leaves was assumed to be reduced by the canopy above them absorbing most of the solar radiation. Leaf temperatures were similar for morning and late night when there was limited transpiration and limited solar radiation.

The VPD, and solar radiation versus transpiration rate were plotted on Figures 6.7-6.11. Consistent with other evapotranspiration studies, these figures show that there is a good correlation between VPD vs. transpiration rate and solar radiation vs. transpiration rate. In the morning time, VPD and solar radiation are very low. However, when the sun rises the VPD and solar radiation gets high so that the transpiration rate reaches its highest rate during the mid-day.

A visual observation of the data indicates that the driving force for transpiration in late afternoon and early morning is VPD. Transpiration tends to be more proportional to solar radiation for sunny days. However, transpiration tends to be more proportional to VPD for cloudy days.
Figure 6.6: Leaf temperature variations for Red Maple on a sunny (9/1/97), (a) and a cloudy day (9/12/97), (b).
The daily transpiration rate of Red Maple was found to range from a minimum of 850 g tree\(^{-1}\) day\(^{-1}\) to a maximum of 1789 g tree\(^{-1}\) day\(^{-1}\) for sunny days. However, for cloudy days, it was found to range from a minimum of 450 g tree\(^{-1}\) day\(^{-1}\) to a maximum of 855 g tree\(^{-1}\) day\(^{-1}\).

Using R\(^2\) coefficient from a regression analysis over two months of continuous data (including all night time data), it was evident that solar radiation with a coefficient of 0.875 was more correlated to ET than VPD with a coefficient of 0.684. (Figure 6.12 and 6.13).

Figure 6.13 shows that when VPD exceeds 1000 Pa, data scatter points seem more correlated to the regression line. Since solar radiation is usually big when VPD is high, possible explanation of this can be a combination effect of both solar radiation and VPD on transpiration rate.

Figure 6.14, 6.15, and 6.16 show that the correlation between calculated and measured hourly ET rates of Red Maple including all night time data for Stanghellini, Fynn and Penman (1948) ET models were 0.814, 0.782, 0.878 respectively.

The Fynn and Stanghellini ET methods were mainly developed for greenhouse conditions whereas Penman was developed for field conditions. While climatic factors are controlled under greenhouse conditions, it is impossible to control the climate at outside conditions. The main differences between these two conditions in terms of meteorological factor are wind and precipitation. Because the wind speed generally is lower than 1 m/s in the greenhouse, the effect of the wind under the greenhouse conditions is usually negligible.
Figure 6.7: The effect of vapor pressure deficit and solar radiation on the transpiration rate of Red Maple on a sunny day (8/14/97).
Figure 6.8: The effect of vapor pressure deficit and solar radiation on the transpiration rate of Red Maple on a cloudy day (8/22/97).
Figure 6.9: The effect of vapor pressure deficit and solar radiation on the transpiration rate of Red Maple on a sunny day (8/23/97).
Figure 6.10: The effect of vapor pressure deficit and solar radiation on the transpiration rate of Red Maple on a sunny day (9/1/97).
Figure 6.11: The effect of vapor pressure deficit and solar radiation on the transpiration rate of Red Maple on a cloudy day (9/12/97).
Figure 6.12: Correlation between solar radiation and measured ET rate of Red Maple for two months of hourly data (including all night time data).
Figure 6.13: Correlation between vapor pressure deficit and measured ET rate of Red Maple for two months of hourly data (including all night time data).
Figure 6.14: Correlation between calculated and measured hourly ET rates of Red Maple based on the Stanghellini method for two months (including all night time data).
Figure 6.15: Correlation between calculated and measured hourly ET rates of Red Maple based on the Fynn method for two months (including all night time data).
Figure 6.16: Correlation between calculated and measured hourly ET rates of Red Maple based on the Penman method for two months (including all night time data).
The Penman method provided the best predictions of transpiration for the plants used in this study based on a regression coefficient of 0.878. This method contains a wind parameter in the model and was developed for outside conditions. On the other hand, it overestimated the transpiration based on measured transpiration because there was no resistance term in the equation.

In order to see the difference between calculated and measured ET, the following formula was used (Jensen et al., 1990):

\[
\text{Error} = \frac{\text{Calculated ET} - \text{Measured ET}}{\text{Measured ET}}
\]  \hspace{1cm} (6.1.1)

Based on Eq. (6.1.1), the Fynn method had the lowest error even though the model had a low correlation coefficient. While the Penman method had the best R² value, the Penman model overestimated the ET. Table 6.1 shows the results of these error calculations based on two months experimental results.
Table 6.1: Differences between measured ET and calculated ET for two months of data (including all night time data).

<table>
<thead>
<tr>
<th>ET calculation methods</th>
<th>Average Calculated ET (g/day)</th>
<th>Average Measured ET (g/day)</th>
<th>$R^2$</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stanghellini</td>
<td>1100.21</td>
<td>998.75</td>
<td>0.81</td>
<td>10.16</td>
</tr>
<tr>
<td>Fynn</td>
<td>1668.10</td>
<td>998.75</td>
<td>0.78</td>
<td>7.0</td>
</tr>
<tr>
<td>Penman</td>
<td>1255.43</td>
<td>998.75</td>
<td>0.88</td>
<td>25.70</td>
</tr>
</tbody>
</table>

Figure 6.17 shows average hourly transpiration rate for different ET methods along with measured ET during the experimental periods. It was observed that Stanghellini and Fynn methods estimate the transpiration rate to be 7-10% lower than the measured ET during the noon periods whereas they estimate the transpiration rate higher than the measured ET during morning and late afternoon time periods. The Penman method estimated the ET rates higher than the measured ET for all times.
Figure 6.17: Average hourly transpiration rate for different ET methods for two month of experimental data.

Potting medium temperature changes in two different depths along with medium tension is shown in Figure 6.18 (a), and (b). Average potting medium temperatures varied 1.5-2°C from the mean during the experimental period. The temperature of the potting medium at any time depended on the ratio of the energy absorbed to that being
lost. A visual observation of the data indicated that medium temperature variations near the surface were high compared to the lower depth for the clear day and vise versa for the cloudy day. Submedium was cooler than surface medium layers because submedium was not subject to direct effects of solar radiation during the clear day. On clear days, temperatures near the medium surface layer did not reach its maximum until sometime after solar noon due to lag time. Since medium starts to lose energy to the air in late afternoon, medium temperature was lower in the early morning compared to lower depths. On cloudy days, medium temperature changes during the early morning and late nights were very close to each other due to the low incoming solar radiation. Overall, medium temperature changes on cloudy days are low compared to clear days.

Another visual observation from Figure 6.18 (a), and (b) was that medium moisture had a significant influence on medium temperature. High medium moisture levels resist change to medium temperature by virtue of its high specific heat and high energy requirement for evaporation. This supports the idea of Brady (1990) that moisture control in soil has more influence on soil temperature than any other soil management practice such as mulching.
Figure 6.18: Medium temperature changes along with medium tension for a clear day (8/14/97), (a) and a cloudy day (9/12/97), (b).
The temperature changes among leaf, air and medium were shown in Figure 6.19 (a) and (b) for a clear and a cloudy day respectively. Medium tension variations were between 0-5 kPa for these days. Figure 6.19 shows that the temperature difference between air and leaf is big on clear days compared to cloudy days.
Figure 6.19: Air, leaf and medium temperature variations for a clear (8/14/97), (a) and a cloudy day (9/12/97), (b).
6.2 Multiple Linear Regression Analysis

In order to evaluate individual and combined effects of climate factors on the measured ET, linear multiple regression analyses were done with Minitab (Release 12.1, by Minitab Inc.). The multiple linear regression analysis was also used to test sensitivity with first and second order regressions. Since there were three different levels of leaf temperature and two levels of potting medium temperature, average values were used to represent leaf and potting medium temperatures in the statistical analysis.

In the first order regression model, there were seven input parameters with an \( R^2 = 88.4\% \) where:

\[
\text{Measured } ET = -3.78 + 0.370 \text{ (ambient temperature)} - 0.0798 \text{ (relative humidity)} + 0.186 \text{ (radiation)} + 1.04 \text{ (average leaf temperature)} - 0.233 \text{ (tension)} - 0.274 \text{ (average potting medium temperature)} - 1.07 \text{ (windspeed)}
\] (6.2.1)

Table 6.2 shows the result of this statistical analysis. Table 6.2 indicates that the average leaf temperature, soil temperature, ambient temperature, and relative humidity were nonsignificant at the 90% confidence level. Beginning with ambient temperature, nonsignificant terms were eliminated one by one from the model and a new regression model was set up each time till all variables in the model became significant at a 90% confidence level. By doing this backward elimination, the final simple first order model was obtained in equation (6.2.2) with \( R^2 = 88.3\% \). The result of the final first order
model is shown in Table 6.3. Since the $R^2$ value of equation (6.2.1) is only a little larger than the $R^2$ values of equation (6.2.2), it is preferred to use the equation (6.2.2), which is a much simpler model where:

\[
\text{Measured ET} = -13.9 + 0.190 \; (\text{radiation}) + 1.19 \; (\text{average leaf temperature}) - 0.214 \; (\text{tension})
\]  
(6.2.2)

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>Stddev</th>
<th>t-ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-3.778</td>
<td>6.707</td>
<td>-0.56</td>
<td>0.573</td>
</tr>
<tr>
<td>Ambient temp.</td>
<td>0.3699</td>
<td>0.7630</td>
<td>0.48</td>
<td>0.628</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>-0.07977</td>
<td>0.06097</td>
<td>-1.31</td>
<td>0.191</td>
</tr>
<tr>
<td>Radiation</td>
<td>0.185722</td>
<td>0.004660</td>
<td>39.85</td>
<td>0.000</td>
</tr>
<tr>
<td>Ave. leaf temp.</td>
<td>1.0435</td>
<td>0.7379</td>
<td>1.41</td>
<td>0.158</td>
</tr>
<tr>
<td>Tension</td>
<td>-0.23314</td>
<td>0.09277</td>
<td>-2.51</td>
<td>0.012</td>
</tr>
<tr>
<td>Ave. medium temp.</td>
<td>-0.2744</td>
<td>0.1775</td>
<td>-1.55</td>
<td>0.122</td>
</tr>
<tr>
<td>Windspeed</td>
<td>-1.0732</td>
<td>0.5128</td>
<td>-2.09</td>
<td>0.037</td>
</tr>
</tbody>
</table>

Table 6.2: Partial regression coefficients for the first order model in seven variables for measured ET.
<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>Stdev</th>
<th>t-ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-13.890</td>
<td>2.476</td>
<td>-5.61</td>
<td>0.000</td>
</tr>
<tr>
<td>Radiation</td>
<td>0.189660</td>
<td>0.003146</td>
<td>60.29</td>
<td>0.000</td>
</tr>
<tr>
<td>Ave. leaf temp.</td>
<td>1.1949</td>
<td>0.1425</td>
<td>8.39</td>
<td>0.000</td>
</tr>
<tr>
<td>Tension</td>
<td>-0.21366</td>
<td>0.08918</td>
<td>-2.40</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Table 6.3: Partial regression coefficients for the final first order model in three variables for measured ET.

Table 6.3 indicates that a good multiple linear regression model can estimate ET using radiation, leaf temperature and potting medium tension. Since a second order regression analysis can show the interactions among the variables in the model, a second order regression analysis was performed. The resulting regression model was as equation (6.2.3) with an $R^2 = 90.0\%$ where:
**Measured ET** = - 51.5 - 10.2 (ambient temp.) + 0.461 (relative humidity) + 0.208 (radiation) - 16.5 (windspeed) + 9.25 (ave. leaf temp.) - 0.86 (tension) + 5.09 (ave. potting medium temp.) + 0.0232 (ambient temp. * relative humidity) + 0.00213 (ambient temp. * radiation) + 1.26 (ambient temp. * windspeed) + 0.0271 (ambient temp. * ave. leaf temp.) + 0.082 (ambient temp. * tension) + 0.282 (ambient temp. * ave. potting medium temp.) - 0.000202 (relative humidity * radiation) + 0.161 (relative humidity * windspeed) - 0.0111 (relative humidity * ave. leaf temp.) + 0.0016 (relative humidity * tension) -0.0428 (relative humidity * ave. potting medium temp.) - 0.0131 (radiation * windspeed) -0.00146 (radiation * ave. leaf temp.) -0.00531 (radiation * tension) + 0.00094 (radiation * ave. potting medium temp.) - 0.519 (windspeed * ave. leaf temp.) + 0.666 (windspeed * tension) - 0.552 (windspeed * ave. potting medium temp.) + 0.053 (ave. leaf temp. * tension) - 0.344 (ave. leaf temp. * ave. potting medium temp.) - 0.0699 (tension * ave. potting medium temp.) (6.2.3)

The regression coefficients, their standard errors, the t-statistics, and p values for this model are shown in Table 6.4. A similar procedure for establishing a final model of second ordered measured ET was followed to eliminate nonsignificant terms in Table 6.4. The result of the backward elimination procedure for the second ordered model resulted in equation (6.2.4) with $R^2 = 89.9\%$. The equation (6.2.4) represents the full model for ET and Table 6.5 shows the results of this procedure.
\[ \text{Measured ET} = -50.8 - 7.96 \text{ (ambient temp.)} + 0.468 \text{ (relative humidity)} + 0.191 \text{ (radiation)} - 17.5 \text{ (windspeed)} + 7.71 \text{ (ave. leaf temp.)} - 0.524 \text{ (tension)} + 3.72 \text{ (ave. potting medium temp.)} + 0.769 \text{ (ambient temp. * windspeed)} + 0.126 \text{ (ambient temp. * tension)} + 0.282 \text{ (ambient temp. * ave. potting medium temp.)} + 0.165 \text{ (relative humidity * windspeed)} - 0.0336 \text{ (relative humidity * ave. potting medium temp.)} - 0.0128 \text{ (radiation * windspeed)} - 0.00519 \text{ (radiation * tension)} + 0.00169 \text{ (radiation * ave. potting medium temp.)} + 0.668 \text{ (windspeed * tension)} - 0.560 \text{ (windspeed * ave. potting medium temp.)} - 0.319 \text{ (ave. leaf temp. * ave. potting medium temp.)} - 0.0721 \text{ (tension * ave. potting medium temp.)} \quad (6.2.4) \]

By comparing the $R^2$ values of the first and second order regression models, it can be concluded that the effects of interactions to the model do not make the model better. Therefore, it is better to use a simple first order regression model since it requires less input variables.

In order to see the correlation among the variables, Table 6.6 was prepared. Table 6.6 shows that there is high correlation between leaf temperature and ambient temperature. So, the ambient temperature can be used instead of leaf temperature if there is no available leaf temperature data. Table 6.6 shows that there are significant correlations among VPD, radiation and measured ET. However, a model that involves VPD and radiation can be a very practical solution for ET estimates. For this purpose, equation (6.2.5) was obtained with an $R^2 = 87.9\%$ by performing a multiple regression analysis where:
**Measured ET** = 2.47 + 0.187 \( (radiation) \) + 0.0126 \( (VPD) \) - 0.751 \( (windspeed) \) \hspace{1cm} (6.2.5)

Table 6.7 shows the statistical result of the variables used in equation (6.2.5). Since windspeed was nonsignificant at 90% confidence level, a new model was formed by using backward elimination where:

**Measured ET** = 2.16 + 0.185 \( (radiation) \) + 0.0125 \( (VPD) \) \hspace{1cm} (6.2.6)

Equation (6.2.6) predicts the ET with \( R^2 = 87.8\% \) and the statistical results are shown in Table 6.8. In order to compare regression models using only VPD-measured ET and radiation-measured ET, a simple linear regression analysis was performed where:

**Measured ET** = -0.17 + 0.0898 \( (VPD) \) \hspace{1cm} (6.2.7)

**Measured ET** = 4.05 + 0.207 \( (radiation) \) \hspace{1cm} (6.2.8)

The equations (6.2.7) and (6.2.8) predicts the ET with \( R^2 = 68.4\% \) and \( R^2 = 87.5\% \) respectively. The statistical result of these linear regression models is shown in Table 6.9 and 6.10.
<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>Stddev</th>
<th>t-ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-51.51</td>
<td>30.42</td>
<td>-1.69</td>
<td>0.091</td>
</tr>
<tr>
<td>Ambient temp.</td>
<td>-10.191</td>
<td>8.335</td>
<td>-1.22</td>
<td>0.222</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>0.4606</td>
<td>0.3081</td>
<td>1.49</td>
<td>0.135</td>
</tr>
<tr>
<td>Radiation</td>
<td>0.20767</td>
<td>0.03816</td>
<td>5.44</td>
<td>0.000</td>
</tr>
<tr>
<td>Windspeed</td>
<td>-16.495</td>
<td>5.725</td>
<td>-2.88</td>
<td>0.004</td>
</tr>
<tr>
<td>Ave. leaf temp.</td>
<td>9.245</td>
<td>8.045</td>
<td>1.15</td>
<td>0.251</td>
</tr>
<tr>
<td>Tension</td>
<td>-0.864</td>
<td>1.129</td>
<td>-0.77</td>
<td>0.444</td>
</tr>
<tr>
<td>Ave. potting medium temp.</td>
<td>5.086</td>
<td>1.911</td>
<td>2.66</td>
<td>0.008</td>
</tr>
<tr>
<td>Ambient temp. * Relative humidity</td>
<td>0.02324</td>
<td>0.08167</td>
<td>0.28</td>
<td>0.776</td>
</tr>
<tr>
<td>Ambient temp. * Radiation</td>
<td>0.002129</td>
<td>0.005387</td>
<td>0.40</td>
<td>0.693</td>
</tr>
<tr>
<td>Ambient temp. * Windspeed</td>
<td>1.2554</td>
<td>0.7121</td>
<td>1.76</td>
<td>0.078</td>
</tr>
<tr>
<td>Ambient temp. * Ave. leaf temp.</td>
<td>0.02709</td>
<td>0.03932</td>
<td>0.69</td>
<td>0.491</td>
</tr>
<tr>
<td>Ambient temp. * Tension</td>
<td>0.0821</td>
<td>0.1321</td>
<td>0.62</td>
<td>0.535</td>
</tr>
<tr>
<td>Ambient temp. * Ave. potting medium temp.</td>
<td>0.2821</td>
<td>0.1341</td>
<td>2.10</td>
<td>0.036</td>
</tr>
<tr>
<td>Relative humidity * Radiation</td>
<td>-0.0002024</td>
<td>0.0002679</td>
<td>-0.76</td>
<td>0.450</td>
</tr>
<tr>
<td>Relative humidity * Windspeed</td>
<td>0.16080</td>
<td>0.05660</td>
<td>2.84</td>
<td>0.005</td>
</tr>
<tr>
<td>Relative humidity * Ave. leaf temp.</td>
<td>-0.01174</td>
<td>0.07850</td>
<td>-0.14</td>
<td>0.887</td>
</tr>
<tr>
<td>Relative humidity * Tension</td>
<td>0.00165</td>
<td>0.01008</td>
<td>0.16</td>
<td>0.870</td>
</tr>
<tr>
<td>Relative humidity * Ave. potting medium temp.</td>
<td>-0.04285</td>
<td>0.01772</td>
<td>-2.42</td>
<td>0.016</td>
</tr>
<tr>
<td>Radiation * Windspeed</td>
<td>-0.01312</td>
<td>0.004122</td>
<td>-3.18</td>
<td>0.002</td>
</tr>
<tr>
<td>Radiation * Ave. leaf temp.</td>
<td>-0.001465</td>
<td>0.005189</td>
<td>-0.28</td>
<td>0.778</td>
</tr>
<tr>
<td>Radiation * Tension</td>
<td>0.0005143</td>
<td>0.0008155</td>
<td>-6.52</td>
<td>0.000</td>
</tr>
<tr>
<td>Radiation * Ave. potting medium temp.</td>
<td>0.500938</td>
<td>0.00183</td>
<td>0.79</td>
<td>0.428</td>
</tr>
<tr>
<td>Windspeed * Ave. leaf temp.</td>
<td>-0.5193</td>
<td>0.6500</td>
<td>-0.80</td>
<td>0.424</td>
</tr>
<tr>
<td>Windspeed * Tension</td>
<td>0.6664</td>
<td>0.1089</td>
<td>6.12</td>
<td>0.000</td>
</tr>
<tr>
<td>Windspeed * Ave. potting medium temp.</td>
<td>-0.5516</td>
<td>0.1545</td>
<td>-3.57</td>
<td>0.000</td>
</tr>
<tr>
<td>Ave. leaf temp. * Tension</td>
<td>0.0528</td>
<td>0.1258</td>
<td>0.42</td>
<td>0.675</td>
</tr>
<tr>
<td>Ave. leaf temp. * Ave. potting medium temp.</td>
<td>-0.3436</td>
<td>0.3460</td>
<td>-2.35</td>
<td>0.019</td>
</tr>
<tr>
<td>Tension * Ave. potting medium temp.</td>
<td>-0.06987</td>
<td>0.03176</td>
<td>-2.20</td>
<td>0.028</td>
</tr>
</tbody>
</table>

Table 6.4: Partial regression coefficients for the second order model with all main variables and possible interactions for measured ET.
<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>Stdev</th>
<th>t-ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-50.80</td>
<td>27.58</td>
<td>-1.84</td>
<td>0.066</td>
</tr>
<tr>
<td>Ambient temp.</td>
<td>-7.061</td>
<td>2.678</td>
<td>-2.64</td>
<td>0.008</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>0.4677</td>
<td>0.2813</td>
<td>1.66</td>
<td>0.097</td>
</tr>
<tr>
<td>Radiation</td>
<td>0.19116</td>
<td>0.02110</td>
<td>9.06</td>
<td>0.000</td>
</tr>
<tr>
<td>Windspeed</td>
<td>-17.545</td>
<td>5.448</td>
<td>-3.22</td>
<td>0.001</td>
</tr>
<tr>
<td>Ave. leaf temp.</td>
<td>7.715</td>
<td>2.768</td>
<td>2.79</td>
<td>0.005</td>
</tr>
<tr>
<td>Tension</td>
<td>-0.5239</td>
<td>0.4518</td>
<td>-1.16</td>
<td>0.246</td>
</tr>
<tr>
<td>Ave. potting medium temp.</td>
<td>3.722</td>
<td>1.297</td>
<td>2.87</td>
<td>0.004</td>
</tr>
<tr>
<td>Ambient temp. * Windspeed</td>
<td>0.7690</td>
<td>0.1629</td>
<td>4.72</td>
<td>0.000</td>
</tr>
<tr>
<td>Ambient temp. * Tension</td>
<td>0.12601</td>
<td>0.03214</td>
<td>3.92</td>
<td>0.000</td>
</tr>
<tr>
<td>Ambient temp. * Ave. potting medium temp.</td>
<td>0.2823</td>
<td>0.1286</td>
<td>2.20</td>
<td>0.028</td>
</tr>
<tr>
<td>Relative humidity * Windspeed</td>
<td>0.16537</td>
<td>0.05308</td>
<td>3.12</td>
<td>0.002</td>
</tr>
<tr>
<td>Relative humidity * Ave. potting medium temp.</td>
<td>-0.03355</td>
<td>0.01225</td>
<td>-2.74</td>
<td>0.006</td>
</tr>
<tr>
<td>Radiation * Windspeed</td>
<td>-0.012782</td>
<td>0.003850</td>
<td>-3.32</td>
<td>0.001</td>
</tr>
<tr>
<td>Radiation * Tension</td>
<td>-0.0051865</td>
<td>0.0006637</td>
<td>-7.82</td>
<td>0.000</td>
</tr>
<tr>
<td>Radiation * Ave. potting medium temp.</td>
<td>0.0016900</td>
<td>0.0008518</td>
<td>1.98</td>
<td>0.048</td>
</tr>
<tr>
<td>Windspeed * Tension</td>
<td>0.6679</td>
<td>0.1038</td>
<td>6.43</td>
<td>0.000</td>
</tr>
<tr>
<td>Windspeed * Ave. potting medium temp.</td>
<td>-0.5599</td>
<td>0.1370</td>
<td>-4.09</td>
<td>0.000</td>
</tr>
<tr>
<td>Ave. leaf temp. * Ave. potting medium temp.</td>
<td>-0.3190</td>
<td>0.1329</td>
<td>-2.40</td>
<td>0.017</td>
</tr>
<tr>
<td>Tension * Ave. potting medium temp.</td>
<td>-0.07208</td>
<td>0.02956</td>
<td>-2.44</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Table 6.5: Partial regression coefficients for the final second order model for measured ET.
<table>
<thead>
<tr>
<th></th>
<th>Measured ET</th>
<th>Ambient temp</th>
<th>Relative humidity</th>
<th>Radiation</th>
<th>Wind speed</th>
<th>Ave. leaf temp</th>
<th>Tension</th>
<th>Ave. medium temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temp.</td>
<td>0.682</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative humidity</td>
<td>-0.708</td>
<td>-0.526</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation</td>
<td>0.935</td>
<td>0.660</td>
<td>-0.752</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windspeed</td>
<td>0.383</td>
<td>0.295</td>
<td>-0.373</td>
<td>0.424</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ave. leaf temp.</td>
<td>0.698</td>
<td>0.989</td>
<td>-0.532</td>
<td>0.678</td>
<td>0.306</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tension</td>
<td>0.028</td>
<td>0.026</td>
<td>-0.185</td>
<td>0.056</td>
<td>-0.044</td>
<td>0.040</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ave. medium temp.</td>
<td>0.129</td>
<td>0.586</td>
<td>-0.185</td>
<td>0.087</td>
<td>0.006</td>
<td>0.550</td>
<td>0.091</td>
<td></td>
</tr>
<tr>
<td>VPD</td>
<td>0.827</td>
<td>0.707</td>
<td>-0.922</td>
<td>0.850</td>
<td>0.362</td>
<td>0.716</td>
<td>0.158</td>
<td>0.318</td>
</tr>
</tbody>
</table>

Table 6.6: Correlations between input variables and measured ET.
<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>Stddev</th>
<th>t-ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>2.4702</td>
<td>0.8063</td>
<td>3.06</td>
<td>0.002</td>
</tr>
<tr>
<td>Radiation</td>
<td>0.187053</td>
<td>0.004597</td>
<td>40.69</td>
<td>0.000</td>
</tr>
<tr>
<td>VPD</td>
<td>0.012554</td>
<td>0.002189</td>
<td>5.73</td>
<td>0.000</td>
</tr>
<tr>
<td>Windspeed</td>
<td>-0.7507</td>
<td>0.5163</td>
<td>-1.45</td>
<td>0.146</td>
</tr>
</tbody>
</table>

Table 6.7: Statistical result of multiple linear regression model that involves solar radiation, VPD and windspeed.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>Stddev</th>
<th>t-ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>2.1629</td>
<td>0.7785</td>
<td>2.78</td>
<td>0.006</td>
</tr>
<tr>
<td>Radiation</td>
<td>0.185468</td>
<td>0.004468</td>
<td>41.51</td>
<td>0.000</td>
</tr>
<tr>
<td>VPD</td>
<td>0.012554</td>
<td>0.002190</td>
<td>5.73</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 6.8: Statistical result of the multiple linear regression model that involves solar radiation and VPD.
<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>Stdev</th>
<th>t-ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>4.0504</td>
<td>0.7157</td>
<td>5.66</td>
<td>0.000</td>
</tr>
<tr>
<td>Radiation</td>
<td>0.207217</td>
<td>0.002389</td>
<td>86.74</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 6.9: Statistical result of the simple linear regression model that includes only solar radiation.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>Stdev</th>
<th>t-ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-0.170</td>
<td>1.251</td>
<td>-0.14</td>
<td>0.892</td>
</tr>
<tr>
<td>VPD</td>
<td>0.089805</td>
<td>0.001860</td>
<td>48.28</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 6.10: Statistical result of the simple linear regression model that includes only VPD.

In conclusion, it can be said that the second order multiple regression analysis did not make the model significantly better according to the $R^2$ values. So, it is better to use a first order, multiple regression model instead of the second order multiple regression model for simplicity.

Table 6.6 shows that tension levels maintained in this experiment alone did not shown significant correlation with transpiration. However, the results of a multiple linear regression analysis showed that tension was a significant variable as part of the
overall system. Devore and Peck (1993) states that since the correlation is done by comparing only two variables, the correlation coefficient alone may not show the significant level of an input variable in a model. The correlation simply shows the strength of association between two variables. There is no prediction from one variable to another and there is no distinction between dependent and independent variable in the correlation. However, the multiple regression analysis shows the partial contribution of each variable in the model to the system response. So, a nonsignificant variable in the correlation could be potentially a significant variable in the multiple regression analysis since the multiple regression analysis considers each possible variable in the system and its partial contribution to the model response.
6.3 Effect of Medium Tension Levels to Measured Evapotranspiration

The effect of different medium tension levels on measured ET was evaluated by a one-way analysis of variance (ANOVA) using Minitab.

6.3.1 One-way Analysis of Variance (ANOVA)

In order to evaluate the effects of different tension levels on measured ET, a single-factor ANOVA test was performed using all night time transpiration data. The tension values had seven different levels starting with 0 kPa and ending with 21 kPa as shown in Table 6.11. Statistical result of the analysis is shown in Table 6.12.

<table>
<thead>
<tr>
<th>Tension levels</th>
<th>Tension values (kPa)</th>
<th>N</th>
<th>Mean transpiration rate (g/tree h)</th>
<th>StError</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-2.99</td>
<td>445</td>
<td>36.65</td>
<td>2.465</td>
</tr>
<tr>
<td>2</td>
<td>3-5.99</td>
<td>219</td>
<td>43.22</td>
<td>3.445</td>
</tr>
<tr>
<td>3</td>
<td>6-8.99</td>
<td>85</td>
<td>61.34</td>
<td>6.185</td>
</tr>
<tr>
<td>4</td>
<td>9-11.99</td>
<td>52</td>
<td>40.62</td>
<td>6.820</td>
</tr>
<tr>
<td>5</td>
<td>12-14.99</td>
<td>106</td>
<td>39.50</td>
<td>5.157</td>
</tr>
<tr>
<td>6</td>
<td>15-17.99</td>
<td>72</td>
<td>37.51</td>
<td>5.774</td>
</tr>
<tr>
<td>7</td>
<td>18-20.99</td>
<td>101</td>
<td>29.46</td>
<td>4.056</td>
</tr>
</tbody>
</table>

Table 6.11: Mean, standard error of mean, and number of the observation values of different tension classes in the single-factor ANOVA analysis (including all night data).
<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension levels</td>
<td>6</td>
<td>57660</td>
<td>9610</td>
<td>3.69</td>
<td>0.001</td>
</tr>
<tr>
<td>Error</td>
<td>1073</td>
<td>2797152</td>
<td>2607</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1079</td>
<td>2854812</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.12: Statistical result of single-factor ANOVA analysis (including all night time data).

In the first order multiple linear regression analysis, it was found that the tension variable was significant at a 90% confidence level. The single-factor ANOVA analysis using all night time data indicated that the measured ET may have been affected by the tension levels at a 95% confidence level. To examine which tension levels were significantly different from one another, Fisher’s pairwise multivariable comparison analysis was done in the Minitab and shown in Table 6.13. Table 6.13 shows that the tension levels of 1-3, 2-3, 2-7, 3-4, 3-5, 3-6, and 3-7 were significantly different from the others. A plot of tension levels with measured ET is shown in Figure 6.20 with related standard errors.
<table>
<thead>
<tr>
<th>Difference</th>
<th>Confidence Interval</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1-T2</td>
<td>(-14.8, 1.7)</td>
<td>Not significantly different</td>
</tr>
<tr>
<td>T1-T3</td>
<td>(-36.6, -12.8)</td>
<td>Significantly different</td>
</tr>
<tr>
<td>T1-T4</td>
<td>(-18.6, 10.7)</td>
<td>Not significantly different</td>
</tr>
<tr>
<td>T1-T5</td>
<td>(-13.7, 8.0)</td>
<td>Not significantly different</td>
</tr>
<tr>
<td>T1-T6</td>
<td>(-13.6, 11.9)</td>
<td>Not significantly different</td>
</tr>
<tr>
<td>T1-T7</td>
<td>(-3.8, 18.2)</td>
<td>Not significantly different</td>
</tr>
<tr>
<td>T2-T3</td>
<td>(-30.9, -5.3)</td>
<td>Significantly different</td>
</tr>
<tr>
<td>T2-T4</td>
<td>(-12.8, 18.1)</td>
<td>Not significantly different</td>
</tr>
<tr>
<td>T2-T5</td>
<td>(-8.1, 15.6)</td>
<td>Not significantly different</td>
</tr>
<tr>
<td>T2-T6</td>
<td>(-7.9, 19.3)</td>
<td>Not significantly different</td>
</tr>
<tr>
<td>T2-T7</td>
<td>(1.7, 25.8)</td>
<td>Significantly different</td>
</tr>
<tr>
<td>T3-T4</td>
<td>(3.1, 38.4)</td>
<td>Significantly different</td>
</tr>
<tr>
<td>T3-T5</td>
<td>(7.3, 36.4)</td>
<td>Significantly different</td>
</tr>
<tr>
<td>T3-T6</td>
<td>(7.8, 39.9)</td>
<td>Significantly different</td>
</tr>
<tr>
<td>T3-T7</td>
<td>(17.1, 46.6)</td>
<td>Significantly different</td>
</tr>
<tr>
<td>T4-T5</td>
<td>(-15.8, 18.1)</td>
<td>Not significantly different</td>
</tr>
<tr>
<td>T4-T6</td>
<td>(-15.1, 21.3)</td>
<td>Not significantly different</td>
</tr>
<tr>
<td>T4-T7</td>
<td>(-5.9, 28.3)</td>
<td>Not significantly different</td>
</tr>
<tr>
<td>T5-T6</td>
<td>(-13.3, 17.3)</td>
<td>Not significantly different</td>
</tr>
<tr>
<td>T5-T7</td>
<td>(-3.9, 24.0)</td>
<td>Not significantly different</td>
</tr>
<tr>
<td>T6-T7</td>
<td>(-7.4, 23.5)</td>
<td>Not significantly different</td>
</tr>
</tbody>
</table>

Table 6.13: One-way multiple pairwise comparison of Fisher (including all night time data).
Figure 6.20: Mean transpiration rate and standard error for different tension level treatments (including all night time data).
In section 6.3.1, the single-factor ANOVA test was performed using all night time transpiration data. Since there were approximately 55.2% of data between zero and 20 (g/tree h) values affecting the ANOVA test, a revised ANOVA test was prepared ignoring these data points. Results of this revised ANOVA analysis showed that medium tension did not affect the transpiration rate at the 95% confidence level (Table 6.14 and 6.15).

<table>
<thead>
<tr>
<th>Tension levels</th>
<th>Tension values (kPa)</th>
<th>N</th>
<th>Mean transpiration rate (g/tree h)</th>
<th>SdError</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-2.99</td>
<td>178</td>
<td>85.84</td>
<td>3.894</td>
</tr>
<tr>
<td>2</td>
<td>3-5.99</td>
<td>109</td>
<td>82.17</td>
<td>4.466</td>
</tr>
<tr>
<td>3</td>
<td>6-8.99</td>
<td>58</td>
<td>87.19</td>
<td>6.748</td>
</tr>
<tr>
<td>4</td>
<td>9-11.99</td>
<td>26</td>
<td>77.00</td>
<td>9.117</td>
</tr>
<tr>
<td>5</td>
<td>12-14.99</td>
<td>43</td>
<td>84.79</td>
<td>4.836</td>
</tr>
<tr>
<td>6</td>
<td>15-17.99</td>
<td>32</td>
<td>79.41</td>
<td>8.330</td>
</tr>
<tr>
<td>7</td>
<td>18-20.99</td>
<td>37</td>
<td>75.62</td>
<td>5.537</td>
</tr>
</tbody>
</table>

Table 6.14: Mean, standard error of mean, and number of the observation values of different tension classes in the single-factor ANOVA analysis (excluding data between zero and 20 g/tree h).
<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension levels</td>
<td>6</td>
<td>5958</td>
<td>993</td>
<td>0.44</td>
<td>0.851</td>
</tr>
<tr>
<td>Error</td>
<td>476</td>
<td>1069207</td>
<td>2246</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>482</td>
<td>1075165</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.15: Statistical result of single-factor ANOVA analysis (excluding data between zero and 20 g/tree h).

A plot of tension levels with measured ET excluding all night time data is shown in Figure 6.21 with related standard errors. In the experiment, potting medium tension levels were maintained between 0-21 kPa values. However, the experimental results show that these tension levels should have been beyond 25 kPa to observe the potential negative effect of tension levels on transpiration in detail.
Figure 6.21: Mean transpiration rate and standard error for different tension level treatments (excluding data between zero and 20 g/tree h).
In order to further evaluate the effect of the tension levels on transpiration rates, data were selected for some specific days whose tension values and solar radiation were relatively high (Figures 6.22-6.25). A visual observation from these figures showed that there was no apparent effect of high-tension values on transpiration rates during the early morning and late night. However, the effect of the high-tension on transpiration rate was observed by the canopy temperature rising above the ambient temperature in late afternoons. Negative tension slopes in Figures 6.23-6.25 show the effect of irrigation.
Figure 6.22: Air and leaf temperature differences along with transpiration rate and relatively high tension values for a clear day (8/27/97).
Figure 6.23: Air and leaf temperature differences along with transpiration rate and relatively high tension values for a clear day (9/3/97).
Figure 6.24: Air and leaf temperature differences along with transpiration rate and relatively high tension values for a clear day (9/4/97).
Figure 6.25: Air and leaf temperature differences along with transpiration rate and relatively high tension values for a clear day (9/25/97).
6.4 Tensiometer-Controlled Microirrigation Scheduling for Container-Grown Nursery Plants

Potting medium tension (PMT)-based irrigation was done from September 26, 1997 through August 22, 1997. Comparison of the tension-based irrigation with lysimeter data is shown in Table 6.16. The total amount of water applied to the plant for PMT-based irrigation during the experimental period was 31.810 L whereas the measured transpiration from the lysimeter was 29.608 L. The difference between these two values was assumed to be due to biomass production (wet basis). The biomass production of the plant was estimated to be approximately 2.2 kg per month since there was no drainage from the container during the PMT-based irrigation events. This result shows that PMT-based irrigation is efficient in controlling irrigation for container-grown nursery plants. The tensiometers provided a clear understanding of how PMT changes in response to irrigation (Figure 6.26). Immediately following irrigation, tension dropped. Then, as the plants removed water for ET, the tension increased. Figure 6.26 especially shows rapid increases in tension during the day and only minor changes at night. Figure 6.27 compares PMT-based irrigation and the measured ET rate of the plant.

The PMT-based irrigation scheduling system was able to continuously monitor the moisture level of the medium, call for irrigation when the potting medium required water, and turn the water off when an adequate amount had been applied. Figure 6.28 shows a three-day history of tensions along with ambient temperature changes.
<table>
<thead>
<tr>
<th>JULIAN DATE</th>
<th>TIME</th>
<th>IRRIGATION AMOUNT (L)</th>
<th>TOTAL IRRIGATION TIME (MIN.)</th>
<th>MEASURED TRANSPERSION (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>238</td>
<td>9:00 PM</td>
<td>1.46</td>
<td>7.20</td>
<td>1.265</td>
</tr>
<tr>
<td>239</td>
<td>6:30 PM</td>
<td>1.52</td>
<td>7.40</td>
<td>0.891</td>
</tr>
<tr>
<td>240</td>
<td>5:00 PM</td>
<td>1.62</td>
<td>8.00</td>
<td>0.481</td>
</tr>
<tr>
<td>241</td>
<td></td>
<td></td>
<td></td>
<td>0.855</td>
</tr>
<tr>
<td>242</td>
<td>12:15 PM</td>
<td>1.60</td>
<td>8.00</td>
<td>0.570</td>
</tr>
<tr>
<td>243</td>
<td>2:50 PM</td>
<td>1.60</td>
<td>8.00</td>
<td>0.993</td>
</tr>
<tr>
<td>244</td>
<td>4:45 PM</td>
<td>1.60</td>
<td>8.00</td>
<td>1.652</td>
</tr>
<tr>
<td>245</td>
<td>2:50 PM</td>
<td>1.60</td>
<td>8.00</td>
<td>0.958</td>
</tr>
<tr>
<td>246</td>
<td>2:40 PM</td>
<td>1.97</td>
<td>10.00</td>
<td>1.087</td>
</tr>
<tr>
<td>247</td>
<td>3:10 PM</td>
<td>1.94</td>
<td>9.80</td>
<td>1.453</td>
</tr>
<tr>
<td>248</td>
<td>5:15 PM</td>
<td>1.58</td>
<td>9.10</td>
<td>1.588</td>
</tr>
<tr>
<td>249</td>
<td>5:45 PM</td>
<td>1.80</td>
<td>9.20</td>
<td>1.530</td>
</tr>
<tr>
<td>250</td>
<td>6:30 PM</td>
<td>1.58</td>
<td>9.10</td>
<td>1.094</td>
</tr>
<tr>
<td>251</td>
<td></td>
<td></td>
<td></td>
<td>0.926</td>
</tr>
<tr>
<td>252</td>
<td>12:10 PM</td>
<td>1.50</td>
<td>8.70</td>
<td>0.724</td>
</tr>
<tr>
<td>253</td>
<td></td>
<td></td>
<td></td>
<td>0.577</td>
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<td>254</td>
<td></td>
<td></td>
<td></td>
<td>0.685</td>
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<td>255</td>
<td></td>
<td></td>
<td></td>
<td>0.878</td>
</tr>
<tr>
<td>256</td>
<td>2:40 PM</td>
<td>1.68</td>
<td>9.50</td>
<td>1.115</td>
</tr>
<tr>
<td>257</td>
<td>5:50 PM</td>
<td>1.68</td>
<td>9.50</td>
<td>1.383</td>
</tr>
<tr>
<td>258</td>
<td></td>
<td></td>
<td></td>
<td>1.284</td>
</tr>
<tr>
<td>259</td>
<td>12:30 PM</td>
<td>1.80</td>
<td>10.00</td>
<td>0.963</td>
</tr>
<tr>
<td>260</td>
<td>2:45 PM</td>
<td>1.68</td>
<td>9.50</td>
<td>1.359</td>
</tr>
<tr>
<td>261</td>
<td>8:30 PM</td>
<td>1.80</td>
<td>10.00</td>
<td>1.748</td>
</tr>
<tr>
<td>262</td>
<td></td>
<td></td>
<td></td>
<td>0.851</td>
</tr>
<tr>
<td>263</td>
<td></td>
<td></td>
<td></td>
<td>0.789</td>
</tr>
<tr>
<td>264</td>
<td>11:15 PM</td>
<td>1.80</td>
<td>10.00</td>
<td>1.125</td>
</tr>
<tr>
<td>265</td>
<td></td>
<td></td>
<td></td>
<td>0.784</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>31.810</strong></td>
<td><strong>169.00</strong></td>
<td><strong>29.608</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.16: Summary of irrigations during the experimental period along with measured ET.
Figure 6.26: Changes in medium tension during irrigation controlled by medium moisture tension measurements.
Figure 6.27: Comparison of PMT-based irrigation and measured ET rate of the plant.
Figure 6.28: Three-day history of tension and ambient temperature measurements starting with September 31, 1997.
In order to see the difference between PMT-based irrigation and ET estimation methods, Table 6.17 was prepared. Table 6.17 shows that both PMT-based irrigation and ET estimation methods work well to predict measured ET and the PMT-based irrigation method has a low estimation error according to others.

<table>
<thead>
<tr>
<th></th>
<th>Lysimeter</th>
<th>PMT-based irrigation</th>
<th>Stanghellini method</th>
<th>Fynn method</th>
<th>Penman method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total water consumed (g)</td>
<td>29608</td>
<td>31810</td>
<td>25784.331</td>
<td>26448.76</td>
<td>35178.12</td>
</tr>
<tr>
<td>Error based on Measured ET (%)</td>
<td>-</td>
<td>7.43</td>
<td>12.91</td>
<td>10.67</td>
<td>18.81</td>
</tr>
</tbody>
</table>

Table 6.17: Comparison of PMT-based irrigation with ET estimation methods.
6.5 Modeling of Potting Medium Tension vs. Moisture Content Relationship

Modeling of potting medium tension vs. moisture content was the key control function in the design of a feedback control system. Essentially, tension values were determined from moisture content and used as an alarm system for irrigation scheduling. Three different mathematical models were developed to represent this relationship. They are a fourth order polynomial, exponential and power functions. The fourth order polynomial model had an $R^2$ of 0.937 and is illustrated in Figure 6.29.

Since the units in simulation model were g and cm, potting medium-water release curve with gravimetric moisture content was used instead of potting medium-water release curve with volumetric moisture content. Figure 6.30 shows the potting medium-water release curve based on volumetric moisture content. The exponential and power functions are also presented in Figure 6.31.
Figure 6.29: Potting medium-water release curve based on gravimetric moisture content for feedback control system.
Figure 6.30: Potting medium-water release curve based on volumetric moisture content.
Figure 6.31: Comparison of different mathematical models of potting medium-water release curves for experimental data.
6.6 Development of a Simulation Model

Two computer programs in FORTRAN language were written to evaluate the feedback control system. The first program, "Irrigation scheduling," is listed in Appendix C. Irrigation scheduling determined the frequency of irrigation, total irrigation time, and amount of water applied to the plant. Irrigation scheduling was then integrated into another program, "real-tension," to write down the simulated and experimental tension values together in one file. The program real-tension is also listed in Appendix C. A flow chart of the irrigation scheduling program was listed in Appendix D. Major climate factors, system variables, and system parameters in the simulation model are shown in Table 6.18.

6.7 Calibration Process for the Simulation Model

The calibration of the simulation model was done by using the experimental data collected between 238 and 250 Julian days during which there was no precipitation. Figures 6.32-6.34 show the response of the simulation model before starting the calibration process. The simulation model overestimated total amount of irrigation almost 197.3% according to the experimental results. There were only four pump-on cycles in the simulation whereas there were 11 pump-on cycles in the experimental results. Due to this high difference between simulated and experimental results, a calibration process was applied to the simulation model.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE</td>
<td>Ambient temp.</td>
<td>°C</td>
</tr>
<tr>
<td>PREC</td>
<td>Rainfall</td>
<td>cm/h</td>
</tr>
<tr>
<td>P</td>
<td>Rainfall for pot surface</td>
<td>g/h</td>
</tr>
<tr>
<td>ATM</td>
<td>Atmospheric press.</td>
<td>Hg</td>
</tr>
<tr>
<td>RAD</td>
<td>Solar radiation</td>
<td>W/m²</td>
</tr>
<tr>
<td>RH</td>
<td>Relative humidity</td>
<td>%</td>
</tr>
</tbody>
</table>

Environment factors

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>TI</td>
<td>Time</td>
<td>Julian date</td>
</tr>
<tr>
<td>Y</td>
<td>Calculated tension</td>
<td>cm</td>
</tr>
<tr>
<td>ES</td>
<td>Sat. vapor pressure</td>
<td>kPa</td>
</tr>
<tr>
<td>VPD</td>
<td>Vapor pressure deficit</td>
<td>kPa</td>
</tr>
<tr>
<td>ET</td>
<td>Evapotranspiration</td>
<td>g/h</td>
</tr>
<tr>
<td>ERR</td>
<td>Error signal</td>
<td>cm</td>
</tr>
<tr>
<td>XI</td>
<td>Irrigation amount</td>
<td>g/h</td>
</tr>
<tr>
<td>X</td>
<td>Water content</td>
<td>g/g</td>
</tr>
</tbody>
</table>

System Variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>XKP</td>
<td>Pump constant</td>
<td>g/h</td>
</tr>
<tr>
<td>YREF</td>
<td>Reference tension</td>
<td>cm</td>
</tr>
<tr>
<td>AEVP, BEVP</td>
<td>Constants of ET</td>
<td>-</td>
</tr>
<tr>
<td>A0 ... A4</td>
<td>Cons. of release curve</td>
<td>-</td>
</tr>
<tr>
<td>DTIM</td>
<td>Time increment</td>
<td>h</td>
</tr>
<tr>
<td>AP</td>
<td>Area of pot</td>
<td>cm²</td>
</tr>
<tr>
<td>YMS</td>
<td>Mass of dry medium</td>
<td>g</td>
</tr>
<tr>
<td>YMWO</td>
<td>Initial water content</td>
<td>g</td>
</tr>
</tbody>
</table>

System Parameters

Table 6.18: Major climate factors, system variables and parameters in the simulation model.
Figure 6.32: Variations of medium moisture content and tension histories based on the simulation model (before calibration) using YMS=3654.18 g, $\psi_L=6$ kPa, $\psi_U=10$ kPa and VPD based ET model, Julian days 238-250, 1997 at Wooster, OH.
Figure 6.33: Simulated and experimental tension histories (before calibration) using \( YMS=3654.18 \) g, \( \psi_L=6 \) kPa, \( \psi_U=10 \) kPa and VPD based ET model, Julian days 238-250, 1997 at Wooster, OH.
Figure 6.34: Comparison of simulated and experimental irrigation schedule (before calibration) using YMS=3654.18 g, $\psi_L=6$ kPa, $\psi_U=10$ kPa and VPD based ET model, Julian days 238-250, 1997 at Wooster, OH.
In the calibration process, the following steps were carried out:

1- **Changing the initial water content in the potting medium:**

Before calibration, it was assumed that initial water content was 60% of available water capacity of the medium. Then, the initial water capacity was increased to 80%. The effect of these change on model response was observed at the beginning of the simulation process for only a few hours. Thus, the effect of the initial water content (60-80% available water capacity) to the model response was insignificant.

2- **Changing the initial mass of medium in the pot:**

It was assumed that the plant uses only some portion of the medium in the pot as water resources (Figure 6.35). Initial mass of the medium on a dry basis was 3654.18 g. The simulation model response to medium mass change was very sensitive. At the end of the calibration process, only 18.06% of the total medium mass was used as an effective medium mass.

3- **Changing the mathematical model for the potting medium-water release curve:**

Three different mathematical models were developed for medium tension versus moisture content as discussed in section 6.5. The simulation model was modified and run for each mathematical model for potting medium-water release curve.
Figure 6.35: Representation of effective medium mass in the pot.

Simulation results showed that when the power and exponential functions were used, they overestimated total amount of irrigation by 39% and 23.62% respectively. Also, the number of pump-on cycles in both cases were two instead of 11 obtained from experimental data. At the end of this calibration process, it was concluded that a fourth order polynomial equation estimated total irrigation amount and irrigation frequency more precisely than the power and exponential functions.
4- Changing reference tension level

Although medium tension was set for 6-10 kPa in the experimental procedure, the experimental results showed that medium tension variations were between 2-9 kPa. Therefore, the reference tension level was changed from 8 kPa to 5.5 kpa.

Figures 6.36-6.38 show the result of this calibration process. After the calibration process was completed, the simulation model predicted total irrigation amount as 19039 g whereas experimental irrigation for this time period was 18920 g. This was a 0.63% overestimation according to the experimental result. In terms of total irrigation frequency, the calibrated model matched the experimental result very closely.
Figure 6.36: Variations of medium moisture content and tension histories based on the simulation model (after calibration) using YMS=660 g, $\psi_L=2$ kPa, $\psi_D=9$ kPa and VPD based ET model, Julian days 238-250, 1997 at Wooster, OH.
Figure 6.37: Simulated and experimental tension histories (after calibration) using YMS=660 g, $\psi_L=2$ kPa, $\psi_U=9$ kPa and VPD based ET model, Julian days 238-250, 1997 at Wooster, OH.
Figure 6.38: Comparison of simulated and experimental irrigation schedules (after calibration) using YMS=660 g, \( \psi_L=2 \) kPa, \( \psi_U=9 \) kPa and VPD based ET model, Julian days 238-250, 1997 at Wooster, OH.
6.8 Validation of the Simulation Model with Experimental data

Validation of the simulation model was done by using the experimental data collected between 250 and 265 Julian days. There was no rainfall during the experimental data collection period for calibration of the simulation model. On the other hand, there was rainfall (Julian days of 252, 253, 255, 260, 262, and 263) during the experimental data collection for validation of the simulation model. Figures 6.39-6.41 show the result of the validation process. At the end of the validation process, it was concluded that the simulation model underestimated total irrigation amount by 17.5% according to the experimental results. In terms of irrigation frequency, there were 8 pump-on positions during the experimental period whereas there were 11 pump-on positions at the end of simulation.

At the end of the validation process, it was found that experimental and simulated tension trends followed each other, but did not fully match each other. Possible reasons of this were:

1- In the experimental procedure, only one tensiometer was used to measure the medium tension and irrigation was scheduled due to this sensed tension. However, it should be noted that at least two tensiometers at two different depths should be used to get a more representative and accurate results based on container size.
2- Location of the tensiometer inside the pot was very critical. A tensiometer or tensiometers should be placed inside the pot considering the root distribution of the plant. However, root analysis of the plant in the experimental procedure was not done before placing the tensiometer in the pot.

3- In the simulation model, lag time was set at zero based on Fynn (1995). However, the effect of lag time could have been significant and could have been analyzed with an experimental procedure.

4- Accuracy of the tensiometer used in the experiment was very critical since irrigation was scheduled based on potting medium matric potential. Calibration of the tensiometers was done before the experimental procedure was started. However, since the experimental procedure took a two months, tensiometers should have been calibrated one more time during the experimental procedure to obtain more accurate readings. Zazueta et al. (1995) stated that the tensiometer had a significant response time since they measured the water tension when the moisture in the soil and in the porous cup reached equilibrium. This response time mainly depended on the conductance of the porous cup, amount of entrapped air, and hydraulic characteristics of the soil. Thus, the response time of the tensiometer used in this experiment could increase the difference between experimental and simulated tension values.
5- According to the block diagram of the feedback control system in Figure (4.1), plant water consumption was predicted with an ET transfer function. Thus, the accuracy of the ET transfer function directly affects the simulation results.

6- In the simulation model, growth stage of the plant and root development were not considered. Growth stage of the plant particularly affects plant water consumption as developing plant consumes more water as the LAI increases. Therefore, a LAI growth model should be incorporated with the simulation model.

7- A medium water-release curve gives very important information about the tension level of the medium at a certain depth. In order to show the spatial variability, two replicates were used for medium analysis in the experimental procedure. However, medium analysis for determining medium-water release curve should be done by using at least three replicates in order to reduce the effect of the spatial variability.
Figure 6.39: Variations of medium moisture content and tension histories based on the simulation model (after validation) using $YMS=660$ g, $\psi_L=2$ kPa, $\psi_U=9$ kPa and VPD based ET model, Julian days 250-265, 1997 at Wooster, OH.
Figure 6.40: Simulated and experimental tension histories (after validation) using YMS=660 g, $\psi_L=2$ kPa, $\psi_U=9$ kPa and VPD based ET model, Julian days 250-265, 1997 at Wooster, OH.
Figure 6.41: Comparison of simulated and experimental irrigation schedule (after validation) using YMS=660 g, ψ_L=2 kPa, ψ_U=9 kPa and VPD based ET model, Julian days 250-265, 1997 at Wooster, OH.
6.9 Sensitivity Analysis of Evapotranspiration Transfer Function in the Control System

In order to test the consistency of the simulation model, a radiation based stochastic ET model and the Fynn ET model were compared to a VPD based stochastic ET model. When replacing different ET transfer functions in simulation model, calibration of the model was not altered.

The results of this test showed that the simulation model worked well for different ET transfer functions. Besides, it was observed that the simulation model was sensitive to the ET transfer function. When the Fynn ET model and radiation based ET model were applied, the simulation results showed that they underestimated total irrigation 24.2% and 25.05% according to the experimental data. Both Fynn and the radiation based stochastic ET model gave the same number of pump-on positions which were 10. Figures 6.42-6.44 and 6.45-6.47 show the result of this test for the Fynn and radiation based ET model respectively.
Figure 6.42: Variations of medium moisture content and tension histories based on the simulation model (after validation) using YMS=660 g, $\psi_L=2$ kPa, $\psi_U=9$ kPa and Fynn ET model, Julian days 250-265, 1997 at Wooster, OH.
Figure 6.43: Simulated and experimental tension histories (after validation) using YMS=660 g, $\psi_L=2$ kPa, $\psi_U=9$ kPa and Fynn ET model, Julian days 250-265, 1997 at Wooster, OH.
Figure 6.44: Comparison of simulated and experimental irrigation schedule (after validation) using $\text{YMS}=660$ g, $\psi_l=2$ kPa, $\psi_u=9$ kPa and Fynn ET model, Julian days 250-265, 1997 at Wooster, OH.
Figure 6.45: Variations of medium moisture content and tension histories based on the simulation model (after validation) using $\text{YMS}=660 \text{ g}$, $\psi_l=2 \text{ kPa}$, $\psi_u=9 \text{ kPa}$ and solar radiation based stochastic ET model, Julian days 250-265, 1997 at Wooster, OH.
Figure 6.46: Simulated and experimental tension histories (after validation) using YMS=660 g, $\psi_L=2$ kPa, $\psi_U=9$ kPa and solar radiation based stochastic ET model, Julian days 250-265, 1997 at Wooster, OH.
Figure 6.47: Comparison of simulated and experimental irrigation schedule (after validation) using YMS=660 g, $\psi_L=2$ kPa, $\psi_U=9$ kPa and solar radiation based stochastic ET model, Julian days 250-265, 1997 at Wooster, OH.
6.10 Possible Stability Factors that can Affect the System

The pumping rate and effective pot size were possibly two main factors that could affect the stability of the system. The ratio between them may also be a factor. Also, characteristics of the medium (especially, infiltration rate and movement of the water under unsaturated conditions) can be factors that affect system stability. If these factors can not be chosen or represented correctly, an instability problem (overshoot-undershoot) may occur.

If the pumping rate is low according to the ET rate of the plant, instability is very likely. In general, pumping rate should be larger than maximum ET rate of the plant to prevent this instability problem. When the effective pot size is very small, the system can be very sensitive to small changes in the system. For example, if a plant with a high ET rate is placed in a small sized pot, instability problems should be expected.

6.11 Modification of ET Parameters

In section 6.1, the correlation between stochastic ET models vs. measured ET and deterministic ET models vs. measured ET included all night transpiration rates. Figure 6.12-6.16 shows that there were approximately 32% of data scatter points between zero and 50 (g/tree h) values affecting the correlation coefficient statistically. Therefore, a revised correlation was prepared ignoring night transpiration values and daytime values less than 50 g/tree h (Figure 6.48-6.52).
From this, it was observed that the $R^2$ value of the VPD based stochastic ET model was very close to the $R^2$ value of the deterministic ET models. The radiation based stochastic ET model was still the best one in terms of the absolute $R^2$ value. The $R^2$ value of all ET models reduced from 0.875, 0.684, 0.782, 0.814, and 0.878 to 0.758, 0.647, 0.644, 0.644, 0.582 for radiation, VPD based stochastic models, Fynn, Stanghellini and Penman ET models respectively. The $R^2$ value of Penman method dropped relatively more than the other ET models indicating that correlation between measured ET and Penman prediction for the early morning and late night was better than the correlation of noon time.

One interesting observation interpreted from the data scatter points of the VPD based stochastic ET model (Figure 6.49) was that there was almost a constant relationship between VPD and measured ET for small (until 500 Pa) and high VPD values (>2250 Pa). On the other hand, there was a positive trend between VPD and measured ET for the VPD values of 500-2250 Pa. This observation suggests that solar radiation is the main driving force of the transpiration when VPD is relatively high.
Figure 6.48: Correlation between solar radiation and measured ET rate of Red Maple for two months of hourly data (excluding all night time data and/or data less than 50 g/tree h).
Figure 6.49: Correlation between vapor pressure deficit and measured ET rate of Red Maple for two months of hourly data (excluding all night time data and/or data less than 50 g/tree h).
Figure 6.50: Correlation between calculated and measured hourly ET rates of Red Maple based on Fynn method for two months (excluding all night time data and/or data less than 50 g/tree h).
Figure 6.51: Correlation between calculated and measured hourly ET rates of Red Maple based on Stanghellini method for two months (excluding all night time data and/or data less than 50 g/tree h).
Figure 6.52: Correlation between calculated and measured hourly ET rates of Red Maple based on Penman method for two months (excluding all nighttime data and/or data less than 50 g/tree h).
CHAPTER 7

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary and Conclusions

A comprehensive experimental and theoretical study was initiated to develop an accurate water delivery system based on demand irrigation. Two different experimental studies were conducted. The purpose of the first experimental study was to determine the evapotranspiration rate of the red maple. In the second experiment, tension-based irrigation scheduling was used to validate the results of a closed-loop, feedback control system.

In the first experiment, a lysimeter was used to measure the evapotranspiration losses of the plant. To compare three different equations (Penman, Stanghellini, and Fynn) with a lysimeter, climatological data for the period of Aug. 1997 to Sept. 1997 were collected. In the second experiment, a tension-based irrigation schedule was achieved using a tensiometer placed in the container medium. Irrigation was scheduled for 6 and 10 kPa deadband width.

In the theoretical part of the study, a closed-loop, feedback control system was developed using medium tension as a controller element. There were seven control elements in the block diagram of the system including: ET transfer function, integration

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of medium water, calculation of the medium water content, medium water release curve, on-off controller, pumping rate, and lag time. A multi-parameter, first and second order regression analysis was performed to investigate the individual and combination effect of input climate variables to measured evapotranspiration.

The most important conclusions from analysis of experimental data and computer simulations can be summarized as follows:

1- Results of the linear regression analysis showed that there was high correlation between solar radiation, VPD and measured ET. A solar radiation or a VPD based stochastic ET model could be successfully used to predict ET rate of the plant. Comparing $R^2$ values of these two stochastic ET models, it could be said that the solar radiation based stochastic ET model predicted ET better than the VPD based stochastic ET model.

2- The Stanghellini and Fynn ET models were similar to each other in terms of $R^2$ values and error in the prediction of ET. Even though Stanghellini and Fynn ET models were developed under greenhouse conditions, they predicted ET under field conditions very well. The Penman model predicted ET well in terms of an $R^2$ of 0.878 when all nighttime data was used. However, its $R^2$ value dropped to 0.582 with only daytime data. The Penman model overestimated ET especially during the high transpiration periods. On the other hand, Fynn and Stanghellini models underestimated ET during high transpiration periods.
3- The visual observation of the data showed that transpiration tended to be more proportional to VPD for cloudy days whereas it tended to be more proportional to solar radiation for sunny days. The driving force for transpiration in late afternoon and early morning was VPD.

4- The average daily evapotranspiration rate of the plant during the two months experimental period was approximately 1000 g per tree per day.

5- Using a first order linear regression model was more practical than using a second order model since the more complex second order model did not improve the $R^2$ of the ET model significantly.

6- The first order linear regression analysis showed that at the 90% confidence level, the most important input climate factors affecting ET were media-water tension, average leaf temperature, and solar radiation.

7- The second order linear regression analysis showed that interactions between windspeed and ambient temperature, windspeed and medium tension, were the most significant factors affecting ET at the 90% confidence level.

8- Analysis of variance (ANOVA) and visual observation from data showed that the medium tension was not highly correlated with ET (Figure 6.20 and 6.21).
9- The tension-based irrigation system showed that it could be used to schedule irrigation under controlled medium matric potentials since there was a measured 2.2 kg per month biomass production (wet basis) and no drainage during the experimental period. A tension-based irrigation scheduling more closely approximated the response of the medium-plant-atmosphere system for water demand than other approaches. High-frequency irrigation systems can be controlled accurately with the help of a medium matric potential sensor placed in the root zone of the plant.

10- A closed-loop, feedback controller system using medium matric potential as the control variable was developed. Several operational criteria were required for real time accurate monitoring of medium tension and scheduling irrigation system. Validation results of the simulation model indicated that the feedback control system works based on medium tension could be successfully used to schedule irrigation.

11- The calibration process of the simulation model indicated that the plant does not use the total water content of the medium inside container. It only uses a portion of the medium in the container called the effective medium mass.
7.2 Recommendations for Future Research

Future research which addresses the following issues are recommended:

1- A similar experiment should be run with a broader range of medium tensions in order to investigate the effect of the medium tension on actual evapotranspiration.

2- The performance and usefulness of a tension-based irrigation system on consumptive use of water by plants under controlled medium matric potentials by using different plants, medium type and container volume should be further investigated.

3- In the experimental procedure for the feedback control system, the following issues should be considered:

3.1 Before starting ET studies, the medium for potting medium-water release curve, and other hydraulic characteristics of the medium such as infiltration capacity, unsaturated hydraulic conductivity should be analyzed.

3.2 Before the tensiometer is placed inside the container, a root distribution analysis of the plant should be done; then, the tensiometer or tensiometers should be located in the effective root area.
3.3 During the experimental procedure, the water pressure in the pipe line should be kept constant to eliminate effect of pressure changes on system response.

3.4 Tensiometers should be calibrated at the beginning, middle and end of the experimental period to minimize errors due to drift.

3.5 The sampling interval of the medium tension data should be set at the same interval with a pause time setting in the Q-COM software used in the tension-based irrigation scheduling.

4- The simulation model should be run considering lag time and sensor response time in order to reduce error between measured and predicted medium tension. The effective lag time can be determined by considering the unsaturated hydraulic conductivity and infiltration rate of the medium. The sensor response time can be determined by placing a tensiometer in an oven dried and/or in a saturated medium and observing the water changes in the tube of tensiometer. The possible effect of diameter of porous cup of the tensiometer should also be investigated.

5- The control program should be modified with a growth model in order to more effectively account the effect of LAI on evapotranspiration.
6- Proportional (P) control, proportional plus integral (PI) control, and proportional plus integral plus derivative (PID) control actions should be tested instead of on-off controller in order to increase system stability.

7- Alternative controller approaches for irrigation scheduling such as lysimeter, canopy-air temperature difference, or crop water stress index (CWSI) should be investigated.

8- The simulation model should be run using modified ET models developed in section 6.11.
LIST OF REFERENCES


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APPENDIX A

Procedure for water release curve and experimental results
PROCEDURE FOR WATER RELEASE CURVE

A- Procedure for water release curve for 0.5 bar and under:

1- Prepare the tempe-cells by placing exco porous plastic in the bottom of the tempe-cell. Then, replace the tempe-cell sleeve into the tempe-cell.

2- Weigh the empty tempe-cell with the lid and wing nuts and record this number as the tare weight.

3- Fill each tempe-cell with its corresponding medium sample. Place the tempe-cell inside a container that has a cylinder stand inside it.

4- After all the samples are prepared and inside a container saturate the medium with degassed water by slowly filling the container until water level is just to the top of the tempe-cell bottom.

5- Allow sample sit overnight. Place the tempe-cell lids onto their corresponding tempe-cell so that the lid is snapped all the way down onto the sleeve forming a seal. Screw the corresponding wing nuts onto the tempe-cell tightly but not so tightly as to damage the wing nut or tempe-cell.
6- Put the tempe-cells onto a tempe-cell stand and attach tubing. Adjust manometer to 10 cm of water tensions.

7- Let sample equilibrate for about 3-5 days. It was assumed that if the weight change of the sample is equal or less than 0.05 g/8hr, it means that the sample is at equilibrium.

8- Record weight of the sample under 10 cm and also date.

9- Repeat the steps #11-14 at 20 cm, 40 cm, 60 cm and, 80 cm on manometer set-up; and at 100 cm, 150 cm, 200 cm, and 300 cm on the pressure manifold set-up.

10- After the samples have completed steps # 8 through 12, remove the tempe-cell lid keeping track of wing nuts.

11- Dry the sample in the oven for about 48 hours at about 100 °C.

12- Weigh oven dried samples with their corresponding lid and wing nuts. Record weigh and date (McCoy, 1998; Hillel, 1980; Jury et al., 1991).
B- Procedure for water release curve for 2 bar

1- Place two sheets of filter paper on the bottom of a copper sleeve using 2 layers of cheese cloth and a rubber band to hold them in place.

2- Weigh the empty sleeve with filter paper, cheese cloth, and rubber band (tare weight).

3- Fill the sleeve with soil and then tap the sleeve five times on the table top. Soak the samples in degassed water overnight.

4- Put the samples in the pressure plate extractors. Place a moist paper towel over the top of the samples.

5- Moisten the rubber ring. Then screw down the lid of the extractor firmly but not so tightly that the bolts are destroyed.

6- Adjust the pressure to two bars. The pressure should be adjusted periodically.

7- After about 7 days, dry the samples 2 days at about 105 °C and weigh each sleeve.

8- After the samples have finished at two bar pressure, the samples will be done in the psychrometer on the same day (McCoy, 1998).
C- Psychrometer Analysis for Permanent Wilting Point

I- To prepare standard solutions:

1- Moisten plastic in humidity box, shut doors. Plug in nanovoltmeter.

2- Turn on nanovoltmeter to let it warm up.

3- While machine is equilibrating to zero, prepare calibration samples.
   - Inspect cups to make sure they are clean and dry.
   - Weigh cups 1-9 on the analytical balance. Seven cups were used in this experiment since two samples were used.
   - Put filter paper strips in cups to line the wall of cup, making certain paper strip is pushed to bottom.

4- Zero the nanovoltmeter. The range should be set on 1, the zero suppress on 1.
   Adjust the fine tuner to attain zero. Make sure the reading remains on zero. Zeroing should take less than 10 minutes.

5- Add calibration solutions, in order, to cups from 100, 500, 900, 1100, 1500 mOsm/Kg H₂O. Put in only enough solution to wet the strip and cover the bottom of the cup.
6- Add distilled water to the well, so meniscus is just even with the top of the well.

7- Put cups in changer apparatus, water well is in 0 position and 100 mOsm/Kg H₂O is in # 1 position, continue putting cups in sampler changer in order ending with 1500 mOsm/Kg H₂O position # 5.

8- Put plug in and rotate so that an empty chamber is over under the “read” position. Put lid on. Close humidity box doors. Keep yellow lever down except while reading.

9- Let the cups and changer equilibrate. This should take 30 min.

10- When equilibration is reached. Take lid off changer and rotate so # 0 is at the arrow. Very carefully raise yellow lever till just clicks in place. Then lower immediately but carefully to the lowest point. Rotate changer to #1 at arrow. Always have the yellow lever down before rotating the chamber. Carefully raise yellow lever until it clicks and locks into place. Place styrofoam lid on, close door of humidity box and allow chamber to equilibrate. Equilibration is indicated when the needle of the nanovoltmeter stops. Normally, it takes about 10 min.

11- Record the reading of microvolt and temperature.

12- Take off styrofoam lid, carefully lower yellow lever. Rotate to position # 0, raise yellow lever to wet the temocouple, then lower yellow lever. Rotate the chamber to
position # 2, then raise yellow lever carefully till it clicks into place. Put on the lid, make sure the door is closed and wait for equilibration.

13- Write down reading of microvolt and temperature as before.

14- Repeat steps above for standard solutions 900, 1100 and 1500 mOsm/Kg H₂O.

15- Remove all cups except water well and 500 mOsm/Kg H₂O. The 500 mOsm/Kg H₂O solution is used as a check throughout the procedure.
II- To prepare soil samples:

1- Get soil from 2 bar pressure chamber. Keep lid on to reduce evaporation by placing sample between two large petri dishes. Keeping the soil samples in humidity box also helps reduce evaporation.

2- Carefully, place soil in cups with small spatula. Fill cups only ½ full, tapping on table top occasionally to settle the soil. You should do all this step inside the humidity box.

3- Wipe off outside surfaces of cups thoroughly and place in psychrometer sample changer.

4- Once the sampler changer is full rotate sample chamber so that the driest sample is under the “read” arrow. This should be either the “check” solution or an empty chamber. Place styrofoam lid on and close doors of humidity box. Wait for equilibration of system. The driest sample should always be kept under the read arrow during equilibration.

5- After equilibration is reached, wet thermocouple then rotate and lock the chamber with the check solution (500 mOsm/Kg H₂O standard) carefully into place with the yellow lever. Equilibrium takes about 5 min. Record temperature and microvolt. This reading should be close to the values obtained from the standard run. If not,
check the system. Always make sure this “standard” solution is within range with each round of measurements.

6- If the reading of calibration solution looks reasonable, wet thermocouple then rotate to the first soil sample. Record microvolt and temperature readings.

7- When all the soil samples have been measured, take out soil cups one at a time and weigh on the analytical balance. During the weighing process keep the cups in a petri dish with a lid to slow down evaporation. After all the samples have been weighed, dry the samples on wax paper for about 2-10 minutes depending on the soil type. Since our sample is a soilness medium sample, drying took 5-15 min.

8- Put the samples back into the psychrometer and allow to equilibrate for 30 min.

9- Repeat procedure measuring the check solution and soil samples obtaining the temperature and microvolt for each. Then, weigh soil samples, dry and run in the psychrometer again. Continue with this procedure till voltmeter shows big numbers like 40 μm or up.

10- After psychrometer has been finished oven dry the samples for about 48 hours at about 105 °C. Do necessary calculations to get water release curve of the sample (McCoy, 1988; Stephen and Campbell, 1986).
<table>
<thead>
<tr>
<th>Potting medium tension (cm)</th>
<th>Volumetric moisture content (cm³/cm³)</th>
<th>Gravimetric moisture content (g/g)</th>
<th>Potting medium tension (cm)</th>
<th>Volumetric moisture content (cm³/cm³)</th>
<th>Gravimetric moisture content (g/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.843</td>
<td>4.4554</td>
<td>0</td>
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<td>4.3286</td>
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<tr>
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<td>2000</td>
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Table A.1: Gravimetric and volumetric moisture content calculation results based on potting medium tension values.
### POTTING MEDIUM EXPERIMENT RESULTS UP TO 300 CM TENSION

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Tare weight (g)</th>
<th>Weight @ 0 cm (g)</th>
<th>Weight @ 10 cm (g)</th>
<th>Weight @ 20 cm (g)</th>
<th>Weight @ 40 cm (g)</th>
<th>Weight @ 60 cm (g)</th>
<th>Weight @ 80 cm (g)</th>
<th>Weight @ 100 cm (g)</th>
<th>Weight @ 150 cm (g)</th>
<th>Weight @ 200 cm (g)</th>
<th>Weight @ 300 cm (g)</th>
<th>Dry weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>356.20</td>
<td>427.12</td>
<td>408.06</td>
<td>403.64</td>
<td>400.07</td>
<td>398.04</td>
<td>397.11</td>
<td>395.77</td>
<td>393.48</td>
<td>392.26</td>
<td>390.02</td>
<td>369.2</td>
</tr>
<tr>
<td>B</td>
<td>353.27</td>
<td>424.30</td>
<td>405.92</td>
<td>400.95</td>
<td>397.84</td>
<td>395.73</td>
<td>394.70</td>
<td>393.37</td>
<td>391.06</td>
<td>389.79</td>
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### POTTING MEDIUM EXPERIMENT RESULTS UP TO 300 CM TENSION

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<tr>
<th>Sample ID</th>
<th>Sleeve radius (cm)</th>
<th>Sleeve height (cm)</th>
<th>Tare weight (g)</th>
<th>Weight @ 2 bar (g)</th>
<th>Dry weight (g)</th>
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</thead>
<tbody>
<tr>
<td>A</td>
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<td>2.95</td>
<td>73.45</td>
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<td>71.54</td>
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Table A.2: Experiment results of potting medium analysis up to 2 bars.
<table>
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<tr>
<th>NACI standard solutions</th>
<th>Cup ID</th>
<th>V (μm)</th>
<th>T (°C)</th>
<th>Tare weight (g)</th>
<th>Cup ID</th>
<th>V (μm)</th>
<th>T (°C)</th>
<th>Tare weight (g)</th>
<th>Cup ID</th>
<th>V (μm)</th>
<th>T (°C)</th>
<th>Tare weight (g)</th>
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<table>
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<tr>
<th>Cup ID</th>
<th>V (μm)</th>
<th>T (°C)</th>
<th>Tare weight (g)</th>
<th>Cup ID</th>
<th>V (μm)</th>
<th>T (°C)</th>
<th>Tare weight (g)</th>
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<th>V (μm)</th>
<th>T (°C)</th>
<th>Tare weight (g)</th>
<th>Dry Weight (g)</th>
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Table A.3: Experiment results of psychrometer for the determination of permanent wilting point.
APPENDIX B

Procedure for determination of container and air capacity
DETERMINATION OF CONTAINER AND AIR CAPACITY

Determination of the container capacity and air capacity gives important information about physical characteristics of the medium used in the container. In the irrigation scheduling of the nursery plants, container capacity plays an important role in the determination of irrigation amount that has to be given to the plant without giving any harmful effect to the environment. According to Rose (1997) and White and Mastalerz (1966), a procedure for determination of container and air capacity can be summarized as follows:

A- Preparation

Before starting this test, a hole from the bottom of the container has to be opened for drainage purpose and container should have nonporous characteristics. It is better to do this test as three replications.

1- Fill the containers to the rim. Do not pack excessively, but do not loosely fill either.

2- Use a fine mesh plastic screen fastened by a rubber band across the top and bottom of the container to prevent loss of medium during the test.
B- Procedure

1- Place the containers into a larger container such as a dishpan for subirrigation of the containers. It is better to use separate dishpan for each container that is tested. Replace the container in dishpan on a heavy object like a brick.

2- Add water to the dishpan to the level of the rim of the container. Be careful not to let water enter from above. The air may get trapped in the pore space. Allow the water level to remain at rim level for one hour for saturation of the medium.

3- After water has appeared at the surface of the medium, quickly remove the container and weight it. This is the saturated weight of the container (W1).

4- Allow the container of medium to drain freely at least one night in an area where there is no sun or high temperature to avoid moisture loss due to evaporation process.

5- After draining overnight, reweigh the container. And, mark the level of the medium in the container for process # 6. This is the weight of the container medium after the draining (W2).

6- In order to determine the volume of the container, the hole under the container should be plugged with tape. Then, fill the container with the water to the level of
the medium in the container and weight it. Call it W3.

7- Weigh the empty container, W4. Then, calculate the air capacity as below:

\[
Air\ -\ capacity(\%) = \left[\frac{W\ 1-W\ 2}{W\ 3-W\ 4}\right]\times 100
\]

8- Dry the medium in an oven @ 105 °C. After medium is waited one day in the oven, weight the dry medium (W5).

9- Calculate the estimated available water as below:

\[AW = W\ 2 - W\ 5\]

10- Calculate the container capacity, as below assuming the density of the water is 1 g/cm³.

\[
Container\ -\ capacity(\%) = \frac{W\ 2-W\ 5}{W\ 3-W\ 4}\times 100
\]
APPENDIX C

FORTRAN Source code of the simulation model
MAIN CONTROL PROGRAM

"irrigation scheduling"

C THIS PROGRAM DETERMINES IRRIGATION DEFICENCY BASED ON A VPD BASED STOCHASTIC ET
C MODEL

DIMENSION TI(1000), TE(1000), RH(1000), PE(1000)
C TI = TIME(JULIAN DATE); TE = AMBIENT TEMPERATURE(C); RH = RELATIVE HUMIDITY(%) 
C PE = PRECIPITATION (CM/H)

OPEN(9,FILE='C:\F32\HALIL\CLIMATES.TXT')
OPEN(10,FILE='C:\F32\HALIL\CONTROL.OUT',STATUS='NEW')

N=1
2 READ(9,*) TI(N), TE(N), RH(N), PE(N)
6 N=N+1
 IF(N.LT.675) GO TO 2
 TIMAX=TI(N-1)

C
C INPUT TO SYSTEM:
C
C YMWO = INITIAL WATER CONTENT(G); YMS = MASS OF SOIL AS A DRY BASIS(G); AP = AREA OF
C POT(CM²)
C XKP = PUMP CONSTANT, DETERMINED FROM EXPERIMENTAL DATA (G/HR);
C YREF = REFERENCE TENSION (CM)
C AEVP = CONSTANT FOR ET CALCULATION; BEVP = CONSTANT FOR ET CALCULATION
C A0,A1,A2,A3,A4 = CONSTANTS FOR WATER RELEASE CURVE; DTIM = TIME INCREMENT(H)
C
C PARAMETERS
C
C AP = 961.625
XKP = 12166
YREF = 55
AEVP = 0.0898
BEVP = 0.17
A0 = 30123
A1 = -38297
A2 = 17846
A3 = -3625
A4 = 271.3
DTIM = 0.0001

C

C INITIAL CONDITIONS

C

NPT = 100
NCOUNT = 1
GP = 0.0
YMWO = 1160
YMS = 660
TIM = TI(1)
N = 1
YMW = YMWO

C

C DYNAMIC

C

5 IF(TIM.LE.TI(N+1)) GO TO 10

   N = N+1
   GO TO 5

10 M = N+1

NPRINT = NPT
CALL EQSOLV(RHX,RH(N),RH(M),TI(N),TI(M),TIM)
CALL EQSOLV(TEMP,TE(N),TE(M),TI(N),TI(M),TIM)
CALL EQSOLV(PREC,PE(N),PE(M),TI(N),TI(M),TIM)
ES = 0.6108*EXP((17.27*TEMP)/(TEMP+273.3))
VPD = (ES*(100-RHX)/100)*1000
ET = AEVP*VPD-BEVP
IF(ET.LT.0) ET = 0

C

C CALCULATE SOIL MOISTURE AND TENSION
C

X = (YMW/YMS)
Y = A0+A1*X+A2*X**2+A3*X**3+A4*X**4
IF(Y.LE.0) Y = 0
ERR = Y-YREF
IF(ERR.GE.35) GP = 1.0
IF(ERR.LT.-35) GP = 0.0
IF(GP.GE.1) NPRINT = 1
XI = GP*XKP
P = PREC*AP/1.0

C

C DENSITY OF WATER WAS ASSUMED 1g/cm^3
C

IF(NCOUNT.LT.NPRINT) GO TO 63
WRITE(10,60) TIM,X,Y,PREC,TEMP,RHX,VPD,ET,P,XI
NCOUNT = 0
60 FORMAT(1X,3(F8.4,1X),3(F6.2,1X),E8.3,1X,2(F6.2,1X),F7.0)
63 YDMW = P+XI-ET
NCOUNT = NCOUNT+1
TIM = TIM+DTIM
CALL YINTEG(YMW,YDMW,DTIM)
IF(N.GE.675) GO TO 65
IF(TIM.LE.TIMAX) GO TO 5
STOP
END

C

SUBROUTINE EQSOLV(Y,Y1,Y2,X1,X2,X)
Y = Y1+(X-X1)*(Y2-Y1)/(X2-X1)
RETURN
END

C

SUBROUTINE YINTEG(Y,DY,DX)
Y = Y+DY*DX
RETURN
END
OUTPUT DATA FORMAT

"Real tension"

C THIS PROGRAM WRITES DOWN EXPERIMENTAL AND SIMULATION TENSION DATA INTO A
C NEW FILE
DIMENSION TI(1000),TEN(1000)
C TI = TIME(JULIAN DATE), TEN = TENSION
OPEN(9,FILE='C:\F32\HALI\REALDATA.TXT',STATUS='OLD')
OPEN(10,FILE='C:\F32\HALI\REALDATA.OUT',STATUS='NEW')
OPEN(11,FILE='C:\F32\HALI\CONTROL1.OUT',STATUS='OLD')
M = 1
TIM = 0
READ(9,*,END=888) TI(M),TEN(M)
WRITE(6,*) TI(M),TEN(M)
5 N = M
M = N+1
READ(9,*,END=888) TI(M),TEN(M)
WRITE(6,*) TI(M), TEN(M)
GO TO 6
8 READ(11,65,END=888) TIM,XX,TENCAL
WRITE(6,*) TIM, XX, TENCAL
6 IF(TIM.LE.TI(M).AND. TIM.GE.TI(N)) THEN
   GO TO 10
END IF
IF (TIM.LT.TI(N)) GO TO 8
GO TO 5
888 CLOSE(9)
CLOSE(11)
10 CALL Eqsolv(TENXP,TEN(N),TEN(M),TI(N),TI(M),TIM)
WRITE(10,60) TIM,TENXP,TENCAL
WRITE(6,60) TIM, TEnable, TEncal

60  FORMAT(2X,F8.4,2X,F8.4,2X,F12.4)

65  FORMAT(1X,F8.4,2X, F6.4,1X,F8.4)

    GO TO 8
    IF(N.GE.5) GO TO 70
    CLOSE(10)

70  STOP

    END

SUBROUTINE Eqsolv(Y,Y1,Y2,X1,X2,X)
    Y = Y1+(X-X1)*(Y2-Y1)/(X2-X1)

RETURN

    END
APPENDIX D

Control routine flowchart
Figure D.1: Control routine flowchart. (continued)
Figure D.1 (continued)

Y

Is
TIM ≤ TI(N+1)?

N

N=N+1

M=N+1

NPRINT=NPT

Call
Linear Interpolation
Subroutine for Relative
Humidity

Call
Linear Interpolation
Subroutine for
Ambient
Temperature

Call
Linear Interpolation
Subroutine for
Precipitation

C

(continued)
Figure D.1 (continued)

- Calculate Saturated Vapor Pressure
- Calculate Vapor Pressure Deficit
- Calculate Stochastic ET model based on VPD

- Is ET < 0 ?
  - Y: ET=0
  - N: Calculate Gravimetric Moisture Content
    - Calculate tension, Y
      - Is Y ≤ 0 ?
        - Y: Y=0
        - N: Calculate ERR=Y-YREF
          - E

(continued)
Figure D.1 (continued)
Figure D.1 (continued)

H

Y

Is NCOUNT < NPRINT ?

N

Write (TIM,X,Y,PREC,TEMP,RHX,VPD,ET,P,XI)

NCOUNT=0

Calculate Net Irrigation, YDMW

NCOUNT=NCOUNT + 1

TIM=TIM+DTIM

Call Subroutine for Integration of Moisture Content

Y

Was all input data read?

N

Is TIM ≤ TIMAX ?

Y

D

N

Stop Program

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