AN ABSTRACT OF THE THESIS OF

David J. Gochis for the degree of Master of Science in Bioresource Engineering presented on January 23, 1998. Title: Estimated Plant Water Use and Crop Coefficients for Drip-Irrigated Hybrid Poplars.

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Richard H. Cuenca

Estimations of plant water use can provide great assistance to growers, irrigators, engineers and water resource planners. This is especially true concerning the introduction of a new crop into irrigated agriculture. Growing hybrid poplar trees for wood chip stock and veneer production under agronomic practices is currently being explored as an alternative to traditional forestry practices. To this author's knowledge, no water use estimates or crop coefficients, the ratio of a specified crop evapotranspiration to a reference crop evapotranspiration, have been verified for hybrid poplars grown under drip irrigation.

Four years of weekly, neutron probe measured, soil water data were analyzed to determine averaged daily, monthly and seasonal plant water use, or crop evapotranspiration . The plantation studied was located near Boardman, Oregon on the arid Columbia River Plateau of North-Central Oregon. Water was applied by periodic applications via drip irrigation. Irrigation application data, weekly recorded rainfall and changes in soil water content permitted the construction of a soil water balance model to calculate weekly hybrid poplar water use. Drainage was estimated by calculating a potential soil water flux from the lower soil profile. Sites with significant estimated potential drainage were removed from the analysis so that all sites used in the development

coefficients were calculated using reference evapotranspiration estimates obtained from a nearby AGRIMET weather station. Mean crop coefficients were estimated using a 2^{nd} order polynomial with 95% confidence intervals. Plant water use estimates and crop curves are presented for one, two and three year old hybrid poplars.

Numerical simulation of irrigation practices was attempted using weekly soil water content and soil physical characterization data. Parameter optimization and numerical simulations were attempted using the HYDRUS-2D Soil Water and Solute Transport model. Parameter optimization and numerical simulations were largely unsuccessful due to lack of adequate soil physical and root zone system representation and dimensional differences between drip irrigation processes and the model design used in this study.

Estimated Plant Water Use and Crop Coefficients for Drip-Irrigated Hybrid Polars

by

David J. Gochis

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David J. Gochis, Author

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1. Introduction

1.1 Purpose

The purpose of this thesis is to determine weekly, monthly and seasonal plant water use of hybrid poplar trees grown under drip irrigation. Such estimates are crucial in the design of efficient plantation irrigation systems and in plantation water management. Currently, no experimental water use estimates exist for multiple age stands of drip irrigated-hybrid poplars. Several authors have provided guidelines for hybrid poplar water use but large discrepancies exist between estimates. Recognizing the growing importance of growing cultivated timber, specifically poplars, by agronomic practices, as opposed to traditional forestry practices, this thesis will provide plant water use or crop evapotranspiration estimates for three years of growth of drip irrigated, hybrid poplar trees grown on the arid Columbia Plateau of north-central Oregon, USA.

1.2 Data

1.2.1 Potlatch Soil Water Monitoring Program

Current Oregon water law does not incorporate irrigation efficiency into water appropriation. The transfer of appropriated water to acreage other than that specified by the appropriation is considered illegal. Such practices are called "water spreading" and can results in loss of right and possibly criminal charges. Plantation managers, working for the Potlatch Corporation near Boardman, OR, contend that water saved by using high efficiency drip irrigation, should be allowed to be moved to acreage other than that to which it was first appropriated.

In 1994, the Potlatch Corporation, in cooperation with the Oregon State Board of Water Resources and the Hydrologic Science Team at Oregon State University, developed a monitoring program to evaluate irrigated versus non-irrigated areas in a field under drip irrigation. It was decided that a two-foot strip between drip irrigation lines should remain beyond the influence of any irrigation water. This zone of non-irrigation was called the "two-foot dry zone."

Drip lines in each field were spaced ten feet apart. Emitters on the drip lines were spaced every four feet. Trees were planted eight feet apart along each emitter line. Soil water monitoring transects were created to facilitate monitoring procedures. Monitoring transects consisted of six neutron probe access tubes placed every two feet at zero, two, four, six, eight and ten feet between emitter lines (See Figure 1.2.1.1). The two-foot dry zone is the area between the four foot and six foot tubes. Soil water status was measured at one foot intervals starting at one foot down to five feet in each of the tubes on a weekly basis.

Alternative monitoring sites called "Paired Sites" were also implemented. Paired sites consisted of two tubes placed along the sides of the two-foot dry zone. Paired sites were not used in the determination of poplar evapotranspiration because readings from these sites do not include the root zone. Control sites, consisting of a single tube placed outside of an irrigated field, were also established to provide background soil water status.

The private company IRZ Consulting from Hermiston, OR measured weekly soil water status. The farm mangers at Potlatch provided irrigation application data at weekly intervals. Rainfall was measured on a weekly basis at each monitoring site. Water balances were constructed on a weekly basis to determine poplar evapotranspiration. Weekly values of poplar evapotranspiration were summed into monthly and yearly evapotranspiration estimates.

1.2.2 AGRIMET Reference Evapotranspiration

Reference evapotranspiration estimates were calculated using the Kimberly-Penman equation, also called the Wright-modified Penman (Wright, 1982), from data provided by the AGRIMET agricultural meteorology monitoring network. The AGRIMET network is a regional network of satellite linked, remote weather stations operated by the U.S. Bureau of Reclamation (BUREC). As of October 1996, 51 stations were connected to the AGRIMET network covering a region bounded by the Columbia and Snake River watersheds. The network is "piggy-packed" onto a larger water resource network operated by the BUREC called HYDROMET started in 1983 (McVay, 1992). The purpose of HYDROMET is to provide real-time weather data and water information on snowpack, seasonal runoff conditions, river and reservoir levels while the main purpose of the AGRIMET system is to provide site specific agricultural weather and crop water use modeling data (Powers, 1992). Both networks are linked to the BUREC's central computer in Boise, Idaho through the Geostationary Operational Environmental Satellite (GOES) via satellite telemetry.

The standard AGRIMET station consists of the following instruments though individual stations may have additional sensing equipment (USBR, 1994):

Sensor	Manufacturer
Thermistor, YSI #44212	Yellow Springs Instruments
Wind Monitor, #05103	R.M. Young
Pyranometer, Model LI-200SB	Li-Cor
Relative Humidity Probe, Model 2013A	Texas Electronics
Relative Humidity Probe, Model HMP-35 A	Viasala
Tipping Bucket Rain Gauge	Qualimetrics
Precipitation Collector, 12 inch	Belfort

Processing and communication equipment:

Instrument	Manufacturer
Data Collection Platform, Model VX1004	Vitel Corporation
Data Collection Platform, Model 8004	Sutron Corporation
Yagi antenna & cable, Model 8200 A	
100 amp-hr battery & cable, #8200 PSC	
Solar panel & cable, Model SX-10	
190 amp hr battery	
Integrator, solar	USDA-ARS (Burgess)
Integrator, wind run	USDA-ARS (Burgess)

The stations transmit data at four hour intervals using an FM signal in the 401-402 Mhz range.

In order to calculate reference evapotranspiration (ET_{ref}) using the Kimberly-Penman equation, measurements of daily maximum and minimum temperature, relative humidity, solar radiation and wind "run" or movement are required. Details of the Kimberly-Penman equation are discussed later in Section 2.2.5. Estimates of ET_{ref} are computed using AGRIMET data taken over uncultivated land in the corners of center pivot fields. Once estimates of ET_{ref} have been made, estimated crop water use is calculated for the local area using locally derived crop coefficients. Crop coefficients are empirical ratios of crop ET to the reference ET. Usually crop coefficients are calculated using a soil lysimeter or other soil water balance methods. The time distribution of crop coefficients for a particular crop through the growing season is called a crop curve. Locally derived crop curves and reference ET estimates have been shown to have a good correlation with individual field conditions within a 15-25 mile radius except in the case of extremely heterogeneous terrain (Dockter, 1996). The Potlatch hybrid poplar plantation near Boardman, OR is approximately 5 miles due south of the HERO AGRIMET station.

2. Literature Review

2.1 Overview of Poplars

2.1.1 Characterization of Poplars (*Populus sp.)*

The crop under investigation in this study is the hybrid poplar tree. The term poplar is widely applied to all members of the genus *Populus*. There are over 125 known species of poplar trees including fossils (FAO, 1985). Only 30-40 species are still in existence and only about 10 of these are considered to be of major timber producing importance (Pryor and Willing, 1982). The hybrid poplar, not formally considered a natural species, is a cross of two or more species of poplar (George, 1996). Hybridization of poplars can occur naturally or through plant breeding. An abbreviated classification of poplars is as follows (FAO, 1980):

genus - *Populus*
family - *Salicaceae*
group - *Amentiflorae*
subclass - *Monochlamydae*
class - *Dicotyledonae*
subdivision - *Angiospermae*
division - *Phanerogamae*

Members of the *Salicaceae* family reproduce through vegetative portions of the living plant as opposed to seeds. This allows poplars to be propagated by cuttings where the cuttings have an identical genetic code as its parent. Often new trees emerge from the stumps of recently cut or damaged trees.

The leaves of poplars are broadly triangular-lozenge shaped and typically have a long petiole. Buds are elongated, sometimes pointed and are often covered by several layers of overlapping scales. The natural range of poplars is shown in Figure 2.1.1.1. Of the 10 major poplar species, two are common throughout North America: *Populus deltoides* and *Populus trichocarpa. Populus deltoides*, commonly called Eastern Cottonwood, ranges westward from the Atlantic Ocean to the central Great Plains and southward from the Great Lakes region to the Gulf of Mexico. *Populus trichocarpa* range from central Alaska to southern California and eastward from the Pacific Ocean to the Rocky Mountains (FAO, 1980). Being a hydrophyllic plant poplars are generally found in alluvial flats and near stream beds. Poplars become less common below latitudes of 30°N and are virtually non-existent in the wild in the southern hemisphere (FAO, 1980).

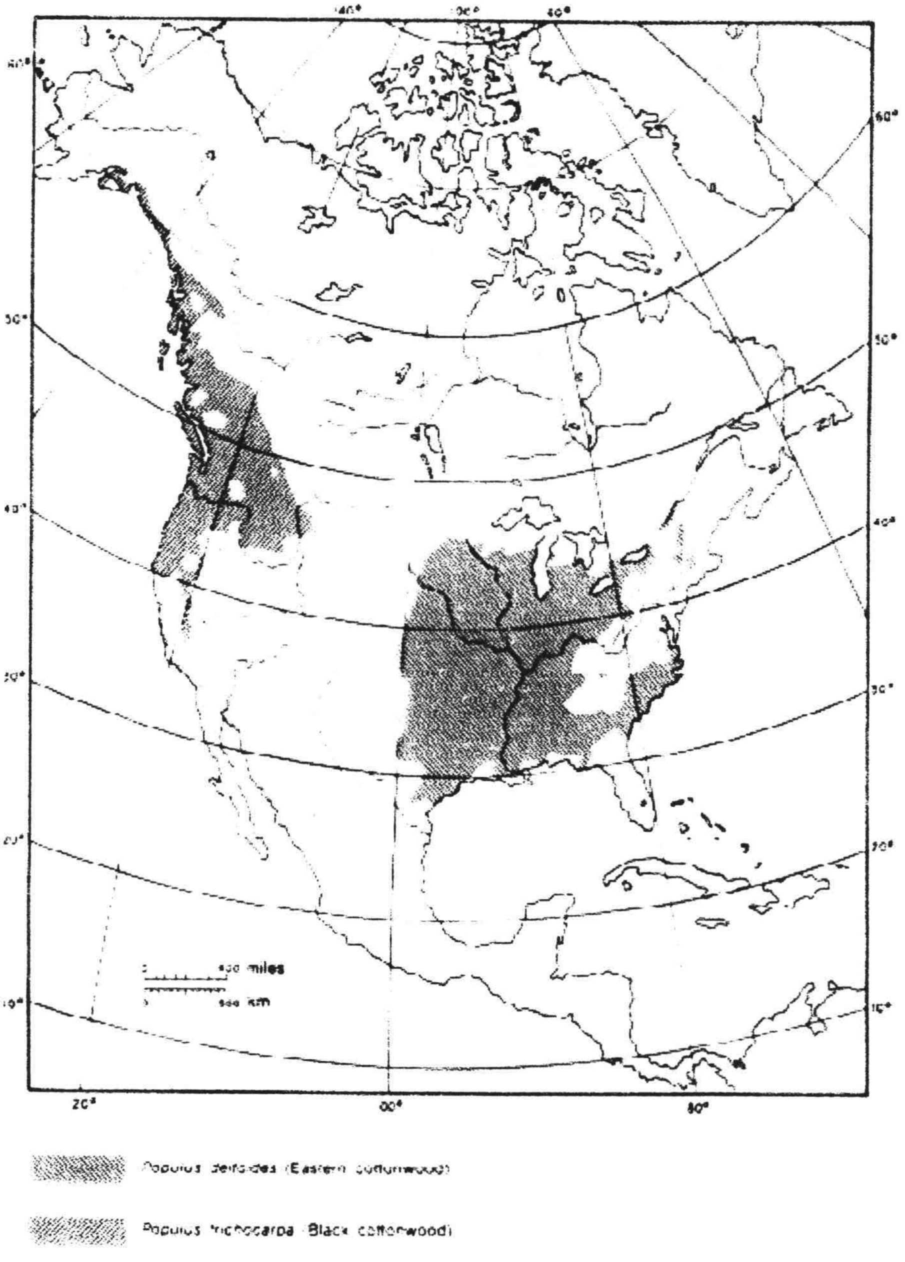
2.1.2 History and Uses

The rapid growth of poplars in temperate regimes along with their relative ease of propagation has made them (*Populus sp.*) an ideal crop in Short Rotation Intensive Culture (SRIC) (FAO, 1985). Primary uses for poplars and other SRIC crops has been for production of woody biomass for energy and fiber (Sigurdsson, 1995). Poplars have exhibited a great potential for growth compared to other temperate species. Brown *et. al* (1996) found that hybrid poplar stem volume at 3-6 months may be comparable to that of conifers at 13 years.

Hybridization of poplars for intensive culture is a technique dating back to the late 18th century when European stocks (predominately *P. nigra*) were crossed with stocks from the United States (*P. deltoides*) (FAO, 1980). The increased productivity of the hybrids resulting from heterosis (a condition among plants in which hybrids are more vigorous than their parents) quickly led to widespread artificial hybridization throughout North America and Europe. Due to the success of hybridization, many exotic hybrids emerged that were susceptible to pests and disease. The general "ignorance and disorder" in poplar cultivation led to the formation of poplar commissions during the early to mid 20th century (FAO, 1980). In 1937 the Istituto di Sperimentazione per la Pioppicoltura was formed in Italy followed by a French commission in 1942 and then the International Poplar Commission in 1947 under the aegis of the United Nations Food and Agriculture Organization (FAO, 1980). The goal of these commissions was to insure that information on poplars is widely available and properly understood.

Early use of poplars was for forestry and the production of wood for energy, products and economic development (FAO, 1985). Recognizing a shift in values in regards to the environment among industrialized and developing nations, other functions of "natural" forests have emerged (FAO, 1980). Forests are now recognized as recreation areas, landscape enhancements and even atmospheric regeneration mechanisms. This shift in ideals and awareness has led to increased restrictions on the harvesting of trees on many public lands throughout the world. The reduction in available timber has increased the market value of cultivated

Figure 2.1.1.1 Range of Native North American Poplars (*Populus spp*) (from FAO, 1980)



V. *Natural distribution of* P. deltoides *and* P. trichocarpa timber. During the 1970's both the United States Department of Energy and the Ontario Ministry of Natural Resources funded research projects for the purpose of increasing the productivity of hybrid poplars for cultivation on traditional agricultural lands (Brown, et al (1996), George (1996)). In 1984 the 17th Session of the FAO International Commission noted that poplar sales were declining in developed countries and increasing in developing countries (FAO, 1985).

Many other uses have emerged for hybrid poplar trees besides fuel for energy and timber products. The decline in available wood in during the 1980's led to an increase in the price of paper pulp stocks. It was found that chips from hybrid poplar trees could supplement traditional stocks of conifer chips for pulp stocks (Kaiser, 1994). Since 1988 poplars have been researched for removing pesticides, toxic organic chemicals and nutrients from soil and groundwater (George, 1996). Current applied research on hybrid poplars has included treatments of municipal and industrial wastewater, processing of biomass into fuels such as ethanol and methanol, and providing shade along stream banks for stream temperature remediation.

2.1.3 Ecology and Physiology of Poplars

Most members of the *Salicaceae* family, including poplars, are light-demanding plants thus occupying open sites as pioneers (FAO, 1980). They are also highly phototropic. The native range of poplars is the mid-latitudes of the Northern Hemisphere where strong seasonal changes occur . This results in distinct growth rhythms in the plants (Pryor and Willing, 1982). In relatively high latitudes, wild species will form resisting or winter protective buds in late summer to early fall. Shorter days, not temperature reductions, result in budset and reduced growth. (Pryor and Willing, 1982). Breeding and hybridization have sought to extend or otherwise manipulate the natural growing season.

Poplars in the wild have been observed to exhibit intense photosynthetic action compared to other species. Table 2.1.3.1 (Roussel, 1972) shows carbon dioxide fixation rates for several common tree species. Poplar trees meet or exceed most other hardwood fixation rates.

Table 2.1.3.1

Oak	*Quercus pedunculata*	10-11	mg CO_2/hr/dm^2
Fig	*Fagus sylvatica*	10-12	
Oak	*Quercus pubesens*	13	
Ash	*Fraximus excelsior*	20	
Aspen	*Populus tremula*	20	
Hybrid Poplar	*Populus* x *euramericana**	15-25	

(* Regulations of the international code of nomenclature for cultivated plants require that designations be assigned at the genus, species and cultivar levels. In this case: genus = *populus*, hybridized species = *euramericana* and if listed cultivar = c.v. "Robusta" for example. Another nomenclature that has emerged when discussion are strictly focused on poplars are the referral to "TxD", "TxM" or "DxN" etc. This nomenclature represents the hybrid of the two parent species such as TxD = *P. trichocarpa* crossed with *P. deltoides*.)

Analogous to carbon fixation rates, root respiration rates of poplars are also very high in comparison with other species. (Table 2.1.3.2 from Bibelriether et al., 1968) This high root respiration rate demands that oxygen be readily available to the root zone. Soils must be even textured with clay contents not exceeding 20-30% (FAO, 1980). It is suggested that macroporosity be greater than 10% and that inundation of

Table 2.1.3.2

Fir	*Abies*	23 mg CO_2/g dry matter produced
Oak	*Q. pedunculata*	32
Fig	*F. sylvatica*	43
Aspen	*P. tremula*	75
Larch	*Larix*	82
Birch	*Betula*	186
Poplar	*Populus*	403

the root zone should not be persistent, especially by stagnant waters. Herpka (1985) also suggests that for best results in plantation plantings, sites should be chosen on deep alluvial soils formed by river deposits.

Poplars have been characterized as being hydrophyillic (or hydrophilous), meaning "water loving." Eidman (from FAO, 1980) compares water use estimates of wild poplars per gram of dry matter produced shown in Table 2.1.3.3 to other wild tree species. A range of 750-1200 mm of rainfall per year has been suggested by Pryor and Willing (1982) as minimum water requirements for poplars growing in the lower latitudes of Australia. Estimates of water use among cultivated poplars have not, as of yet, been firmly established. Madison and Licht (1994) have estimated that cultivated hybrid poplar trees can remove 600 to 1000 pounds of water per pound of dry matter produced. Water uptake was also reported to vary with age, ranging from 2 acre-inches per year at age 1 to 86 acre-inches per year at age five (Madison and Licht, 1994). However, no method was provided.

Table 2.1.3.3

Fir	*Abies*	5.1	cm^3 H_2O/ 24 hrs / g dry matter
Fig	*F. sylvatica*	19.6	
Oak	*Q. pedunculata*	20.6	
Aspen	*P. tremula*	35.5	
Birch	*Betula sp.*	45.1	
Poplar	*Populus sp.*	50.1	

2.1.4 Growing Poplars Under Irrigation

Comparatively little has been published on growing poplar trees under agronomic practices as opposed to traditional forestry practices. Most literature has focused on clonal selection for disease and pest resistance or on plant spacing (Herpka, 1985). The short production cycle of poplars make them more suitable than other tree species to change from traditional timber production to agricultural production (FAO, 1980). The principal considerations for growing hybrid poplars are site selection and minimum water requirements.

Beneficial site characteristics pertaining to soils were briefly discussed in the previous section. Water requirements have been discussed less in the literature because most forest practices do not involve irrigation management but rely on natural precipitation or the local hydrology for all of the plant water requirements. Pryor and Willing (1982) discuss growing hybrid poplars on plantations in their book <u>Growing and Breeding Poplars in Australia</u>. In this work water management of poplars is compared to water management of citrus orchard crops. At 29°S latitude they estimate an annual water requirement of 1,200 mm. At a particular site, the annual application was partitioned as 350 mm of rain and 900 mm of irrigation using channel irrigation. Deciduous poplar clones at higher latitudes in

Australia were observed to use approximately 12 megalitres per hectare (1200 mm) while semi-evergreen poplar clones closer to the equator were observed to use up to 14 megalitres per hectare (1400 mm).

While no indication was given as to their measurement methods, Pryor and Willing (1982) suggest determining irrigation frequency by monitoring soil moisture conditions. Leaf shed will commence if irrigation is neglected or the irrigation interval is too long. Progressive moisture stress will result in complete defoliation and reductions in shoot growth. Stress due to insufficient water lowers the resistance of the trees and they become susceptible to pests such as *Capnodis miliaris* and *Melanophila picta* or disease-like *Cytospora*. In hot, arid ,"irrigated" climates, advanced moisture stress will usually result in death.

Due to the strong seasonality of poplars grown at higher latitudes, it is difficult to compare water use estimates taken at locations differing by large latitudinal distances. Bialobok (1976) provides some transpiration rate estimates of water use in irrigated and un-irrigated black cottonwood (*P. deltoides*) in Poland where the latitude is approximately 45° N. Table 2.1.4.1 shows that large reductions in transpiration can occur with inadequate soil moisture.

Table 2.1.4.1

Transpiration of Watered and Un-watered Black Cottonwood Trees (*P. deltoides*) During Dry Weather in mg/sqdcm • hr (mm/hr)

Successive days after first exhaustion of moisture	Irrigated	Un-irrigated
3	640(6.4)	503 (5.0)
5	430 (4.3)	211 (2.1)
6	326 (3.3)	182 (1.8)

A few authors (Bialobok (1976), FAO (1980)) have indicated that the position of the groundwater table can be of great benefit to satisfying the high water demands of hybrid poplars. Optimum water table levels should range between 50-200 cm below the surface and be well provided with oxygen. Higher oxygen levels are observed where horizontal groundwater movement is greater than 2 m per day (Bialobok, 1976). Drainage ditches or tiles may have to be installed in areas with stagnant water to avoid root asphyxiation. With sufficient groundwater access, poplars are able to withstand low air humidity and scarce rainfalls (from Tarris, 1966 in Bialobok, 1976).

FAO (1980), made estimates of polar water use for areas surrounding the Mediterranean using an empirical method developed in Turkey. (Table 2.1.4.2) The Poplar Institute of Izmut in Turkey developed an empirical method for determining the evapotranspiration potential (ET_p) of a poplar plantation (Turc, 1963). Monthly ET_p is calculated by equation (1).

Table 2.1.4.2

Estimated Plant Water Use for Poplars
For Mediterranean Locations (Taken form FAO, 1980)

Turkey	700-800 m^3 / ha / mo (70-80 mm/mo)
"Hot" Mediterranean	1200-1300 (120-130 mm/mo)
Interior Deserts	> 1800 (>180 mm/mo)
Other Estimates	up to 4000 m^3 / ha / season (400 mm/season)

$$0.40\frac{t}{t+15}\left(Ig+50\right)=ET_p \qquad (1)$$

where, t is the average monthly air temperature in the shade (°C) and Ig is the total solar radiation in calories per square centimeter of horizontal surface per day during a given month. Turc also included a correction factor in cases where the relative humidity (RH) is less than 50%:

$$ET_p = ET_p\left(1+\frac{50-RH}{70}\right) \qquad (2)$$

In cases where Ig is not measured it may be estimated by the following:

$$Ig = Ig_A(0.18+0.62h/H) \qquad (3)$$

where: h represents the daily duration of insolation measured at the station, H is the astronomical duration of the day and Ig_A is the value of the total radiation if there were no atmosphere (a function of latitude and time of year). Using the Turc method, irrigation applications may be calculated by subtracting the average or measured monthly precipitation from the calculated potential demand (ET_p).

FAO (1980) and Pryor and Willing (1982) suggest either channel irrigation or sprinkler systems in young nurseries. It was noted that irrigation with sprinklers becomes difficult after trees are more than 2 years old. Also, early indications in Italy from FAO (1980) suggested that drip irrigation yielded good results.

2.2 Methods of ET Estimation

2.2.1 Introduction

According to Burman and Pochop (1994) evapotranspiration is the combined process of both evaporation from the soil and plant surfaces and transpiration through plant surfaces. Montieth (1997) contends that the term evapotranspiration is both cumbersome and redundant as the physical process of the evaporation of water from a leaf's surface or some other surface is, in essence, the same process. For the remainder of this document the term evapotranspiration will be used interchangeably with the term plant water use as is conventional in U.S. agriculture.

The ability to quantify the amount of water that is withdrawn from a soil profile to a plant or directly to the atmosphere has importance in a multitude of disciplines. Numerous references are dedicated solely to describing the importance of water for maintaining proper plant growth and metabolism (Nobel (1983), Jones (1996), Williams et al., (1996)). Recognizing the physiological importance and the diverse applications of evaporative processes, many different methods have been developed to provide estimates of plant and canopy evapotranspiration. (see: Burman and Pochop (1994), Jones (1996) Montieth and Unsworth (1990), Jensen et al. (1990)).

The practicality of applying evapotranspiration estimates to field situations in irrigated agriculture varies greatly. Many methods such as the combination methods and lysimeter methods are only applicable to research studies due to relatively large instrumentation requirements. Other, less instrument intensive methods, such as temperature, radiation or climate methods are applicable to remote, small-scale operations. Generally, when more resources available for evaporation determination a more theoretical approach may be used. In the absence of resources needed for proper parameter estimates, less theoretical, more empirical methods must be employed.

An inclusive summary of all evaporation estimating methods is beyond the scope of this report. The first method to be discussed in this paper will be the theoretical evolution of the combination method from initial components to its original form given by Penman in 1948. Emphasis in this discussion will be placed on the proper parameterization of variables consistent with evaporation theory although some discussion will focus on empirical parameter estimation. The second method presented will be the adaptation of the combination method used in the AGRIMET network (USBR, 1996), known as the Kimberly-Penman method (Wright and Jensen, 1972). The final section presents the current theoretical representation of the combination method known as the Penman-Montieth equation (Montieth, 1965).

2.2.2 Foundations of Evaporation Estimation

Evaporation has been considered on a theoretical level for only about 130 years (Montieth, 1981). Early attempts to quantify evaporative processes were divided into two schools of thought: the energy balance concept and the aerodynamic transfer concept. Bowen (1926) was the first to describe how to partition components of sensible and latent heat, H and λE, respectively, of the energy balance equation (see Equation (4) below).

Aerodynamic methods estimated vapor transfer by means of a flux equation similar to Fick's first law for diffusion. Thornwaite and Holzman (1939) used such an approach to estimate evaporation from pasture by measuring vapor pressure gradients and determining a mass transfer coefficient from the wind profile. It was not until 1948 that these two different concepts were brought together into a "combination" method by Howard Penman. This section discusses the energy balance and the aerodynamic concepts to provide a foundation for presentation of the combination method later.

2.2.2.1 Energy Balance Considerations

The energy balance method sought to partition incoming radiant energy into appropriate components in recognition of the *First Law of Thermodynamics* such that all energy is conserved. The overall surface energy budget may be described by the following:

$$R_n = \lambda E + H + G \tag{4}$$

where R_n is the net incoming radiation, λE is the amount of energy going to evaporation of water, λ is the latent heat of vaporization of water, H is the amount of energy used in heating the surrounding air (i.e. sensible heat production) and G is the amount of energy used in heating the surface (usually the ground). Generally, G is neglected on a daily basis because it is small compared to H and λE. For increasing time scales it may be necessary to consider the ground component.

Estimates of latent heat flux (λE) can be made from measurements of net radiation (R_n), soil heat flux (G) and gradients of temperature and vapor pressure. To calculate λE from a method introduced by Bowen (1926), the energy balance equation (4) is divided by λE. Re-arranging terms and setting $\beta = H/\lambda E$ yields:

$$\lambda E = \frac{(R_n - G)}{1 + \beta} \tag{5}$$

β is known as the Bowen ratio and estimates of ET made using this approach are called the Bowen ratio ET estimates. The Bowen ratio may be found from measurements of temperature and vapor pressure at a series of heights as described by Jones (1994):

$$\beta = \frac{H}{\lambda E} = \left(\frac{P\rho c_p}{0.622\rho}\right)\frac{(T_s - T_a)}{(e_s - e_a)} = \gamma\frac{\delta T}{\delta e} \tag{6}$$

where P is the atmospheric pressure, c_p is the specific heat of dry air and the quantity $\left(\frac{P\rho c_p}{0.622\rho\lambda}\right)$ is sometimes called γ, the psychometric "constant", which is a direct function of pressure and a weak function of temperature through the latent heat of vaporization (λ), T_s and e_s are the temperature and saturation vapor pressure at the surface, respectively and T_a and e_a are the temperature and actual vapor pressure of the air, respectively.

2.2.2.2 Aerodynamic Considerations

The aerodynamic method, also referred to as the "mass transfer" method by Jensen et al. (1990), permits the calculation of any flux of entity (*s*) by incorporating general diffusion equations. The general diffusion equation, known as Fick's First Law, for water vapor in a turbulent atmosphere has the form:

$$E = -K_v \frac{\partial q}{\partial z} \qquad (7)$$

where, E is the flux per unit area of water vapor, K_v is the eddy diffusivity for water vapor (similar to the diffusion coefficient for water vapor but used in regards to turbulent air regimes where the transport is made primarily by eddies as opposed to molecular diffusion) and $\left(\frac{\partial q}{\partial z}\right)$ is the vertical gradient of specific humidity (Jones (1994), Montieth and Unsworth (1990)). For neutral atmospheric conditions (i.e. where potential temperature does not change with height) it is assumed that the eddy diffusivities for heat, momentum, water vapor and other gases are all equal (Montieth,1965). This allows the flux of any entity to be estimated by the negative of the flux of momentum from the atmosphere to the surface.

Fick's first law for the transfer of momentum is written as:

$$\tau = \rho K_M \frac{du}{dz} \qquad (8)$$

where, τ is the flux of momentum called the shear stress, ρ is the density of the air and K_M is the eddy diffusivity for momentum. From Jones (1994), τ may also be written as the product of the fluctuations of horizontal and vertical wind velocities u and w, respectively:

$$\tau = \rho u'w' = \rho u^{*} \tag{9}$$

u^* in equation (9) is known as the friction velocity. Equating (8) and (9), setting $K_M = ku^{*}z$ as prescribed in Montieth and Unsworth (1990), and integrating yields the horizontal wind velocity profile with height which is logarithmic in shape under neutral conditions and is often called the "log wind profile":

$$u_z = \left(\frac{u^{*}}{k}\right)\ln\left(\frac{z}{z_o}\right) \tag{10}$$

where, z_o is the "roughness length" such that $u = 0$ when $z = z_o$, and k is the von Karman constant which has been empirically determined to be equal to 0.41. This equation describes the wind profile over a smooth surface. For rough surfaces, such as crops, the horizontal wind speed, u, is linearly related to ln (z-d) instead of ln (z) where d is the zero-plane displacement height or the effective sink for momentum (Jones, 1994). Incorporating d into (10) yields:

$$u_z = \left(\frac{u^{*}}{k}\right)\ln\left(\frac{z-d}{z_o}\right) \tag{11}$$

and hence,

$$K_M = ku^{*}(z-d) \tag{12}$$

Substituting K_M from (12) into the basic diffusion equation (8) yields:

$$\tau = \rho k u^{*}(z-d)\frac{\partial u}{\partial z} \tag{13}$$

Recalling that for neutral atmospheres $K_M = K_v$ equations (12), (8) and (7) may be combined and evaporation (E) may be solved for by:

$$E = -\left(\frac{\partial q}{\partial u}\right)u^{*2} \tag{14}$$

2.2.3 The Combination Method of Penman (1948)

Instrument limitations of the time during which Penman conducted his research at Rothamsted Experimental Station in the United Kingdom made estimates of some of the required parameters in the energy balance and aerodynamic methods difficult if not impossible to obtain. Empirical formulations were, and continue to be, substituted into the aerodynamic and energy balance equations. Penman (1948) parameterized the evaporation due to turbulent transport by the following:

$$\lambda E = (e_s(T_s) - e_s(T_d))f(u) \tag{15}$$

where $e_s(T_s)$ is the saturation vapor pressure at the surface temperature, $e_s(T_d)$ is the vapor pressure at the dewpoint temperature and $f(u)$ is an empirical function of the horizontal wind velocity used instead of the eddy diffusivity term (K_v).

A difficult term to measure or estimate according to Penman (1948) and restated in Jones (1996) is the surface temperature, T_s and hence $e_s(T_s)$. T_s is difficult to measure in field situations due to highly variable surface conditions. Penman eliminated T_s (and $e_s(T_s)$) from evaporation estimates by combining the aerodynamic and energy balance equations. By dividing the following by Eq. (15) and rearranging:

$$\lambda E_a = (e_a - e_s(T_d))f(u) \tag{16}$$

where, e_a is the vapor pressure of the air, the result is:

$$\frac{\lambda E_a}{\lambda E} = 1 - \frac{(e_s(T_s) - e_a)}{(e_s(T_s) - e_s(T_d))} \tag{17}$$

Setting $T_s - T_a = (e_s(T_s) - e_a)/\Delta$, where Δ is the slope of the saturation vapor pressure versus temperature curve (at T_s) and substituting into (6) the result of (5) becomes:

$$R_n - G/\lambda E = 1 + \gamma(e_s(T_s) - e_a)/\Delta(e_s(T_s) - e_s(T_d)) \tag{18}$$

If R_n is calculated by the following:

$$R_n = I_s(1-\alpha) + I_{LD} + \varepsilon\sigma T^4 \tag{19}$$

where, I_s is the incoming shortwave radiation, α is the surface reflectance or albedo, I_{LD} is the longwave incoming (downward) radiation and $\varepsilon\sigma T^4$ is the longwave outgoing (upward) radiation, equation (17) may then be substituted into (18) and E may be solved for by:

$$E = \frac{(\Delta R_n + \gamma E_a)}{(\Delta + \gamma)} \tag{20}$$

Using (20) evaporation estimates may be made from "air conditions only" (Penman, 1948) utilizing standard meteorological and climatological information.

2.2.4 Parameter Estimation in the Penman Combination Method

Some of the terms in the Penman equation are not directly measurable and must be estimated from other measurable atmospheric conditions. Also, at the time of development of the original Penman equation, instrument technology was not capable of acquiring all of the parameters required for computation. These shortcomings, admitted by Penman in 1948, led to an evolution of several empirical estimating methods to calculate necessary parameters. This section will provide methods by which all of the required parameters in the Penman equation may be calculated. Units for all parameters will also be given where they have been left out in the theoretical discussion.

The psychometric "constant" (γ) introduced in equation (6) is not a constant (Montieth and Unsworth 1990). It is a dimensional term that is a function of the physical properties of dry air that was introduced by Brunt (1939):

$$\delta e = \gamma \delta T \qquad (21)$$

This relationship assumes an adiabatic process governing the exchange of latent and sensible heat (Montieth, 1965). Using Dalton's law of partial pressures, the derivative of the ideal gas law with respect to temperature for a constant volume is:

$$\frac{\lambda \rho (0.622) \delta e}{P} = \rho c_p (\delta T) \qquad (22)$$

where, λ is the latent heat of vaporization (cal/g/ °C), ρ is the density of air(g/cm^3), 0.622 is the molecular mass ratio of water vapor to dry air, P is the atmospheric pressure (kPa) and c_p is the specific heat of dry air (cal/g/ °C). The psychometric "constant" is therefore the function, $\left(\frac{c_p P}{\lambda 0.622} \right)$. Since atmospheric pressure (P) varies with passing weather systems and with altitude, γ also will change. Similarly, λ changes with temperature although changes over typical atmospheric conditions are often considered insignificant.

Assuming a standard lapse rate of $\left(\frac{dT}{dz} \right) = \Gamma = 6.5°\mathrm{C} / \mathrm{km}$, and ignoring the local changes in surface air pressure due to the passage of frontal systems, the ideal gas law may be integrated to yield atmospheric pressures at any altitude (Robertson and Crowe, 1980).

$$P = P_o \left[\frac{(T_o - \Gamma z)}{T_o} \right]^{\frac{g}{\alpha R}} \tag{23}$$

where, z is the altitude above mean sea level (m), P is the atmospheric pressure (mb) at altitude z, P_O is the atmospheric pressure at mean sea level (mb), T_o is the standard temperature at mean sea level (K), g is the gravitational constant, R is the gas constant (287 J / kg^{-1} K^{-1}) Other simplified relations using regression techniques have been given by Cuenca (1989), Doorenbos and Pruitt (1977).

The slope of the saturation vapor pressure versus temperature curve (Δ) was defined by Montieth and Unsworth, (1990) for a range of air temperatures (T) up to 40°C as:

$$\Delta = \lambda M_w e_s(T) / RT^2 \tag{24}$$

where, M_w is the molecular weight of water (18.001 g/mol), $e_s(T_a)$ is the saturated vapor pressure at air temperature T (°K) and R is the gas constant.

As stated earlier, the latent heat of vaporization λ varies with temperature. Several empirical relations have been created (e.g. Harrison (1963), Brunt (1952). A more physically based method was presented in Montieth and Unsworth (1990) by stating that the latent heat of vaporization is the amount of work done expanding an unspecified large volume (V) between pressures equal to the actual ($e_a(T_a)$) and saturation vapor pressures ($e_s(T_a)$). This relation is given by:

$$\lambda = \int_{e_a(T_a)}^{e_s(T_a)} e\,dV \tag{26}$$

With appropriate substitution from the ideal gas law and upon integration equation (26) becomes:

$$\lambda = \frac{RT}{M_w}\ln\left[e_a(T_a)/e_s(T_a)\right] \quad (27)$$

where all variables are as described previously. Typically, λ will decrease with temperature by about 2.4 J g^{-1} K^{-1}.

Saturation vapor pressure is a strong function of temperature and will change significantly over the range of standard atmospheric conditions. A rigorous expression for the dependence of $e_s(T_a)$ on T is given by integrating the Clausius-Clapeyron equation (Montieth and Unsworth, 1990). Simpler empirical methods have also been developed by Tetens (1930), Bosen (1960), and Murray (1967). Teten's method has been shown to give excellent results using the following equation and is given in the form presented by Jensen et al. (1990):

$$e_s(T_a) = \exp\left[\frac{16.78 - 116.9}{T_a + 237.3}\right] \quad (28)$$

where, T_a is in °C and $e_s(T)$ is in kPa. The actual vapor pressure ($e_a(T_a)$) may be computed very easily when the relative humidity (RH) is known:

$$e_a(T_a) = e_s(T_a)\left(\frac{RH}{100}\right) \quad (29)$$

For most practical situations relative humidity is easily measurable.

The aerodynamic term ($f(u)$) used by Penman in equations (15) and (16) had a general form similar to standard flux equations such as Fick's Law for diffusion:

$$Flux = gradient \times transport \quad (30)$$

In field evaporation, the "transport" term is the sum of molecular diffusion and turbulence. The transport term must be representative of the rate at which the surrounding air is exchanged with a leaf's surface. It is primarily dependent upon the mean wind speed (i.e. mechanical turbulence or "forced convection") but is also determined by the stability of the boundary layer (i.e. thermal turbulence or "free convection"). Penman developed empirical relations for this transfer process over open water, bare ground and grass turf surfaces using linear regression by plotting ($E/\delta e$) versus wind speed (u). The general form of his equation was:

$$\lambda E = 6.43 W_f \delta e \qquad (31)$$

where, λE is the latent heat flux (MJ m^{-2} d^{-1}), W_f is an empirical wind function, δe is the vapor pressure deficit (kPa) and 6.43 is a coefficient dependent upon units.

The general form of the wind function Penman obtained was:

$$W_f = a_w + b_w u_2 \qquad (32)$$

where a_w and b_w are empirical regression coefficients and u_2 is the wind speed (m/s) at 2 m height. W_f was solved for empirically by Penman by measuring all other variables including reference evapotranspiration (Cuenca, 1989). This results in a wind function, which is sensitive to the computation and estimation methods of all other variables. Cuenca and Nicholson (1982) showed that appreciable errors in estimating ET_{ref} can result when different methods of computing the saturation vapor pressure deficit are used compared to the method used when calibrating the wind function. Penman (1963) calculated the values of a_w and b_w to be 1.0 and 0.53, respectively, for a well-watered short grass with an albedo of 0.25.

Net radiation in Penman (1948) is calculated by the following empirical relationship first given by Brunt (1939):

$$R_n = R_c(1-\alpha-\mu) - \sigma T_a^4\left(0.56 - 0.92(e_s(T_a))^{\frac{1}{2}}\right)(1-0.09m) \qquad (33)$$

where, R_c is the measured or calculated short wave radiation (calories/cm^2/day), α is the surface albedo (decimal), μ is the fraction of R_c used in photosynthesis (usually negligible), σ is the Stephan-Boltzman constant (= 4.8995 × 10^{-3} J m^{-2} (d) K^4), T_a is the air temperature (°C), e_s is the saturation vapor pressure (kPa) and $m/10$ is the fraction of sky covered with cloud. If R_c is not directly measured it can be estimated by the following relationship:

$$R_c = R_A(0.18 + 0.55n / N) \qquad (34)$$

where R_A is the radiation at the top of the atmosphere (cal/cm^2·sec) (generally available from solar tables), n is the actual duration of sunshine (hours) and N is the possible duration of sunshine (hours).

Numerous attempts were made to refine the empirical relationships used in the original Penman combination method (Doorenbos and Pruitt (1975), Doorenbos and Pruitt (1977), Montieth (1965), Penman and Long (1960), Wright and Jensen (1972) Wright (1982), Priestley and Taylor (1972)). Only two will be discussed here: the Kimberely-Penman adaptation and the Penman-Montieth adaptation.

2.2.5 The Kimberly-Penman Adaptation

The Kimberly-Penman equation, like the original Penman equation, is not purely physically based. However, it has been adopted by a wide range of irrigators because it has been specifically calibrated for arid, advective environments similar to those at Kimberly, Idaho, where it was first developed (Wright and Jensen, 1972). It is fairly easy to use and all required parameters are usually available from standard agricultural weather stations such as the AGRIMET (Powers, 1992) network. Also, Wright (1982) and Wright (1995) have presented a number of crop coefficients calculated from a pair of sensitive weighing lysimeters for use with Kimberely-Penman reference ET estimates making it simple to compute crop specific ET estimates. Jensen et al. (1990) ranked the Kimberly-Penman method 2 out of 20 for lowest weighted sum of squared error in estimating ET_{ref} versus lysimeter measured ET for an inclusive combination of climate types (See Table A.1). The Kimberly-Penman method was surpassed only by the more physically based Penman-Montieth method in overall reference ET estimating performance.

The general form of the Kimberly-Penman equation is similar to that of the original Penman equation and is given by the following:

$$\lambda ET_{ref} = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma}15.36(Wf)\delta e \qquad (35)$$

where, G is the ground heat flux ($MJm^{-2}\ d^{-1}$) and is positive when the ground is warming.

The Kimberly-Penman adaptation assumes alfalfa as the reference surface as opposed to the grass turf used in earlier methods. Besides physiological differences in the two crops, alfalfa is a much taller crop and therefore has a significantly different aerodynamic relationship with the surrounding atmosphere. Wright and Jensen (1972) developed new empirical coefficients from lysimeter measured ET rates for use in the Penman wind function when calculating reference evapotranspiration from alfalfa in arid and semi-arid areas:

$a_w = 0.75$

$b_w = 0.993$

Wright (1982) modified the wind function again in order to allow the value of coefficient a_w and b_w to change with the day of year (D). As presented in Jensen et al. (1990), when u_2 is the 24 hour daily wind the expressions are:

$$a_w = 0.4 + 1.4\exp\left\{-\left[(D-173)/58\right]^2\right\}$$
$$b_w = 0.605 + 0.345\exp\left\{-\left[(D-243)/80\right]^2\right\}$$

Wright and Jensen (1972) also approximated the procedure for calculating the vapor pressure deficit in (35) by the following equation:

$$\delta e = \frac{e_s(T_{\max}) - e_s(T_{\min})}{2} - e_s(T_d) \qquad (36)$$

where, e_s (kPa) is the saturated vapor pressure at temperatures T_{max} and T_{min}, T_{max} and T_{min} are the maximum and minimum daily temperatures (°C), respectively and T_d is the dewpoint temperature (°C).

Net radiation for equation (35) is estimated from daily solar radiation, temperature and humidity data (Wright, 1982). The following equations summarize the procedure used in obtaining R_n:

$$R_n = (1-\alpha)R_s - R_b$$
$$R_b = \left(a\frac{R_s}{R_{so}} + b\right)R_{bo} \qquad (37)$$
$$R_{bo} = \left(a_1 - 0.044\sqrt{e_s(T_d)}\right)\left(11.71\times10^{-8}\right)\left(\frac{T_{\max}^4 + T_{\min}^4}{2}\right)$$

where R_s is the measured incident short wave radiation ($MJm^{-2}\ d^{-1}$), α is the crop albedo, R_b is the net outgoing longwave radiation, R_{so} is the clear day solar radiation, R_{bo} net clear day outgoing longwave radiation, a_l is a parameter for estimating the effective emittance of the atmosphere and other variables are as listed before.

Coefficients a and b in (37) were determined empirically and have the purpose of weighting the clear day outgoing longwave radiation (R_{bo}) by the ratio of actual to possible incoming shortwave radiation or cloud cover. For values of $R_s/R_{so} \leq 0.7$; a=1.017 and b=-0.06 and when $R_s/R_{so} > 0.7$; a=1.126 and b=-0.07.

Albedo (α) was also determined empirically as a function of the month (M) and the day of that month (N) by:

$$\alpha = 0.29 + 0.06\sin[30(M + 0.0333N + 2.25)] \qquad (37a)$$

Wright (1982) notes that M and N are combined to approximate the day of the year so that the sin function in (37) equals -1 on June 1 and 0 on September 22. This ensures that the surface albedo has a minimum value at the sun's highest point, on the summer solstice, and a maximum value at the end of the growing season on the autumnal equinox.

2.2.6 The Penman-Montieth Method

The Penman-Montieth equation has proven to be the most accurate method for estimating evaporation from a variety of different surfaces in all climates. Jensen et al. (1990) ranked the Penman-Montieth method first out of 20 different ET_{ref} estimating methods by having the lowest weighted sum of squared error when compared to actual measured evapotranspiration from a weighing lysimeter.

Using the general flux equation given in (30), Montieth (1965) incorporated an electrical resistance analog in order to parameterize the aerodynamic transport term. The resistance to diffusive transport, r_a (s/m) is defined as "the time for 1 cm^3 of air to exchange heat (calories) with 1 cm^2 of surface." Using the same procedure for determining the flux of momentum as outlined in the *Aerodynamic Method* section (equations (7)-(14)) Montieth (1965) was able to calculate the resistance term, r_a, as:

$$r_a = \frac{\{\ln[(z-d)/z_o]\}^2}{k^2 u_z} \tag{38}$$

where, d is the zero plane displacement height which serves as a sink for momentum, k is the von Karman constant (= 0.41; dimensionless), u_z is the wind speed at height z (m/s and m, respectively) and r_a is the diffusive resistance to momentum transfer (s/m).

The use of equation (38) assumes a neutral atmosphere (one where potential temperature does not change with height) and that the transport of momentum, heat and water vapor are all transported similarly (Montieth, 1965). It was later discovered (Allen, 1986) that the roughness length for momentum can differ significantly from the roughness length for heat and vapor and the following relation was given in Jensen et al. (1990) as the aerodynamic resistance term:

$$r_a = \frac{\{\ln[(z_w-d)/z_{om}]\}\{\ln[(z_h-d)/z_{oh}]\}}{k^2 u_z} \tag{39}$$

where z_w is the height at which the wind is measured (m), z_{om} is the roughness height for momentum (m), z_h is the height at which humidity is measured (m), and z_{oh} is the roughness length for heat and water vapor (m).

Roughness heights may be determined experimentally by plotting ln(z-d) versus u_z and setting the ln(z-d) intercept equal to z_{om}. The roughness height of heat and water vapor have been estimated by Stricker and Brutseart (1978) as being approximately 10 percent of the roughness height for momentum. Zero plane displacement heights, d, are usually estimated empirically and Montieth (1981) suggests that d is approximately two-thirds of the canopy height. Jarvis et al. (1976) and Campbell (1977) also provide empirically based estimates for roughness heights and zero plane displacement heights.

Montieth (1965) also introduced a physiological resistance to vapor diffusion r_l. This resistance is managed primarily by the stomatal pores although some vapor diffusion may occur through leaf cuticles. It was suggested that when diffusion within the leaf and in the external air are equal the following relationship exists:

$$e_s(T_s) - e_a = \left(1 + \frac{r_l}{r_a}\right)(e_o - e_a) \tag{40}$$

where, $e_s(T_s)$ is the saturation vapor pressure at the leaf's surface (kPa), e_a is the actual vapor pressure of the air (kPa), r_l is the leaf resistance (s/m), r_a is as above (s/m) and e_o is the actual vapor pressure at the leaf's surface (kPa). Using (40) the psychometric constant in equation (20) may be solved for as γ*:

$$\gamma_* = \gamma\left(1 + \frac{r_l}{r_a}\right) \tag{41}$$

Typically r_l is solved for empirically by measuring ET and measuring or estimating all other variables. When considering an entire canopy, the canopy resistance (r_c) has been suggested to be a function of the leaf area index (LAI) (the measure of the total leaf area of a plant per shade area on the ground) r_c may be estimated by the following relationship (Jensen et al. (1990)):

$$r_c = 100 / (0.5 LAI) \tag{42}$$

Substituting $\gamma*$ back into (20) and using Montieth's aerodynamic function (39) as r_a, the final form of the Penman-Montieth equation is:

$$\lambda E = \frac{\Delta(R_n - G)}{\Delta + \gamma_*} + \frac{\rho c_p \frac{\delta e}{r_a}}{\Delta + \gamma_*} \tag{43}$$

The Penman-Montieth method is most accurate when used on an hourly basis. Therefore the measurement requirements are high. Daily estimates of evapotranspiration are obtainable by using daily totals and or daily means of required variables (Jackson, et al. 1983).

2.3 Methods of ET Measurement

There are many different methods of measuring evapotranspiration. A non-inclusive discussion of evaporation measurement methods is provided in this section. Methods discussed are:

Soil Water Balance
Lysimeter
Meteorological (eddy flux, Bowen Ratio, Aerodynamic)

2.3.1 Soil Water Balance

Evaporation in bare soil fields or evapotranspiration in cropped fields can be measured by measuring the change in soil water content with respect to time. Traditionally, destructive soil sampling and gravimetric analysis was required in order to determine periodic changes in soil moisture content. Several techniques utilizing instrumentation such as the neutron probe, time domain reflectometry or porous resistance blocks have emerged in the last few decades allowing for *in situ* measurements. Wallace et al. (1981) used a soil water balance to derive seasonal trends in evaporation. With a continuous sampling scheme the average rate of evapotranspiration (*ET*) between sampling dates, Δt, can be calculated by the following mass balance equation:

$$ET = \text{Precip} + \Delta SM + \text{Irrigation} + \text{Drainage} \tag{44}$$

or in a more functional form given by Jensen et al. (1990):

$$ET = \frac{W_{et}}{\Delta t} = \frac{\sum_{i=1}^{n_r} (\theta_1 - \theta_2)_i \Delta z_i + R_e - W_d}{\Delta t} \tag{45}$$

where n_r is the number of layers to the depth of the effective root zone, Δz_i is the thickness of each layer, θ_1 and θ_2 are the volumetric water contents on the first and second dates of sampling, respectively, R_e is rainfall that does not runoff or is intercepted by the canopy, W_d is drainage from the root zone (W_d<0 for water moving into the root zone from an underlying water table) and Δt is the time interval between measurements (Jensen et al. 1990).

The method provides satisfactory results if measurements are made with sufficient care and there is a reasonable assurance that there is no water transfer by deep percolation or from a water table. Additional considerations that have been developed are listed below:

(Jensen, 1974) Use at least 6 sampling sites per field
The depth to the water table must be greater than the depth of the root zone
Use only the active root zone depth for ET calculations
Only periods where light rainfall are used

Burman and Pochop (1994) suggest that drainage losses may be minimized by:
Applying the pre-plant irrigation at least 10 days before planting
Applying less water each irrigation than could be retained in the soil
Waiting at least 2 days after an irrigation for soil water measurements if a light rain/irrigation is applied or longer for heavier applications

2.3.2 Lysimetric Measurement

A lysimeter is a tank used to isolate a soil mass containing a growing crop or bare soil from the surrounding soil. The word lysimeter is derived from the Greek roots *lysis* meaning dissolving and *metron* meaning measuring. (Aboukhaled et al., 1982) Lysimetry refers to any device used to examine the rate and amount of a fluid substance passing into or out of some controlled volume, be it another fluid or porous media.

One of the main purposes of a lysimeter to irrigated agriculture is to permit the calculation of a water balance by creating a control volume. In field conditions this allows for the elimination of uncertainties involved in estimating deep percolation past the root zone, capillary rise from a water table, horizontal moisture advection and surface runoff. Lysimeters vary in size due to the scope of the project and the availability of resources.

The water balance equation for a lysimeter is similar to that of the soil water balance method (Equation 45) and is given in Burman and Pochop (1994) as:

$$ET = P + \Delta SM + \text{water added} - \text{water removed} \qquad (46)$$

where, ΔSM is the change in soil moisture, P is rainfall provided over-topping does not occur. "Water added" and "water removed" refer to irrigation applications or water drained from the lysimeter.

The most common way of classifying lysimeters is by the following: after (Jensen et al. (1990), Burman and Pochop (1994), Katul (1990))

1. Drainage
2. Non-Weighing
3. Weighing

Drainage lysimeters are periodically drained of excess irrigation water and rainfall that has percolated past the root zone. They are usually considered to be the simplest of all non-weighing types. Soil water contents are maintained near field capacity (Katul, 1990) so that the water balance equation for a drainage lysimeter reduces to:

$$ET = P + \text{water added} + \text{water removed}$$

Non-weighing lysimeters typically involve supplemental measurements of soil moisture such as described in Section 2.3.1 or the monitoring or maintenance of a ground water table level. Non-weighing lysimeters using soil moisture measurements can use (46) to calculate ET.

Non-weighing lysimeters that either measure or maintain a water table height work on the principle of water availability due to capillary rise. It is assumed that water used in ET is withdrawn from the area of capillary rise in the root zone so that the amount of water added to maintain a water table height or the depth over which a water table has fallen is equal to the crop ET.

Weighing lysimeters are regarded as the most reliable of all methods for estimating ET (Burman and Pochop, 1994). Weighing lysimeters also allow for the finest time-scale resolution of ET measurements (Jensen et al., 1990). They directly measure the change in weight of the control volume at all practical time intervals. Several different devices have been employed to make these measurements (from Katul, 1990):

1. Mechanical Weighing Lysimeters
2. Electronic Weighing Lysimeters
3. Hydraulic Lysimeters
4. Floating Lysimeters

Typically two containers are used in weighing lysimeter systems. The inner container holds the soil, water and crop while the outer container allows for free movement of the inner one.

Mechanical and electronic lysimeters are very similar differing only in the device that is making the weight measurement. Mechanical devices consist of lift scales, or spring scales in smaller systems. Electronic devices employed are strain gauges or load cells. It is often necessary to use counter weights to assist in supporting larger lysimeters so that measuring devices are not damaged.

Hydraulic lysimeters consist of resting the inner container on a liquid filled bag or shock and measuring the load by a manometer. Weight changes of the container are registered by a change in the level of the liquid in the manometer.

Floating lysimeters operate on a displacement or buoyancy (Archmedes) principle and can be much more cost effective than other lysimeters. The outer container is partially filled with a fluid such as water or zinc chloride ($ZnCl_2$). The inner container then floats inside the outer container such that changes in the weight of the inner container caused by rainfall, irrigation or ET can be measured by the change in level of the floating container.

Several precautions are mentioned in Burman and Pochop, (1994) in the use of lysimeters. Lysimeters must be placed well away from the edge of a crop (at least 100 m) to avoid microclimatic variations due to sensible heat advection and high vapor pressure deficits. The ratio of the rim area of the lysimeter to the plant area in the lysimeter should be less than 0.1. The lysimeter should not be so shallow as to limit root growth and produce an unrepresentative thermal regime. Most importantly, the crop and management practices need to be identical for the crop in the lysimeter and the surrounding crop. "The proper use of lysimters is somewhat of an art." (Burman and Pochop, 1994)

2.3.3 Meteorological Methods

2.3.3.1 Eddy Correlation

The eddy correlation method is the only meteorological method that provides direct flux estimates of evapotranspiration (Itier and Brunet, 1996). For the past 10 years it has become the standard technique for measuring evaporation at canopy scales. The principle of eddy correlation is to sense the contributions of all turbulent motions responsible for the vertical transfer of water vapor.

The general flux equation for vertical transport of any entity, *s*, can be written as (Montieth and Unsworth, 1990):

$$F = -\overline{\rho w l}\left(d\bar{s} / dz \right) \tag{47}$$

where, ρ is the air density, w is the mean vertical velocity, l is the mixing length for turbulent transport and ds/dz is the vertical gradient of specific mass (mass entity / mass of air) of some entity, s.

The general flux equation may also be written in terms of component velocities using instantaneous values of s and w such as:

$$\overline{\rho ws} = \overline{\left(\rho \bar{w} + \rho w'\right)\left(\bar{s} + s'\right)} \tag{48}$$

where ρ, w and s are all described as before except that the (′) indicates a deviation from the mean value. Expansion of the right hand side of (48) yields the following:

$$\overline{\rho ws} + \overline{\rho \bar{w} s'} + \overline{\rho w' \bar{s}} + \overline{\rho w' s'}$$

(1) (2) (3) (4)

Terms (1) and (2) equal 0 assuming that the mean vertical motion is equal to zero and term (3) also reduces to 0 since there is no net change in entity, s. Therefore term (4) remains leaving:

$$\overline{\rho ws} = \overline{\rho w' s'} \tag{49}$$

such that the mean vertical transport of s is equal the time averaged values of the deviations of the mean vertical velocity and the entity (s).

Equation (49) is a general form of the eddy correlation flux equation. The eddy correlation equation for evaporative fluxes is given by Jensen et al. (1990) as:

$$E = \frac{0.622}{P} \overline{\rho w' e'} \tag{50}$$

where, $\left(\frac{e' 0.622}{P}\right)$ is the instantaneous deviation of specific humidity, q, (q = mass of water vapor / mass of moist air), e' is the instantaneous deviation of the actual vapor pressure, 0.622 is a constant equal to the molecular weight of water divided by the molecular weight of air and P is the atmospheric pressure.

Measurements of w' and e' must be made on time scales similar to that of the turbulent transfer of the atmosphere. This scale is a function of the size of the turbulent eddies carrying the flux (Leuning, 1982). Montieth and Unsworth (1990) suggest response times of 0.1-10 Hz for forest canopies and 0.001 Hz for smooth surfaces. These measurements are provided by sonic anemometers and fast response hygrometers.

Itier and Brunet (1996) discuss some important considerations when making evapotranspiration measurements from eddy correlation methods. The time series used in averaging the instantaneous deviations must be stationary at the time scale of the averaging period. This may require de-trending the time series in some situations. Also, air density corrections may need to be made to the standard air density calculation especially in situations with large Bowen Ratios (β = sensible heat flux / latent heat flux) or large lapse rates.

2.3.3.2 Bowen Ratio

Prior to introduction of the eddy correlation method the Bowen Ratio method was considered the standard meteorological method for determining evaporation (Itier and Brunet, 1996). It has the benefits of being simple in methodology and the instrumentation is relatively easy to operate. The Bowen ratio method is based on the conservation of energy or the energy balance principle and was discussed in detail in the energy balance discussion (Section 2.2.1)

Jones (1994) states that when β is small (i.e. when λE is large compared to H) the Bowen ratio method is relatively insensitive to the measurements of T and e since most of the energy is used in evaporation is derived from the available energy $(Rn - G)$. Conversely, problems do occur when estimates are made during periods with high values of β. Difficulties also have been noted by Itier and Brunet (1996) to occur in sparse or rough canopies and when gradients of T and e are not very significant such as at nightfall or on very cloudy days.

2.3.3.3 Aerodynamic Method

The aerodynamic method, also referred to as the "mass transfer" method by Jensen et al., (1990) permits the calculation of any flux of entity (s) by incorporating eddy diffusion equations. Theoretical considerations were discussed previously in Section 2.2.1. The following discussion elaborates on some of the required measurements or estimates needed to compute fluxes from the aerodynamic method.

The required measurements to obtain evapotranspiration estimates in neutral stability conditions are wind speed and humidity at, at least two different heights. $u*$ in (14) may be solved for from the wind profile described in equation (11) as:

$$u^* = \frac{u_z k}{\ln\left(\frac{z-d}{z_o}\right)} \tag{51}$$

where, d and z_o are crop specific parameters and must be determined empirically from the observed wind profile. Vapor pressure (e) may be measured instead of specific humidity, and using a conversion of $q = 0.622\, e / P$ a similar flux equation found in Jensen et al. (1990) may be used to solve for the latent heat flux:

$$\lambda E = \frac{-\lambda \rho 0.622}{P} K_v \left(\frac{\partial e}{\partial z} \right) \tag{52}$$

In non-neutral stability conditions it is necessary to know the actual profiles of u and q as opposed to the assumed log profile and K_M and K_v cannot be considered equal and other adjustments must be made (Montieth and Unsworth, 1990).

2.4 Crop ET Estimates

Two factors need to be considered when developing estimates of crop evapotranspiration. According to Jensen (1990) "Meteorological conditions determine the evaporative demand while the crop canopy and soil moisture conditions determine the extent to which that demand will be met." Evaporative demand is determined by calculation of the reference or potential ET (ET_{ref}). ET_{ref} is the rate at which water will be evaporated from a given crop and soil surface, assuming the crop is well watered, in full canopy, occupying and extensive surface and is disease free (Wright (1995), Doorenbos and Pruitt (1977)). Using reference crop ET permits a physically realistic characterization of the effect of the microclimate of a field on the evaporative transfer of water from the soil-plant system to the atmosphere above (Wright, 1996).

Allen et al. (1996) state that three primary characteristics distinguish crop ET (ET_{crop}) from ET_{ref}: crop height, crop-soil surface resistance, and the albedo of the combined crop-soil surface. Crop height affects the roughness of the crop which directly affects aerodynamic resistance. As crop height (h) increases, aerodynamic resistance (r_a) decreases. Crop surface resistance describes the physiological control of vapor transfer unique to a particular crop. The soil resistance will also be unique overlying crop as it is influenced by canopy structure, root structure, radiation transmittance and organic composition. Canopy structure and canopy and soil physical characteristics influence the net radiation available for evapotranspiration and are therefore unique to each canopy-soil system.

These characteristics are accounted for in the determination of ET_{crop} by the use of a crop coefficient K_c where:

$$ET_{crop} = ET_{ref} \cdot K_c \tag{53}$$

In effect, K_c relates the evapotranspiration of a disease-free crop grown in large fields under optimum soil water and fertility conditions to the reference evapotranspiration (Doorenboos and Pruitt, 1977). ET_{ref} may be determined using any of the previously discussed estimating methods at an appropriate interval of time using available meteorological data. According to Wright (1995), crop coefficients need to be adjusted when determining crop ET from a reference ET other than that reference ET estimating method that was used to derive the crop coefficient. For example, estimated crop ET will differ using the Kimberely-Penman reference ET from estimated crop ET using the Blaney-Criddle reference ET.

2.4.1 Crop Curve Determination

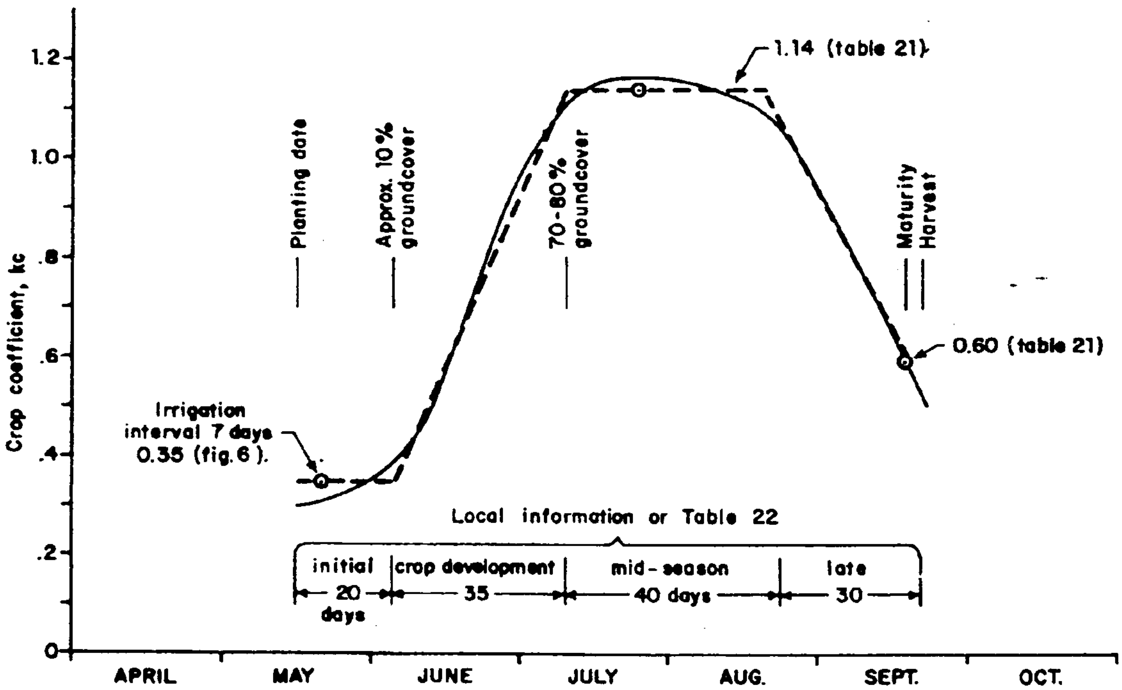
Crop coefficients vary throughout the growing season in response to plant morphology and changes in the physical environment surrounding the plant. Therefore the seasonal distribution of crop coefficients for a particular crop as a function of time constitutes a crop curve (Wright, 1982). Originally, determination of K_c values in accordance to stage of development followed the procedure outlined by Doorenbos and Pruitt, (1977):

1. Establish planting or sowing date from local information or from practices in similar climatic zones
2. Determine total growing season and length of crop development stages from local information
3. Initial Stage: Predict irrigation and/or rainfall frequency and obtain K_c from Fig. 2.4.1.1
4. Development Stage: Assume a straight line between K_c value at end of initial stage to start of mid-season stage (5)
5. Mid-Season Stage: For a given climate (f(RH and wind)), select K_c value from Table A.2 and plot as a straight line
6. Late-Season Stage: For time of full maturity select K_c from Table A.2 for a given climate and plot value at end of growing season or full maturity. Assume straight line between K_c values at end of mid-season period and at end of growing season.

Once completed a curve may be drawn as indicated in Figure 2.4.2.1. Crop coefficients and crop morphology data for a variety of crops and climates are provided in FAO Irrigation and Drainage Paper 24 (Doorenbos and Pruitt, 1997). Wright (1982) used a sensitive weighing lysimeter to obtain measurements of ET_{crop} and an alfalfa reference ET to experimentally determine crop coefficient curves for a variety of field crops in southern Idaho. Weighing lysimeter derived crop coefficients permit more accurate estimates of ET_{crop} than soil water balance methods and thus yield more accurate crop coefficient curves (Wright, 1982). Crop coefficients calculated from experimental sites having weighing lysimeters have become the most widely accepted values for use in ET_{crop} estimation.

Polynomial expressions derived by regression methods may also produce crop curves when the ratio of ET_{crop}:ET_{ref} is plotted a time scale designating the growing season of the crop. (Burman and Pochop, 1994)

Figure 2.4.1.1 Example of Crop Coefficient Curve (from Doorenbos and Pruitt, 1977)



2.4.2 Factors Affecting ET_{crop}

Several factors can affect ET_{crop} in a particular field such that the "universal" application of crop coefficients may lead to significant errors in final ET_{crop} estimates. Usually these factors are caused by local environment alterations from the environment in which the original crop coefficients were developed.

Climate differences, particularly at the micro-scale can produce significant deviations in actual ET_{crop} from estimated ET_{crop}. Microclimate variables such as wind, vapor pressure deficit, temperature and net radiation can vary greatly from field to field. In arid climates, advection of warmer, drier airmasses can produce appreciably higher ET_{crop} values along upwind edges of a field compared to actual

ET_{crop} values obtained 100-200 m inward from the upwind edge (Doorenbos and Pruitt (1977), Wright (1982, 1996), Jensen et al. (1990)). Variations in net radiation due to external shading by shelter belts or heterogeneous canopy structure can produce variations in stomatal resistance which in turn produces altered ET_{crop} values (Al-Shooshan and Ismail, 1996). Allen et al. (1986) estimated stomatal resistance as a function of leaf area index (*LAI*). The presence of water, dew, carbon dioxide within the crop canopy may also affect stomatal resistance (Montieth and Unsworth, 1990, Jones, 1994). Actual ET_{crop} may also vary with altitude due to changes in temperature, humidity, wind, net radiation and the value of the psychometric coefficient (γ) due to pressure changes (Pochop and Burman, 1987, Jones, 1994).

Though one of the basic assumptions in using crop coefficients for the determination of ET_{crop} is that the crop is well watered (i.e., not water limited), the level of available soil water can influence actual values of ET_{crop} depending on irrigation practices. (Doorenbos and Pruitt, 1977). Soil water retention and hydraulic conductivity that varies with soil texture will influence the amount of water available to a particular crop so that crop curves developed on a markedly different soil than the field upon which ET_{crop} estimates are being applied could lead to substantial errors. The quality of the irrigation water and soil water in regards to salinity can influence actual ET_{crop} values. (Ritzema, 1994)

Methods of irrigation can have a wide range of effects in regards to the accuracy of ET_{crop} estimates. Doorenbos and Pruitt (1977) suggest that differences are more a function of the management of the irrigation practices than the irrigation systems themselves.

2.4.3 Basal Crop Coefficients

Difficulty in meeting the assumptions of a dry soil surface and adequate soil moisture led to a refinement of the crop curve concept. Wright (1982) introduced the basal crop coefficient curve (K_{cb}) as the smooth curve produced by manually fitting a curve to calculated crop coefficients using ET_{ref} and ET_{crop}. Crop coefficients can be factored into components representing soil surface wetness and soil water limitations by Eq. (54):

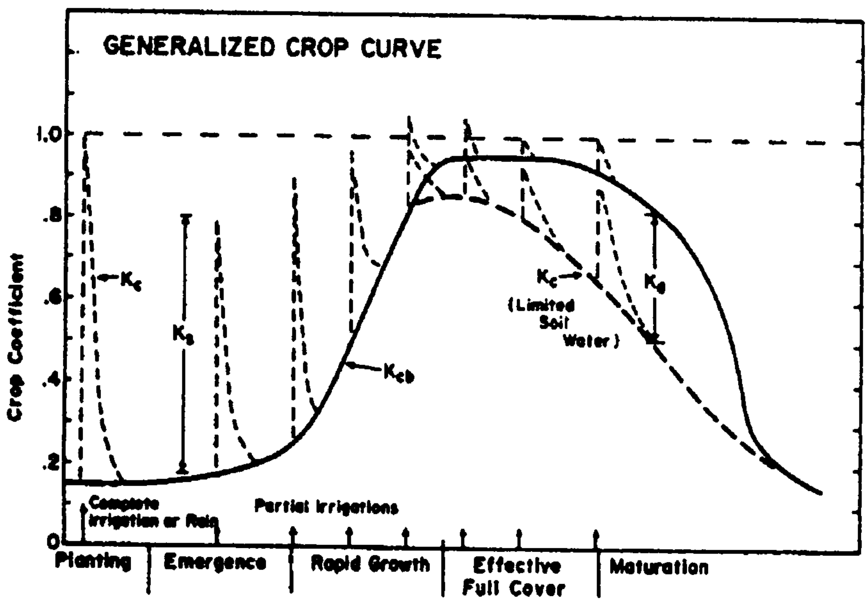
$$K_{cc} = K_{cb}K_a + K_s \tag{54}$$

where: K_{cc} is the adjusted daily crop coefficient, K_a is a coefficient dependent upon available soil moisture and K_s is a coefficient that adjusts for increased soil surface evaporation occurring after rainfall or irrigation. K_a is equal to 1 unless available soil water limits transpiration, in which case it has a value less than 1. If the soil surface is wet, $K_s > 0$ so that $K_{cc}>K_{cb}$ (Jensen, 1990). Figure (2.4.3.1) shows a graphical representation of the crop coefficient adjustment. Spikes in crop coefficient values indicate periods of increased ET_{crop} due to evaporation of irrigation water or rainfall from the soil surface. These spikes represent a departure form the basal crop coefficient due to soil evaporation of irrigation (K_s). More realistic estimates of ET_{crop} may then be obtained by using K_{cc} in equation (53) to yield:

$$ET_{crop} = K_{cc}\, ET_{ref} \tag{55}$$

K_a is a fraction between 0 and 1 where a value of 1 corresponds to 100% available water (AW) at field capacity and 0 at wilting point when AW goes to 0. Since transpiration is not linearly related to AW a number functions have been derived to

Figure 2.4.3.1 Generalized Crop Curve (from Wright, 1982)



estimate K_a values as a function of AW. Jensen et al. (1990) listed a few:

$K_a = \ln(AW + 1) / \ln(101)$ (Jensen et al., 1971)

$K_a = 1$ for $AW > 50\%$

$K_a = AW/50$ for $AW <= 50\%$

Similarly, a relationship for the degree of surface wetness K_s has been derived as a function of days after irrigation:

$$K_s = (K_l - K_{ci})\, e^{-\xi t} \quad \text{for } K_l > K_{ci} \qquad (56)$$

where, t is the number of days after irrigation or rainfall, ξ represents the combined effects of soil characteristics and evaporative demand, and K_{ci} is the value of K_c at the time the rain or irrigation occurred. K_l varies with soils and locations. (Jensen et al., 1971)

2.4.4 Mean Crop Coefficients

When attempting to determine seasonal ET_{crop} estimates from climatic data it may be more practical to employ an average or mean crop coefficient than a basal crop coefficient. A mean crop coefficient (K_{cm}) is not adjusted for increased evaporation from surface soil moisture so that K_s in Eq. (53) is equal to zero. (see Figure 2.4.3.1). Adjustments due to limiting AW can be made using K_a as before:

$$K_c = K_{cm} K_a \tag{57}$$

The mean crop coefficient can be used with soil water balance data for time periods of several days since the effects of surface drying are not included (Jensen et al., 1990).

2.5 Numerical Simulation of Irrigation Practices

2.5.1 Introduction

A numerical model was employed to assist in the optimization of soil water retention parameters and simulate irrigation practices. Constraints placed on the model selection process were that the model had to be able to simulate daily irrigation applications and estimates of poplar ET under variable atmospheric forcing while providing spatial soil water content representation. Therefore, the model the model must be rigorous in its physical representation of soil-water-plant-atmosphere interaction.

Soil water monitoring transects described in Section 1.2.1 yield a two-dimensional distribution of soil water content. The numerical simulation model of choice should be capable of providing predictive estimates of soil water content across a standard monitoring transect while maintaining adequate representation of plant water uptake, irrigation and rainfall processes. The HYRDUS-2D Soil Water Flow and Solute Transport numerical simulation model (Simunek et. al, 1994) is a two dimensional, quasi-three dimensional simulation model capable of simulating water flow and evapotranspiration processes through isothermal, partially saturated media. The model was developed at the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) Salinity Laboratory and has been extensively verified (Gribb (1996), van Genuchten and Simunek (1996, 1997)).

The model simulates soil water flow processes by solving a set of water flow equations through time over a finite element domain. A detailed discussion of model physics, variables, data requirements, output products and source code are provided in Simunek et. al (1994). The following sections will not repeat the entire discussion but merely summarize model processes relevant to this thesis. Section 2.5.2 introduces the governing water flow equations used in HYDRUS-2D. Section 2.5.3 elaborates on the soil water retention and hydraulic conductivity functions used in the solution of the governing equations. Section 2.5.4 describes the initial and boundary conditions required to run simulations of drip irrigation processes and Section 2.5.5 describes the process of root water uptake.

2.5.2 Governing Equation

The governing flow equation in HYDRUS-2D is a modified form of the Richard's equation (Richards, 1931). The general form of Richard's equation as given by Kabat and Beekma (1994) is:

$$\frac{\partial \theta}{\partial t} = \nabla \cdot \mathrm{K}(\theta)\nabla \mathrm{H} - S \tag{58}$$

where, $\frac{\partial \theta}{\partial t}$ is the change in volumetric water content with time (t^{-1}), $\nabla \cdot \mathrm{K}(\theta)$ is the three dimensional gradient in hydraulic conductivity as a function of volumetric water content (length/time), S is a source or sink term (t^{-1}) and $\nabla \mathrm{H}$ is the three dimensional hydraulic gradient where $\mathrm{H} = h + z$ and h is the local soil water potential (length) and z is the height above some datum (length).

HYDRUS-2D accounts for two-dimensional anisotropy of hydraulic conductivity by including the dimensionless anisotropy tensor ($\mathrm{K}_{ij}{}^{A}$). Richard's equation for two-dimensional flow as used in HYDRUS-2D becomes:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[\mathrm{K}\left(\mathrm{K}_{ij}^{A}\frac{\partial h}{\partial x} + \mathrm{K}_{ij}^{A}\right)\right] - S \tag{59}$$

2.5.3 Unsaturated Hydraulic Conductivity Estimation

In order to solve (59) a relationship of the hydraulic conductivity (K) and soil water content (θ) (or soil water potential (h)) must be specified. Several analytical functions have been proposed for this purpose (Gardner (1959), Brooks and Corey (1964)). Problems that exist with some of these functions are that discontinuities exist in the hydraulic conductivity-soil water content relationship thereby making numerical solution difficult (van Genuchten, 1980) or that they inadequately define the θ-h (or soil water retention curve) relationship. HYDRUS-2D uses a set of closed form equations proposed by van Genuchten (1980) which provides a reliable soil water retention function and is free of discontinuities in both the retention curve and the conductivity-soil water content relationship.

Using pore-size distribution model of Mualem (1976a), van Genuchten established the following closed-form equation for the relative hydraulic conductivity (K_r):

$$K_r = S_e^{\frac{1}{2}}\left[1-\left(1-S_e^{\frac{1}{m}}\right)^m\right]^2 \tag{60}$$

where, S_e is the effective or relative saturation and is given by:

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r} \tag{61}$$

where, θ is the actual volumetric water content (cm^3/cm^3), θ_r is the residual soil water content and θ_s is the saturated soil water content.

m, in equation (60) is a shape parameter. In order to obtain m a pore-size model and a θ-h retention relationship must be specified. van Genuchten (1980) recommended using the Mualem (1976a) model which gives $m = 1-1/n$ where n is a dimensionless shape parameter of the following θ-h retention function:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} \tag{62}$$

where, α is the reciprocal of the air entry pressure (1/cm).

2.5.4 Initial and Boundary Conditions

Initial conditions required by HYDRUS-2D are time and length units, duration of simulation, soil profile geometry, initial soil water tensions and soil water retention and hydraulic conductivity parameters as presented in Section 2.5.3. A choice of rectangular or general (i.e. triangular) finite element geometry is also required. A rectangular geometry afforded the ease of importing gridded, soil water monitoring data and was ultimately chosen.

Three types of boundary conditions are commonly prescribed in numerical models; the first-type (Dirichlet) condition, the second-type (Neumann) condition and the third-type (Cauchy) (McCord, 1991). First-type boundary conditions are when the boundary is prescribed with a specific pressure head, either constant or time-varying. Second-type conditions occur when the boundary is initialized as a prescribed pressure gradient and third-type conditions consist of a combination of the two. HYDRUS-2D utilizes first-type and second-type boundary conditions as well as an extension of second-type boundary conditions known as a specified flux. McCord (1991) contends that in the case of unsaturated flow, the specified flux boundary condition differs from a second-type boundary condition. This is because the flux is dependent not only on the hydraulic gradient across the boundary, but also on state of the boundary or nodal pressure head, which directly affects the local hydraulic conductivity. Simunek et. al (1994) acknowledge this but remands that the "specified flux" boundary condition is common terminology in hydrology. The specific boundary conditions used will be discussed later in the Methods section. (Section 3.7)

2.5.5 Root Water Uptake Function

The study of soil moisture depletion by plants is generally performed on either microscopic or macroscopic scales. Microscopic studies evaluate root water uptake soil water depletion patterns around single roots. Macroscopic methods generally define a bulk root zone distribution and determine root water uptake from this zone. Both methods use physically based flow equations that are conservative in mass and energy. Macroscopic methods have the advantage of allowing entire plant or multiple plant systems to be simulated. HYDRUS-2D utilizes a macroscopic parameterization scheme to determine root water uptake.

The root water uptake function used in HYDRUS-2D was formulated by Feddes et. al (1974). Root water uptake is defined as the bulk water withdrawal from the soil represented by a volumetric sink term, S, as given in equation (59) with units of cm^3/cm^3/day or simply day^{-1}. S then becomes the unit rate of water withdrawal and is related to the actual plant transpiration (T_{act}) by:

$$T_{act} = \int_{z=0}^{z=L_r^{eff}} S dz \tag{63}$$

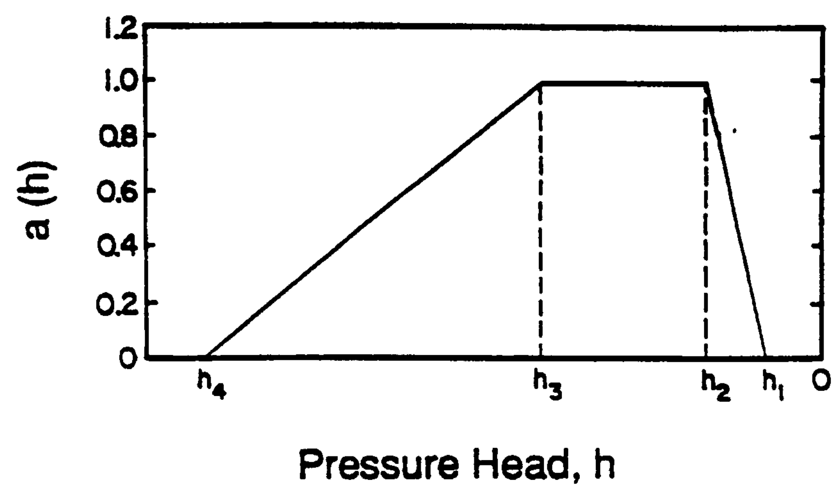
where L_r^{eff} is the length of the "effective" rooting depth. The effective rooting depth may be calculated by:

$$L_r^{eff} = L_r - L_r^{na} \qquad (64)$$

where L_r is the total rooting depth and L_r^{na} is the depth of non-active roots (Feddes et. al, 1978).

The sink term S is not a constant but a function of the pressure head of the soil. This function attempts to describe the effects of decreasing water availability on the actual transpiration rate of the plant. The shape of S is given by Figure 2.5.5.1.

Figure 2.5.5.1 (Reproduced from Simunek et al., 1994)



The horizontal axis of Figure 2.5.5.1 is the soil water pressure head and the vertical axis is the dimensionless relative root water uptake parameter $\alpha(h)$ which ranges from 0 to 1. The shape of the S function is provided by (65) and (66) such that when the soil water pressure head is between h_2 and h_3 $\alpha(h)$ is equal to 1 and the sink term is maximized ($=S_{max}$). When $S(h)=S_{max}$ plant transpiration will proceed at the potential rate, T_{pot}. When the soil water pressure head is less than h_3 but greater than h_4, $\alpha(h)$ decreases linearly to zero by equation (66).

$$S(h) = S_{\max} \qquad h_2 \geq h \geq h_3 \qquad (65)$$

$$S(h) = S_{\max}\frac{h - h_4}{h_3 - h_4} \qquad h_3 \geq h \geq h_4 \qquad (66)$$

where, h_4 is the plant wilting point. h_1 is known as the anaerobiosis point and represents the point at which transpiration ceases due to root asphyxiation caused by an overly saturated root zone.

Once h_1, h_2, h_3, h_4 have all been defined $\alpha(h)$ becomes:

$$\alpha(h) = \frac{S(h)}{S_{\max}} \qquad (67)$$

Inserting (67) into (63) T_{act} becomes:

$$T_{act} = \int_{z=0}^{z=L_r^{eff}} \alpha(h) S_{\max}\, dz \qquad (68)$$

S_{max} may be solved for by setting $\alpha(h) = 1$ and integrating (68) to yield

$$S_{\max} = \frac{T_{pot}}{L_r^{eff}} \qquad (69)$$

Equation (86) represents the potential root water uptake from a one-dimensional root zone. The two dimensional form of (69) used in HYDRUS-2D is given by:

$$S_{\max} = b(x,z) L_t T_{pot} \qquad (70)$$

where, L_t is the length of the transpiring surface and b(x,z) is a function that determines the two dimensional distribution of roots:

$$b(x,z) = \frac{b'(x,z)}{\int_{\Omega} b'(x,z)d\Omega} \tag{71}$$

where, Ω is the region occupied by the root zone and b′ (x,z) is the user-defined distribution function which is the relative intensity of root water uptake on a scale from 0 to 1. Combining (66), (69) and (70) the actual root water uptake function becomes:

$$S(h,x,z) = \alpha(h,x,z)b(x,z)L_t T_{pot} \tag{72}$$

In order to solve (72) a value for the potential transpiration (T_{pot}) must prescribed. T_{pot} may be calculated by:

$$T_{pot} = ET_{pot} - ET_{soil} \tag{73}$$

where, ET_{pot} is the potential evapotranspiration and ET_{soil} is soil evaporation. ET_{pot} may be calculated using many of the standard evapotranspiration estimating methods, though each method may yield somewhat different results. (Penman (Wright, 1995). E_{soil} may be calculated by a similar energy balance method proposed by Ritchie (1972):

$$E_{soil} = \frac{\Delta}{\Delta + \gamma} R_n e^{-.39(LAI)} \tag{74}$$

where all variables have been described earlier. From (74) it can be seen that as leaf area index, *LAI*, increases E_{soil} decreases logarithmically. This means that E_{soil} plays a much less significant role in determining T_{pot} in closed canopies.

2.5.6 Soil Water Retention Parameter Optimization

In order to accurately simulate water movement in the soil using a numerical simulation model, required physical parameters must be accurately defined. Spatial variability in soils inhibits the definition of all physical parameters at all locations in the field however. Mean values of the water flow parameters discussed in Sections 2.1 through 2.6 could provide adequate estimates for simulation purposes provided no large discontinuities in soil physical characteristics exist between sites being simulated. For this exercise, it was assumed that the soils at each monitoring site were similar. This was not actually the case but due to a lack of extensive soil physical characterization the similarity assumption was required.

A lack of extensive soils data required to make reliable mean value parameter estimates, soil water flow parameters were optimized using the HYDRUS-2D simulation model. Error surfaces in a two-dimensional parameter plane should yield both global minima from which estimates of parameters may be taken. Both Simunek and van Genuchten (1997) and Gribb (1996) have utilized error surfaces in two-dimensional parameter planes to optimize values of α, n, K_{sat}, θ_s and θ_r. In both cases error surface optimization procedures were used as a means assessing the value of an analytical method of parameter estimation. Analytical methods are generally sought as they provide a single solution while the creation of error surfaces using a simulation model such as HYDRUS-2D requires a large number of simulations to be executed in order to obtain error quantities for a range of parameters values.

The creation of error surfaces to locate minima does provide a relatively robust method of obtaining good estimates of parameters. Problems do occur when the error surfaces do not yield minima. Such occurrences indicate either the range of parameters evaluated is not large enough or that other parameters, processes or assumptions are contributing to the error. When no minima can be found, alternative methods of parameter optimization should be sought. The quantification of error used to create the error surfaces in this analysis is presented in Section 2.5.7.

2.5.7 Tests for HYDRUS-2D Validation

Model error was assessed on the ability to maintain a volumetric water balance with field measured values and the ability replicate soil water distributions. Soil water content for each grid cell were summed, Eq. 75, for the entire profile at the end of each week of simulation. Simulated totals were compared to the observed soil water totals taken from the following observation period.

$$Volume_{sim,meas} = \sum_{j=1}^{41}\sum_{i=1}^{61}\left(\theta_{i,j}(x)(y)\right) \qquad (75)$$

where, $\theta_{i,j}$ is the volumetric water content of a particular grid cell (i,j) and 41 and 61 are the predetermined number of grid cells in the y and x dimensions, respectively.

The error in the soil water distribution will be quantified by the mean bias error (*MBE*) and the mean absolute error (*MAE*) as described in Mahdian and Gallichand (1996). The *MBE*, equation (76), is an indicator of the model bias and should be approximately equal to zero when simulated values are close to observed values. Negative values of MBE indicate a spatial underestimation of soil water content while positive values indicate an overestimation. *MAE* (77) provides an absolute measure of the error and should approach zero with increasing accuracy and less bias.

$$MBE = \frac{\sum_{j=1}^{41} \sum_{i=1}^{61} \left(\theta_{s(i,j)} - \theta_{m(i,j)}\right)}{61 * 41} \tag{76}$$

$$MAE = \frac{\sum_{j=1}^{41} \sum_{i=1}^{61} \left|\theta_{s(i,j)} - \theta_{m(i,j)}\right|}{61 * 41} \tag{77}$$

where, $\theta_{m(i,j)}$ is the measured variable and $\theta_{s(i,j)}$ is the simulated variable n is the number of observations.

3. Data and Methods

3.1 Site Description

Trees on the Potlatch farm are separated by phases. The term phase denotes the succession of planting dates in the variable-aged stands of trees. By convention, Phase 1 is the oldest tree strand and Phase 4, the final group included in this analysis, is the youngest tree stand. Table 3.1.1 lists the stands of trees under which soil water monitoring occurred as described in Section 1.2.1. Included in Table 3.1.1 are the hybrid, clonal number, average bud flush and bud set dates, and estimated leaf area index (LAI).

Hybrid, clonal number, planting date and average bud flush and set data in Table 3.1.1 were provided by farm managers at Potlatch. LAI was estimated using the Sunfleck Ceptometer. The Sunfleck Ceptometer consists of 80 light sensors uniformly spaced along a 1 m long probe. The sensor provides an average reading from all the sensors. Measurements were made according to a method prescribed by Long (1997, personal communication). Measurements of below canopy light were made at evenly spaced distances, along transects underneath the canopy. Transects ran both parallel and perpendicular to the rows of trees. Each sampling point consisted of 24 measurements made below the canopy, while turning the probe in a clockwise fashion. There were 50 sampling locations in each phase so that the total number of below canopy light measurements in each phase was 96,000 (= 80x24x50).

Table 3.1.1 Transect Site Description

Site	Hybrid	Planting Date	Clonal #	Average LAI	Av. Bud Flush	Av. Bud Set	Leaf Drop
P1T1	TxD	April-94	58-280	6.7	Apr. 1-8	Sept. 14-24	1 mo. after irr. q
P1T2	TxD	April-94	50-197	6.8	Apr. 1-8	Sept. 14-24	1 mo. after irr. q
P2T1	DxN	April-95	OP-367	6.3	Apr. 7-14	Sept. 1-7	1 mo. after irr. q
P2T2	TxD	April-95	50-194	n/a	Apr. 1-8	Sept. 14-24	1 mo. after irr. q
P3T1	TxD	April-96	50-197	2.3	Apr. 1-8	Sept. 14-24	1 mo. after irr. q
P3T2	DxN	April-96	OP-367	2.6	Apr. 7-14	Sept. 1-7	1 mo. after irr. q
P4T1	DxN	April-97	OP-367	0.5	Apr. 7-14	Sept. 1-7	1 mo. after irr. q

Ambient light measurements were also made outside of the canopy. These measurements were taken at the same time as the in-canopy measurements at an interval of 1 per minute until all in-canopy measurements had been made. Both in-canopy and ambient light measurements were averaged separately and LAI was computed as the ratio of average ambient light to the average in-canopy light.

3.2 Data Collection

3.2.1 Soil Water Content

Soil water data were collected from soil water monitoring transects described in Section 1.2.1. Soil water monitoring transects are ten feet long and consist of six neutron probe access tubes spaced two feet apart between two trees located along emitter lines. Each tube is five feet deep and measurements were taken at 30.48 cm (1 ft) depth intervals and at 60.96 cm (2 ft) horizontal intervals. Each transect consisted of 30 sampling points with the exception of Phase 2 Transect 1 (P2T1) which spanned 6.1 m (20ft) and contained 55 sampling points. Soil water measurements were taken once a week during the irrigation season, which typically lasted from April 1 to October 15^{th}.

Volumetric water content was calculated from the following linear calibration equation provided by IRZ Consulting:

$$\theta = a + n \cdot b \tag{78}$$

where a and b are the intercept and the slope of calibration equation and have the following values:

$$a = .315354$$

$$b = 0.0001669$$

θ is the estimated soil water content (cm^3/cm^3) and n is the mean neutron count rate ratio which is equal to the mean neutron count rate at the sampling depth divided by the mean count rate of a known standard material such as water or paraffin.

A total of seven different monitoring transect were used in the analysis. Phases I, II and III each have two soil water monitoring transects. Phase IV had only one monitoring transect due to a shift in management objectives.

Throughout the four years of soil-water monitoring (1994-1997), two weeks occurred (July 15, 1997 and July 29, 1997) when the primary neutron probe was out of operation. A substitute probe was employed during these two weeks. The substitute probe had different calibration coefficients of 0.000178 and 0.500497 for a and b, respectively. No analysis was performed to determine the error created by using the substitute probe.

Measurements were made on a weekly basis beginning at the onset of irrigation. This occurred around the end of March or early April and corresponded with tree bud flush. Bud flush is the time at which new leaf growth emerges from the protective winter bud. Monitoring continued until irrigation ceased in mid-October. Actual leaf drop generally did not occur until a month after irrigation ceased.

3.2.2 Discussion of Error in Neutron Probe Measurements

Estimates of volumetric soil water content ($\hat{\theta}$) using the neutron probe as given by Vandervaere et al. (1994a) are obtained by the following linear equation:

$$\hat{\theta} = \hat{a} + \hat{b} \cdot \hat{n} \qquad (79)$$

where $\hat{a}$ and $\hat{b}$ are, respectively, estimates of the intercept and the slope of the regression line and $\hat{n}$ is the estimate of the count ratio between the mean count rate, $\overline{N}$, of p replications of N_i counts taken over time T in the soil and the mean count rate, $\overline{N_s}$, of q replications of N_{si} counts taken over time T_s in a standard absorber.

Estimates of regression coefficient estimates a and b, $\hat{a}$ and $\hat{b}$, respectively, are obtained as follows:

$$\hat{b} = \frac{s(\hat{n}, \dot{\theta})}{s^2(\hat{n})} \tag{80}$$

$$\hat{a} = \overline{\hat{\theta}} - \hat{b} \cdot \overline{\hat{n}} \tag{81}$$

When the total variance, $s^2(\ )$, is taken as a measure of error of the linear estimating technique in (78), the following errors in the regression coefficients, $s^2(\hat{a})$ and $s^2(\hat{b})$, are obtained:

$$s^2(e) = \frac{m-1}{m-2} \cdot \left[s^2(\hat{\theta}) - \hat{b} \cdot s(n, \hat{\theta})\right] \tag{82}$$

$$s^2(\hat{b}) = \frac{s^2(e)}{(m-1) \cdot s^2(\hat{n})} \tag{83}$$

$$s^2(a) = s^2(\hat{b}) \cdot \overline{n}^2 \tag{84}$$

$$s(\hat{a}, \hat{b}) = -s^2(\hat{b}) \cdot \overline{\hat{n}} \tag{85}$$

where $s^2(e)$ is the stochastic disturbance error, m is the number of data pairs ($\hat{n}$, $\hat{\theta}$) used in the regression analysis and $s(\hat{a}, \hat{b})$ is the estimated covariance between $\hat{a}$ and $\hat{b}$.

There are significant errors in estimating soil water content, changes in soil water content and evapotranspiration with the neutron probe due to the instrument, the calibration procedure and spatial variability of soil moisture. Sinclair and Williams (1979) analyzed instrument, calibration and location variances over a field. Haverkamp et al. (1984) estimated the total variance of soil water storage from a local standpoint by taking into account the method of integration used. The error in estimating actual evapotranspiration was analyzed from a local standpoint by Vandervaere et al. (1994a) and from a spatial standpoint by Vandervaere et al. (1994b) by encompassing errors associated with the instrument, the calibration procedure, the vertical integration technique and spatial variability. Since the estimates of consumptive use of hybrid poplars discussed in this paper were obtained by combining estimates from different locations and different growing seasons the spatial standpoints of error will be discussed here.

3.2.2.1 Estimation of error from a spatial standpoint

Averaging data from, *k*, sampling points can provide spatial estimates of $\hat{\theta}$, $\hat{S}$ and $\hat{ET}$. When spatial averaging is performed location error must be accounted for. Location error is caused by soil heterogeneity so that one measurement is rarely representative of an entire field (Sinclair and Williams, 1979; Vandervaere et al., 1994b). Assuming that the variance is a measure of the error of a specified parameter, Vandervaere et al. (1994b) analyzed the variance of $\langle\hat{\theta}\rangle$, $\langle\hat{S}\rangle$ and $\langle\hat{ET}\rangle$ from a spatial standpoint and determined the following relationships:

$$s^2\left(\langle\hat{\theta}\rangle\right) = s_I^2\left(\langle\hat{\theta}\rangle\right) + s_C^2\left(\langle\hat{\theta}\rangle\right) + s_L^2\left(\langle\hat{\theta}\rangle\right) \quad (86)$$

$$s^2\left(\langle\hat{S}\rangle\right) = s_I^2\left(\langle\hat{S}\rangle\right) + s_C^2\left(\langle\hat{S}\rangle\right) + s_{\text{int}}^2\left(\langle\hat{S}\rangle\right) + s_L^2\left(\langle\hat{S}\rangle\right) \quad (87)$$

$$s^2\left(\left\langle \hat{ET}\right\rangle\right) = s_I^2\left(\left\langle \hat{ET}\right\rangle\right) + s_C^2\left(\left\langle \hat{ET}\right\rangle\right) + s_{\text{int}}^2\left(\left\langle \hat{ET}\right\rangle\right) + s_L^2\left(\left\langle \hat{ET}\right\rangle\right) \quad (88)$$

where the I, C, int and L subscripts represent the instrument, calibration, integration and location components of the total variance, respectively.

Sinclair and Williams (1979) developed a statistical formulae for estimating the total variance of the average volumetric water content, $s^2\left(\langle\hat{\theta}\rangle\right)$:

$$s^2\left(\langle\hat{\theta}\rangle\right) = s^2(\hat{a}) + \left[\hat{b} - s(\hat{b})\right]s^2\left(\langle\hat{n}\rangle\right) + \langle\hat{n}\rangle^2 \cdot s^2(\hat{b}) + 2\langle\hat{n}\rangle \cdot s(\hat{a},\hat{b}) \quad (89)$$

where:

$$s^2\left(\langle\hat{n}\rangle\right) = \frac{1}{k}s^2(\hat{n}) \quad (90)$$

and by definition $s^2(\hat{n}) = \frac{1}{k-1}\sum_{j=1}^{k}\left(\hat{n}_j - \langle\hat{n}\rangle\right)^2$. When the components $s_I^2\left(\langle\hat{\theta}\rangle\right)$ (Eq. 91) and $s_C^2\left(\langle\hat{\theta}\rangle\right)$ (Eq. 92) from Eq. (86) are computed, it is possible to solve for the location error by combining Eqs. (89) and (86) and solving for $s_L^2\left(\langle\hat{\theta}\rangle\right)$.

$$s_I^2\left(\langle\hat{\theta}\rangle\right) = \left[\hat{b}^2 - s^2(\hat{b})\right]\left[\frac{\langle n\rangle}{p \cdot T} + \frac{\langle n\rangle^2}{p \cdot T_s}\right]\frac{1}{k\hat{N}_s^2} \quad (91)$$

$$s_C^2\left(\langle\hat{\theta}\rangle\right) = s^2(\hat{a}) + \langle\hat{n}\rangle^2 s^2(\hat{b}) + 2\langle\hat{n}\rangle s(\hat{a},\hat{b}) \quad (92)$$

Also, if $s_L^2(\langle\hat{\theta}\rangle)$ is defined as:

$$s_L^2(\langle\hat{\theta}\rangle) = [\hat{b} - s^2(\hat{b})]\frac{s^2(L)}{kN_s^2} \tag{93}$$

then the spatial variation, $s^2(L)$ of the soil may be computed.

The components of the variance of the mean storage, $s^2(\langle\hat{S}\rangle)$, were expanded by Haverkamp et al. (1984). The calibration component of the error is given by:

$$s_C^2(\langle\hat{S}\rangle) = \left[1.5^2 s_C^2(\langle\hat{\theta}_i\rangle) + \sum_{i=2}^{f} s_C^2(\langle\theta_i\rangle) + \sum_{i=3}^{f}\sum_{i=3}^{f} s_C(\langle\hat{\theta}_i\rangle, \langle\hat{\theta}_j\rangle)\right]\Delta\zeta^2 \tag{94}$$

where, $s_C^2(\langle\hat{\theta}\rangle)$ is given in Eq. 92. and the covariance of soil moisture at 2 locations is given by:

$$s_C(\langle\hat{\theta}_i, \hat{\theta}_j\rangle) = s^2(\hat{a}) + \langle\hat{n}_i\rangle\langle\hat{n}_j\rangle s^2(\hat{b}) + (\langle\hat{n}_i\rangle + \langle\hat{n}_j\rangle)s(\hat{a}, \hat{b}) \tag{95}$$

The error introduced in the integration technique, using the trapezoidal method is

$$s_{\text{int}}^2(\langle\hat{S}\rangle) = \frac{Z_f^2 \Delta\zeta^4}{144}\max\left[\left(\frac{\partial^2\langle\theta\rangle(\zeta)}{\partial\zeta^2}\right)^2\right] \tag{96}$$

where,

$$\left.\frac{\partial^2\langle\hat{\theta}\rangle(\zeta)}{\partial\zeta^2}\right|_{Z_i} = \frac{\langle\hat{\theta}_{i+1}\rangle - 2\langle\theta_i\rangle + \langle\theta_{i-1}\rangle}{(\Delta\zeta)^2} \qquad (i = 2 \text{ to } f - 1) \tag{97}$$

If the instrument error is given by

$$s_I^2(\langle\hat{S}\rangle) = \left[1.5^2 s_I^2(\langle\hat{\theta}_1\rangle) + \sum_{i=2}^{f} s_I^2(\langle\hat{\theta}_i\rangle)\right]\Delta\zeta^2 \tag{98}$$

and the sum of the instrument and location components of the error, by application of the Central Limit Theorem to the estimated mean storage $\langle \hat{S} \rangle$, is given by

$$s_{I,L}^2\left(\langle \hat{S} \rangle\right) = \frac{1}{k} s^2\left(\hat{S}\right) = s_I^2\left(\langle \hat{S} \rangle\right) + s_L^2\left(\langle \hat{S} \rangle\right) \tag{99}$$

then the location error may be solved by substituting (98) into (99) and solving for $s_L^2\left(\langle \hat{S} \rangle\right)$.

The expansion of Eq. (88), when evaluating the error in the mean estimated ET, is similar to the expansion of Eq. (87). The calibration component may be given as:

$$s_C^2\left(\left\langle \hat{ET} \right\rangle\right) = \left[1.5^2 s_C^2\left(\left\langle \Delta\hat{\theta} \right\rangle\right) + \sum_{i=2}^{m-1} s_C^2\left(\left\langle \Delta\hat{\theta}_i \right\rangle\right) + 0.5^2 s_C^2\left(\left\langle \Delta\hat{\theta}_m \right\rangle\right)\right]\Delta\zeta^2$$

$$+ \left(Z_o - Z_m\right)^2 S_C^2\left(\left\langle \Delta\hat{\theta}_a \right\rangle\right) \tag{100}$$

where m is the number of depths of measurements of $\boldsymbol{\theta}$ and the calibration error in the estimated change in soil water content, $s_C^2\left(\left\langle \Delta\hat{\theta}_i \right\rangle\right)$, is

$$s_c^2\left(\left\langle \Delta\hat{\theta}_i \right\rangle\right) = \left[\langle \hat{n}_i \rangle(t_1) - \langle \hat{n}_i \rangle(t_2)\right]^2 \cdot s^2\left(\hat{b}_i\right) \tag{101}$$

and Zi is the depth between two measurements of *6*.

The error due to integration is given by:

$$s_{\text{int}}^2\left(\left\langle \hat{ET} \right\rangle\right) = \frac{Z_{m+1}^2 \Delta\zeta^2}{144} \max\left[\left(\frac{\partial^2 \left\langle \Delta\hat{\theta} \right\rangle(\zeta)}{\partial\zeta^2}\right)^2\right] \tag{102}$$

where

$$\left.\frac{\partial^2\left\langle\hat{\Delta\theta}\right\rangle(\zeta)}{\partial\zeta^2}\right|_{Z_i} = \frac{\left\langle\hat{\Delta\theta}_{i+1}\right\rangle - 2\left\langle\hat{\Delta\theta}_i\right\rangle + \left\langle\Delta\theta_{i-1}\right\rangle}{(\Delta\zeta)^2} \qquad (\text{ i} = 2 \text{ to m}) \qquad (103)$$

The instrument error in the ET estimate is

$$s_I^2\left(\left\langle\hat{ET}\right\rangle\right) = \left[1.5^2 s_I^2\left(\left\langle\hat{\Delta\theta}_i\right\rangle\right) + \sum_{i=2}^{m-1} s_I^2\left(\left\langle\Delta\theta_i\right\rangle\right) + 0.5^2 s_I^2\left(\left\langle\hat{\Delta\theta}_m\right\rangle\right)\right]\Delta\zeta^2$$

$$+ (Z_o - Z_m)^2 s_I^2\left(\left\langle\hat{\Delta\theta}_a\right\rangle\right) \qquad (104)$$

where the instrument error in the estimated change in soil water content, $s_I^2\left(\left\langle\hat{\Delta\theta}_i\right\rangle\right)$,

is:

$$s_I^2\left(\left\langle\hat{\Delta\theta}_i\right\rangle\right) = \hat{b}^2\left[\frac{\langle\hat{n}_i\rangle(t_1) + \langle\hat{n}_i\rangle(t_2)}{p \cdot T} + \frac{\langle\hat{n}_i\rangle^2(t_1) + \langle\hat{n}_i\rangle(t_2)}{q \cdot T_s}\right]\frac{1}{kN_s} \qquad (105)$$

and t1 and t2 are two different times. As in Eq. (99), when the Central Limit Theorem is applied to the estimate of the mean ET the combined instrument and location error becomes

$$s_{I,L}^2\left(\left\langle\hat{ET}\right\rangle\right) = \frac{1}{k}s^2\left(\hat{ET}\right) = s_I^2\left(\left\langle\hat{ET}\right\rangle\right) + s_L^2\left(\left\langle\hat{ET}\right\rangle\right) \qquad (106)$$

where

$$s^2\left(\hat{ET}\right) = \frac{1}{k-1}\sum_{j=1}^{k}\left(\hat{ET} - \left\langle\hat{ET}\right\rangle\right)^2 \qquad (107)$$

The location error component may then be solved for by substituting (105) into (106).

The most significant component of the total variance for each estimate was the location component as determined by Vandervaere (1994b). Both $s_L^2\left(\left\langle\hat{S}\right\rangle\right)$ and $s_L^2\left(\left\langle\hat{ET}\right\rangle\right)$ are functions of the number of sampling points, *k*, and their respective local variances (Eqs. 99 and 106). An inverse relationship exists between *k* and the location error, therefore, increasing *k* will decrease the variance due to location to an asymptotic limit. Just what the value of *k* should be for a given field is dependent on the soil heterogeneity of the field. Vandervaere et al. (1994b) suggest increasing the value of *k* until the magnitude of the error due to location becomes less than the magnitude of the error due to another component which for $s^2\left\langle\hat{\theta}\right\rangle$ was the calibration error $s_C^2\left(\left\langle\hat{\theta}\right\rangle\right)$ and for $s^2\left\langle\hat{S}\right\rangle$ and $s^2\left\langle\hat{ET}\right\rangle$ were the integration errors $s_{int}^2\left(\left\langle\hat{S}\right\rangle\right)$ and $s_{int}^2\left(\left\langle\hat{ET}\right\rangle\right)$, respectively. $s^2\left\langle\hat{ET}\right\rangle$ may be further reduced by increasing the number of repetitions of count, *p*, because the instrument error is the second largest component of the total error. It has not been shown, however, whether or not the analysis of Vandervaere et al. (1994b) holds true for all soils.

3.2.2.2 Conclusions of error discussion for hybrid poplar ET estimates

Weekly evapotranspiration for different ages of hybrid poplar trees was estimated using a soil water balance method where the weekly change in soil water content was calculated from weekly neutron probe measurements. The measurement procedure involved taking a single neutron probe reading at each measurement depth within a monitoring transect and utilizing a single calibration equation for converting the neutron probe count ratio, $\hat{n}$, to an estimate of soil water content, $\hat{\theta}$, regardless of soil type. Assuming the magnitude of each component of error at the study site is similar to the error obtained by Vanservaere et al. (1994b), substantial errors will be present in the procedure used to estimate weekly ET and crop curves. It was impossible to compute actual values of the component errors due to the lack of access to calibration data. A qualitative discussion can be formulated, however, that should provide insight to the accuracy of the analysis.

Since estimates of weekly ET from different sites were combined to create a single estimate, the error in the ET estimate is dominated by the location error as discussed previously. The location error in the ET estimates for a specific year of growth will also vary between different age classes. This is so because a different number of sampling locations, k, were available for analysis depending upon the year of growth which is a function of the crop rotation. 1 year old estimates were made from 7 different sites using 4 years of data, 2 year old estimates were made using 6 sites for 3 years and 3 year old estimates were made using 4 sites for 2 years. Therefore, for each older year of growth, the location component of the total error increases. This means that the estimates of the weekly ET and the crop curves should have a higher degree of uncertainty in the older stands of trees.

Instrument error will be significant since only one replication of readings was taken at each sampling point. Increasing the number of count replications (p) and/or the number of readings per replication would have decreased the total variance in each ET estimate as described above (See Eq. 105). There may also be contribution to the total error from the calibration component, caused by the uncertainty in the estimate of the calibration equation slope, $\hat{b}$, and the intercept, $\hat{a}$.

3.2.3 Irrigation and Rainfall

Farm managers provided weekly irrigation quantities. The weekly depth of irrigation (I) was determined by dividing the volume (V) of water flowing into an irrigation block by the irrigated acreage (A_{irr}) in the block.

$$I = \frac{V}{A_{irr}}$$

Irrigated acreage was determined by subtracting the total area of the non-irrigated zones within each block from the total area of the block.

Rainfall or precipitation (P) was measured weekly in open "catch-can" type gages located near but not at soil water monitoring sites. The gages contained a layer of oil to prevent rainfall from evaporating. Generally, 2-5 gages were located within each phase depending on the amount of planted acreage within each phase. Rainfall at a soil water monitoring transect was reported as the rainfall measured at the nearest gage.

3.3 Soil Water Balance Computation

Weekly soil water monitoring data were input into the graphical display program Transform (Fortner Research, LLC, 1996) for the purposes of interpolation, matrix analysis and display. Point soil water content estimates were interpolated into a continuous two-dimensional soil water profile using a two-dimensional linear interpolation technique.

Two-dimensional interpolation was performed to remove the bias that occurs in one-dimensional interpolation resulting in non-representative streaking of soil water content. Standard linear interpolation was performed in both the x- and z-dimensions and the resulting two matrices were averaged together. The final matrix had 61 vertical columns, 41 horizontal rows and a total of 2501 cells. Each cell had dimensions of 4.997 (cm) x 1 (cm) x 3.72 (cm) for the x, y and z dimensions, respectively. A typical interpolated soil-water monitoring transect is given in Figure 3.3.

Each week the depth of soil water (*SM*) contained in each transect was computed by the following equation:

$$SM = \left(\sum_{z=1}^{41} \sum_{x=1}^{61} \theta_{i,j} \right) \left(Volume_{cell} \right) \left(\frac{1}{L \cdot W} \right) \tag{110}$$

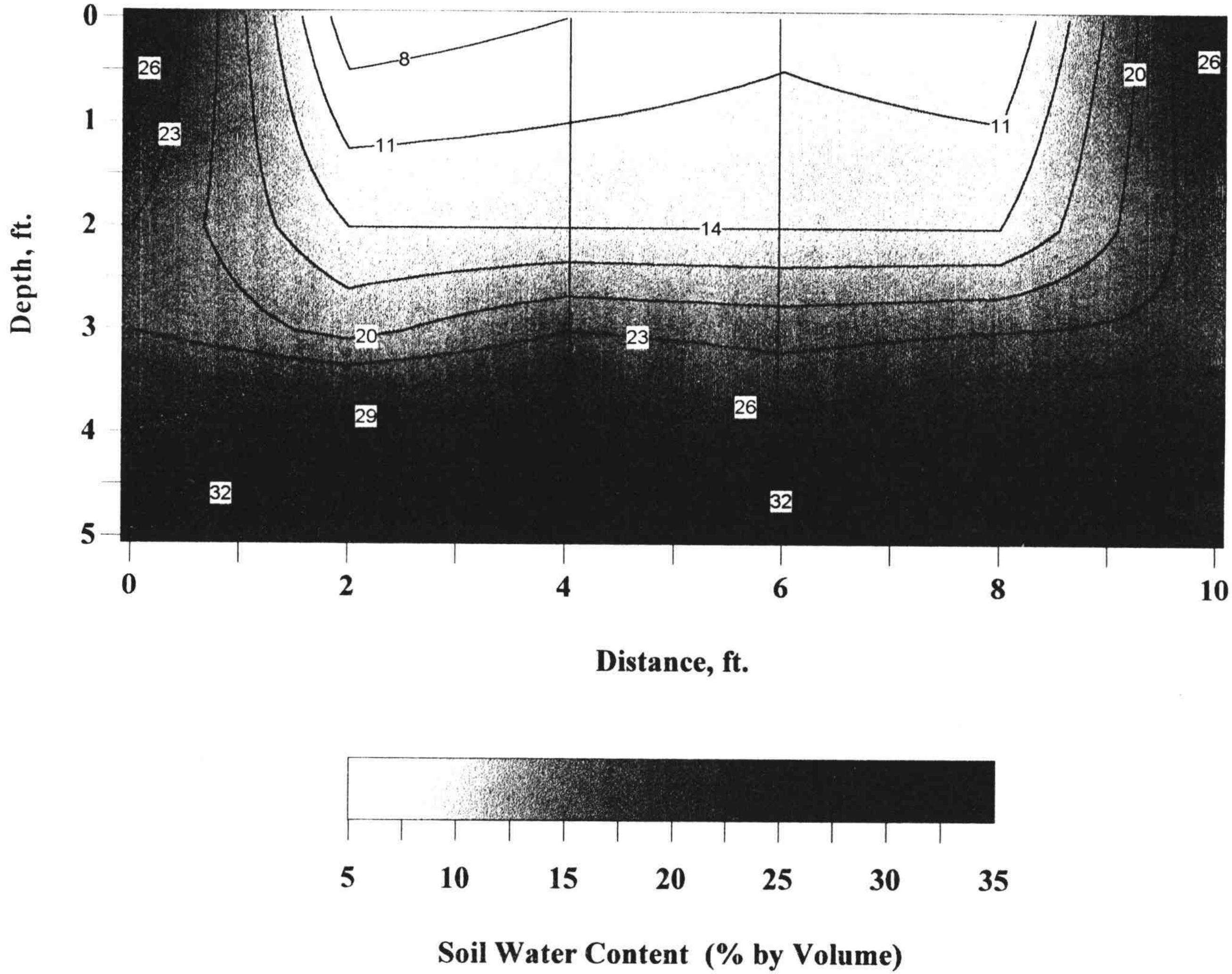
where, $\theta_{i,j}$ is the volumetric water content of the cell (i,j), *W* is the width of each cell (=1), *L* is the length of the transect (cm), and $Volume_{cell}$ is volume of a unit width cell equal to 18.57 cm^3.

Weekly ET was determined by the soil water depletion method described in Jensen et al. (1990). Assuming no lateral flux of water occurred into the monitoring transects, the following equation was used as the water balance equation:

$$ET + D = P + I + \Delta SM = P + I + \sum_{j=1}^{41} \sum_{i=1}^{61} (\theta_1 - \theta_2)_{i,j} \left(Volme_{cell} \right) \left(\frac{1}{L \cdot W} \right) \tag{111}$$

where, *I* is the amount of irrigation per week, *P* is the measured weekly precipitation, drainage, *D*, is the amount of water draining to the lower soil profile and ΔSM is the change in soil moisture from two consecutive weeks.

Figure 3.3 Phase 2 - Transect 2 - Royal 22-Jul-97



3.4 Preliminary Estimation of Significant Drainage

Often the soil water depletion (or balance) method assumes that there is no drainage from the profile (i.e. $D = 0$). This is because drainage is difficult to measure. Since this assumption could not always be met, it was necessary to determine which transects had significant drainage occurring. Drainage was estimated for each week by estimating the flux of water through the lowest five layers of soil. The flux was estimated for each vertical column of the interpolated transect.

Equation (112) was used for the initial estimation of drainage:

$$q_i = K_i(h)\frac{dH_i}{dz} \tag{112}$$

where, q is the vertical flux of water from column (i) (cm/day), $K_i(h)$ is the average unsaturated hydraulic conductivity for the lowest five rows of the interpolated soil profile, and dH_i/dz is the hydraulic gradient, where $H = h + z$ and h is the soil matric potential. The unsaturated hydraulic conductivity and soil water retention functions of van Genuchten (1980) as described in Section 2.5.3 were used in the solution of Eq. (112).

The estimated weekly drainage was compared to the calculated weekly $ET+D$ from Eq. (111). If the drainage from a particular column was found to be greater than or equal to 10% of the calculated $ET+D$ then it was concluded that significant drainage was occurring and that $ET+D$ estimate was discarded from the analysis. If the estimated drainage was less than 10% of the calculated $ET+D$ then it was assumed no drainage was occurring and D was set equal to 0 (i.e. the transect was at steady-state).

3.5 Removal of ET Estimates Biased By Precipitation

Due to the large scale of the irrigation project, spatial variation of precipitation was considered when determining the soil water balance. Occasionally, more water was accumulated in the soil profile than was applied. In effect:

$$|\Delta SM| > I + P \qquad \text{for:} \quad \Delta SM < 0 \tag{113}$$

Neglecting drainage Eq. (113) results in negative ET values, which are physically impossible. Negative ET estimates were calculated only around weeks with significant rainfalls. It was concluded that the point estimates of precipitation, often taken at distances up to a kilometer from the monitoring site, did not always represent the actual precipitation received on a monitoring transect. These transects were discarded from the ET analysis.

Another problem occurred during weeks following relatively heavy precipitation events. In some weeks there was a large reduction in soil moisture (i.e. ΔSM >>0). This resulted in a local overestimation of ET. The overestimation was caused by the inclusion of soil evaporation in the computation procedure. Though not physically unrealistic, the locally overestimated ET values are not useful in the determination of average seasonal hybrid poplar ET values and hence those weeks were discarded from the analysis.

It was impractical to attempt to separate the effects of soil evaporation from the crop coefficient estimates as outlined in Section 2.4.3. This was because the measurement of precipitation was not performed on a daily basis. Without daily precipitation data it would be impossible to calculate the ET contributions of the soil surface as in Eq. 73. Therefore the crop coefficients presented in this work are average or mean crop coefficients.

3.6 Crop Curve Determination

The soil water balance analysis procedure outlined in Section 3.3 was repeated for all ages of trees for the 1994 through 1997 irrigation seasons. Weekly crop coefficients for transects not possessing significant drainage were estimated by dividing the weekly calculated ET provided by equation (111) (where $D = 0$) by the weekly reference ET (Eq. 114). Reference ET was obtained at the Boardman, OR. AGRIMET weather station (HERO), which is located approximately 5 mi. from the Poltatch farm. (Latitude: 45.47.56, Longitude: 119.31.46, Elevation: 600'):

$$K_c = \frac{ET_{crop}}{ET_{ref}} \qquad (114)$$

Alfalfa-based reference ET was calculated by the Kimberely-Penman equation (Wright, 1982) using daily meteorological data taken over fallow sections in the corners of center pivot blocks. Daily values were summed to provide weekly values of reference ET. Weekly crop coefficient values were then plotted against time to yield seasonal crop curves. The crop curve will therefore provide ET estimates of a certain age of hybrid poplar tree as a factor of the reference crop. The crop curve estimates presented are mean crop coefficients. Soil water content was managed to be approximately near field capacity and surface evaporation is likely to be negligible under drip irrigation except in the early season estimates of 1 year old trees.

A continuous mathematical function was regressed through the weekly crop coefficients using Table Curve 2-D (Jandel). This was done so that a crop coefficient may be calculated given the specified week of the growing season. A second-degree polynomial or quadratic was chosen to represent the data. This function provided a general shape representation of the time distribution of the crop coefficients while remaining relatively simple in mathematical form.

3.7 Soil Water Retention Parameter Estimation and Irrigation Simulation

Particle size and soil water retention data were obtained from soil cores extracted from the field in the summer of 1995. Soil cores were analyzed by soil scientists at the Oregon State University Soil Physical Characterization Lab within the Department of Crop and Soil Sciences. Soils were characterized as sands and loamy sands with an average composition of 89.7% sand, 6.0% silt and 4.3% clay. The mean saturated water content from 24 samples was 40.3 ± 4.5 cm^3/cm^3. The mean residual water content was 5.0 ± 2.4 cm^3/cm^3. Residual water content was taken as the soil water content at 15 bar tension value.

Saturated hydraulic conductivity (K_{sat}) was measured by tension infiltrometer and by core analysis. The method for determining K_{sat} from tension infiltrometer is given by Hussen and Warrick (1993). Tension infiltrometer estimates of K_{sat} were taken only at the surface. The mean value for 74 tests of surface K_{sat} was 31.4 ± 31.0 cm/day . Laboratory determined K_{sat} from six of the cores had a mean value of 5.7 ± 5.1 cm/day. K_{sat} was not determined on other cores. The coefficients of variation, 0.98 and .91 for tension infiltrometer and laboratory determinations of

K_{sat}, respectively, indicate a high degree of variability in K_{sat}. A value of 16 cm/day was arbitrarily decided on as a representative value of K_{sat}. Given the large variability in K_{sat} error in this approximation by 2-3 cm/day should not be significant.

A least squares fitting method was used to fit preliminary estimates of shape parameters n and α to the soil water retention function described in Section 2.5.3. Plots of the fitting procedure for five of the soil cores and soil water retention data are provided in the appendix (A.3). Unique values of θ_s (34.64 cm^3/cm^3) and θ_r (5.09 cm^3/cm^3) were used because these values came from a core whose laboratory determined K_{sat} value, 13 cm/day, was closest to the estimated K_{sat} of 16 cm/day. Ideally, values of θ_s, θ_r and K_{sat} should all be optimized. Optimization of these parameters was not done for several reasons. First, given the variability in measured K_{sat}, it is not expected that an optimization procedure could significantly improve its estimate. Second, it has been suggested (Kutilek and Nielson, 1994) that θ_s, and θ_r, only provide limits to the retention function and do not significantly alter the shape of the retention function compared to n and α. Third, including three more variables in the optimization procedure would greatly increase the number of simulations required to reach solutions. For example including 10 values of both θ_s and θ_r would increase the number of simulations by a factor of 100. For these reasons it was decided that n and α would be the only soil physical parameters to be optimized.

The least squares fitting procedure provided initial estimates of n (1.7) and α (0.7). n was discretized for optimization by 0.1 between 1.3 and 2. α was discretized by 0.01 between 0.05 and 0.12. Simulations were run for discretized values of α and n within these ranges. Absolute volume errors, mean biased errors and mean absolute errors discussed in Section 2.5.7 were calculated for each simulation.

A steady-state period from July 22nd to July 29th of 1997 was used for the optimization period. Initial soil water content from the Phase 2 Transect 1 monitoring transect was used for the optimization analysis. This period was free of rainfall and was late enough into the season so that drainage from the transect could be assumed equal to zero. The assumption of zero drainage was confirmed by the estimation of drainage procedure discussed in Section 3.4.

The simulation transect was initialized similar to the monitoring transect with a 61X41 grid matrix. Boundary conditions consisted of a free drainage bottom boundary, zero-flux side boundaries and a combination of an atmospherically forced and time variable top boundary. The time variable boundary surface was required to simulate drip irrigation practices. The length of the application surface was initialized as 66 cm per emitter or 33 cm per half emitter.

The application surface length was estimated by determining the radius of a cylinder that represents the volume of water applied from an emitter. The radius of the cylinder was constrained by the saturated conductivity of the soil. This was because HYDRUS-2D is incapable of simulating runoff so that the rate of water application can not exceed the saturated conductivity of the soil. Therefore, the radius represents the minimum limit of the wetted area surrounding the drip emitter assuming that all flow into the soil is under saturated conditions.

The emitter flow rate was designed to be 0.75 gallons per hour. A two-dimensional daily irrigation rate was estimated using the daily volume of irrigation from an emitter. The daily volume of applied water was assumed to have the geometry of a cylinder with a height less than or equal to the daily saturated conductivity of the soil. This assumption prevented the occurrence of runoff in the model. The radius of the cylinder could then be solved for and initialized as the application surface.

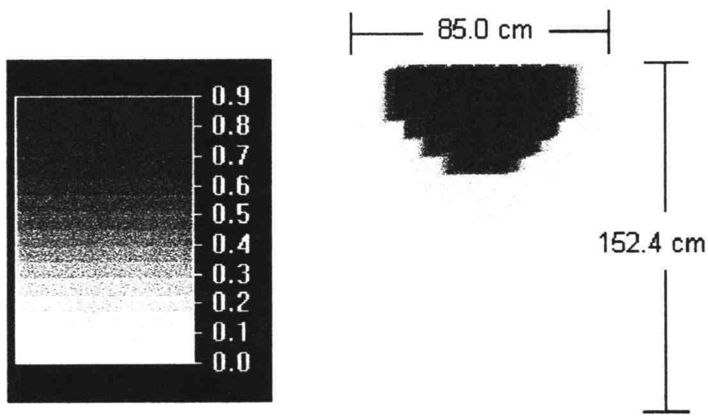
There are inherent problems with prescribing the applied water in this manner. First, water from a drip emitter rarely wets the soil surface in a near circular geometry. Usually ground slope or preferential flow causes the flow to deviate from a truly radial pattern. Second, irrigation from drip emitters is a three dimensional process. The transformation of this process to a two dimensional plane of unit width as presented here is incomplete. It was not known how to adequately transform the three-dimensional application to a two dimensional plane. Therefore, the rate of application was evaluated as one of the optimized parameters. Values of 3 cm/day, 5 cm/day and 7 cm/day were used in the optimization procedure. These numbers do not have any recognizable physical significance but merely serve as fitting parameters to the application rate since the actual two-dimensional application is unknown. Values of application rate were chosen initially by qualitative comparison of simulated versus measured soil water distributions. Farm managers provided durations of irrigation cycles.

Reference ET, obtained from the AGRIMET weather station near Boardman, OR, was input as the potential transpiration (T_{pot}) in HYDRUS 2D. The root sink function parameters described in Section 2.5.5 were prescribed with the knowledge of poplars preferring wet soil conditions. Table 3.7.1 provides estimates upper, peak and lower root sink potentials used in the simulations. The root zone distribution was initialized as in Figure 3.7.1. The root zone distribution and intensities were estimated from root zone excavations of hybrid poplars near Boardman.

Table 3.7.1

Root Water Uptake Parameters	Soil Water Tension (cm)
h1	0.001
h2	5.0
h3	200
h4	500

Figure 3.7.1 Distribution of Root Water Uptake Intensity (3 Year Old Hybrid Poplar)



Each simulation was initialized with soil water data taken on July 22, 1997 and was run for one week with estimated and optimized parameters. Results at the end of the simulation were compared with soil water observations taken on July 29, 1997. Absolute volume errors, mean biased errors and mean absolute errors discussed in Section 2.5.7 were calculated for each simulation. Error surfaces were created from the calculated errors. Minima in the error surfaces were expected to reveal the values of optimized parameters.

4 Analysis and Results

Weekly evapotranspiration (ET) estimates have been computed for 1yr. old, 2 yr. old and 3 yr. old hybrid poplar trees. ET estimates were normalized by the reference evapotranspiration (ET_{ref}) to create crop coefficients. The time distribution of crop coefficients throughout the growing season yields crop curves. Crop curves can provide reliable estimates of future plant water use thereby aiding in irrigation scheduling.

Results from the drainage criteria analysis will be presented (Section 4.1). A summary of the estimated average daily ET is provided in Section 4.2. Crop curves for three years of growth will be presented in Section 4.3. Monthly and seasonal estimated water use will also be provided (Section 4.4). HYDRUS 2-D optimized soil water retention parameters will be presented in Section 4.5.

4.1 Drainage Criteria Results

A drainage criterion was established to remove soil water balance derived ET estimates that were significantly biased by soil water drainage. The procedure for filtering is outlined in Section 3.4. The results of the filtering are shown in Table 4.1.1. 51.2% of the monitoring transects were available for overall soil water balance ET estimation. When separated into age classes it was found that 47.8% of all transects planted with one year old trees, 47.2% of all transects planted with 2 year old trees and 56.9% of all transects planted with three year old trees would be utilized in the analysis.

Table 4.1.1 Number of Transects Used in ET Calculations

Tree Age	Unfiltered	Filtered	% Used
1 yr olds	209	100	47.8
2 yr olds	176	83	47.2
3 yr olds	116	66	56.9
Total	501	249	49.7

The drainage criteria to be met in the filtering process was that the estimated drainage flux from Eq. 112 must be less than 10% of estimated ET + drainage (D) from Eq. 111. It was found that the filtering process was sensitive to both the criteria value and the value of the saturated conductivity, K_{sat}, used in Eq. 112. Halving K_{sat} from its soil core determined value of 16 cm/day to 8 cm/day reduced the number of total transects available for analysis by 20%. Conversely, increasing K_{sat} could yield more transects available for analysis. Therefore, uncertainty in the field saturated conductivity value will influence the accuracy of the drainage estimation in this analysis. Increasing the drainage criteria value above 10% would also increase the number of transects available for analysis. The drainage criteria was not increased because it was felt that drainage over 10% of the estimated ET + D would significantly affect plant water use estimates.

4.2 Weekly and Average Daily ET Results from 1994, 1995, 1996 and 1997

Weekly estimates of evapotranspiration for three years of growth of hybrid poplar trees were obtained from the soil water balance or soil water depletion technique. All transects possessing significant drainage (i.e. > 10% of ET + D) were removed from the ET determination. Transects in which precipitation occurred resulting in large soil water fluctuations also had to be removed from the analysis. Weekly estimates of hybrid poplar ET were divided by 7 to yield an estimated "average" daily ET. This was done as matter of convention in that it is customary to discuss ET estimates on a daily basis as opposed to a weekly basis. Estimated average daily hybrid poplar ET and daily measured alfalfa reference ET for the 1994, 1995, 1996 and 1997 irrigation seasons are provided in Figures 4.2.1, 4.2.2, 4.2.3 and 4.2.4, respectively. Hybrid poplar ET estimates were partitioned by year of growth for each season.

The distribution of hybrid poplar ET generally matches the distribution of alfalfa reference ET. Day to day variations in calculated reference ET were large at times. Similar variations are observed with the daily averaged estimates of hybrid poplar ET. Table 4.2.1 provides a summary of seasonal average, maximum and minimum reference and multi-age hybrid poplar ET. Seasonal average reference ET values ranged between 0.6 and 0.7 cm/day. Maximum ET_{ref} values ranged between 1.0 and 1.2 cm/day while minimum ET_{ref} values ranged from 0.1 to 0.2 cm/day. Seasonal averaged daily hybrid poplar ET values were approximately 0.3, 0.4 and 0.5 cm/day for 1 year old, 2 year old and 3 year old poplars, respectively. Seasonal averaged daily ET estimates do not provide a direct application to any specific day during the season but can help provide estimates in seasonal water planning. Seasonal maximum daily hybrid poplar ET estimates ranged from 0.4 to 0.9 cm/day for 1-3 year old trees while minimum estimates were similar reference ET minimums ranging from 0.1-0.2 cm/day.

Figure 4.2.1 Hybrid Poplar and Alfalfa Reference ET from Boardman, OR AGRIMET Station (HERO)

April 1, 1994 - October 13, 1994

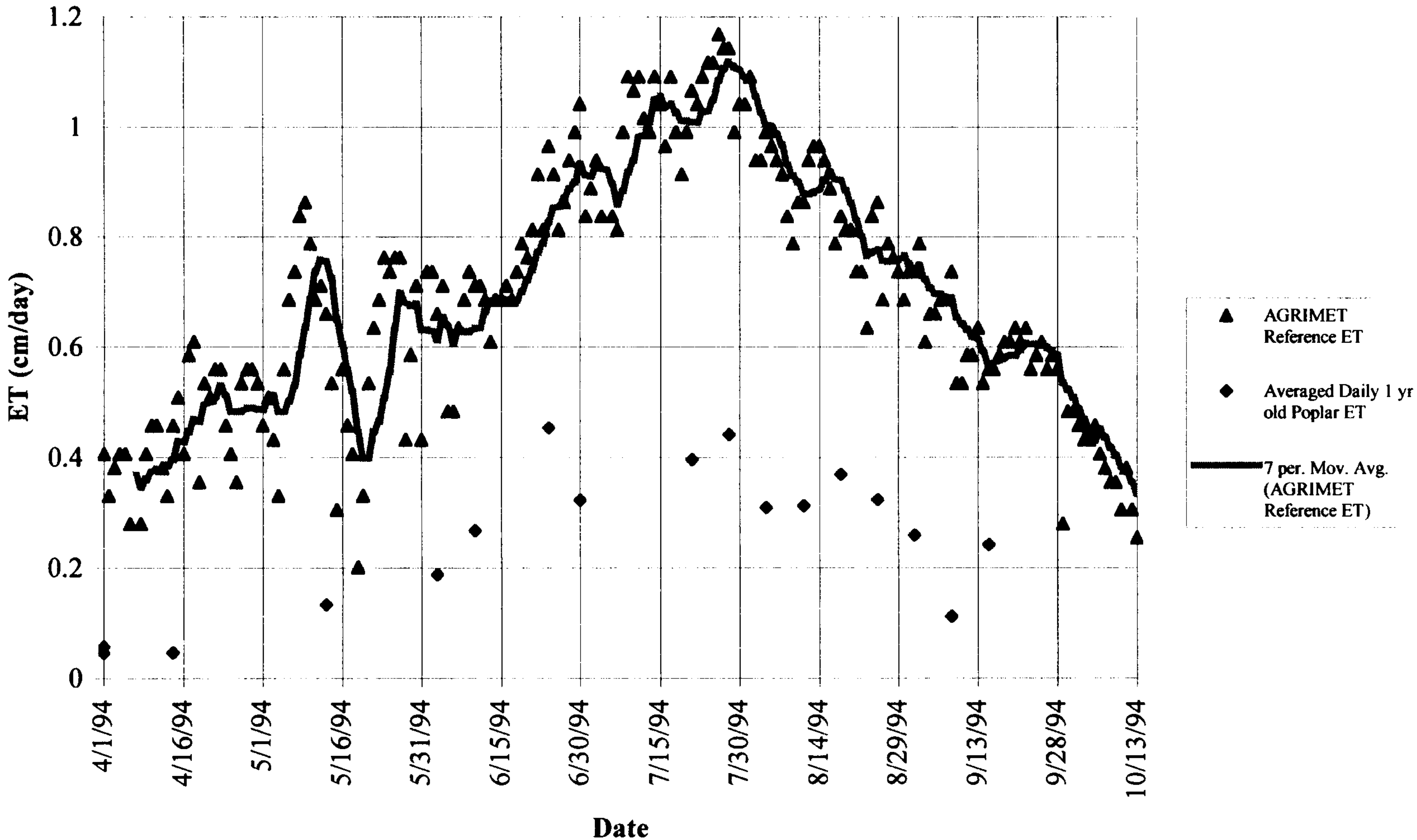


Figure 4.2.2 Hybrid Poplar and Alfalfa Reference ET from Boardman, OR AGRIMET Station (HERO)

April 3, 1995 - October 15, 1995

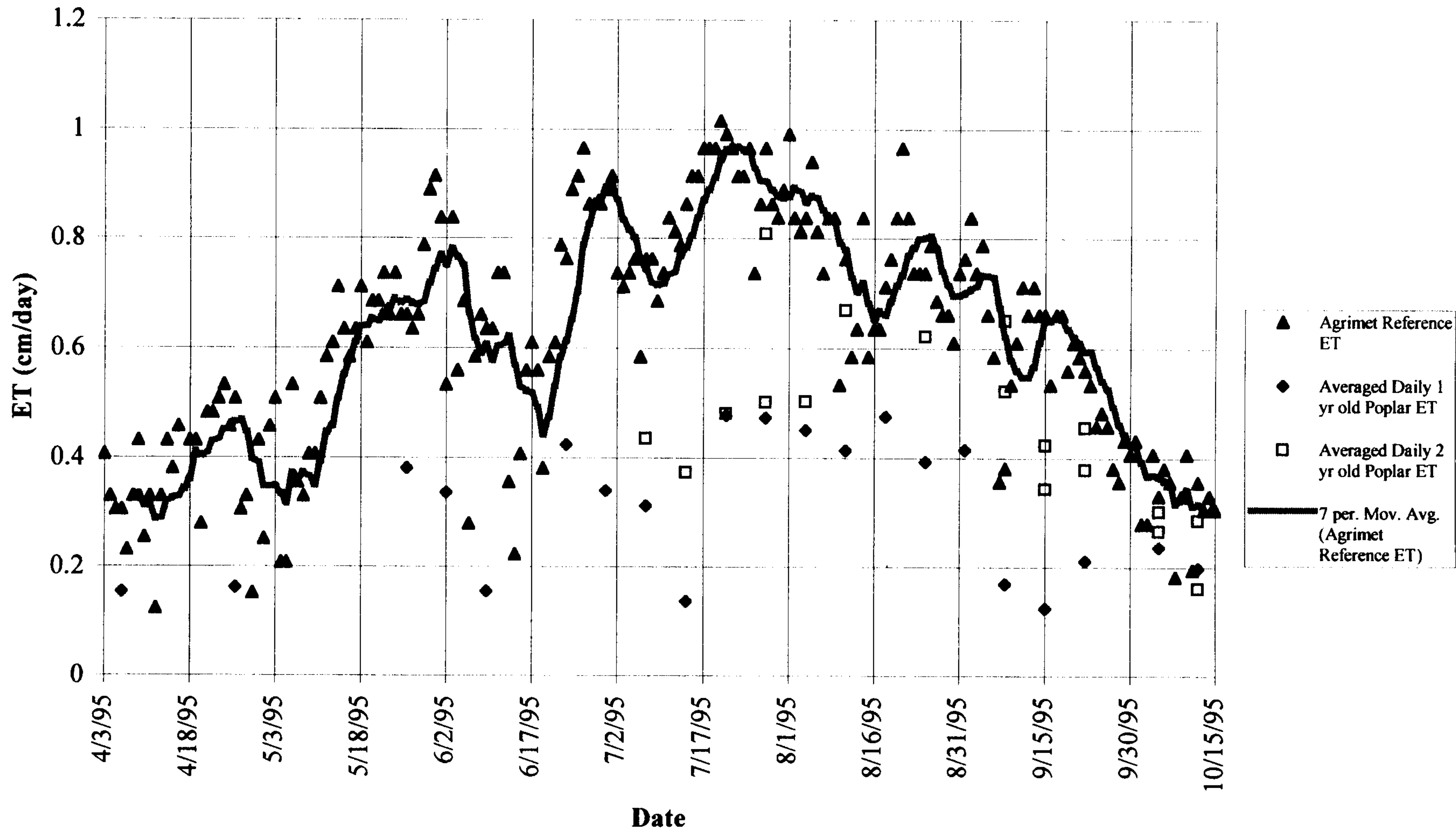


Figure 4.2.3 Hybrid Poplar and Alfalfa Reference ET from Boardman, OR AGRIMET Station (HERO)

April 3, 1996 - October 15, 1996

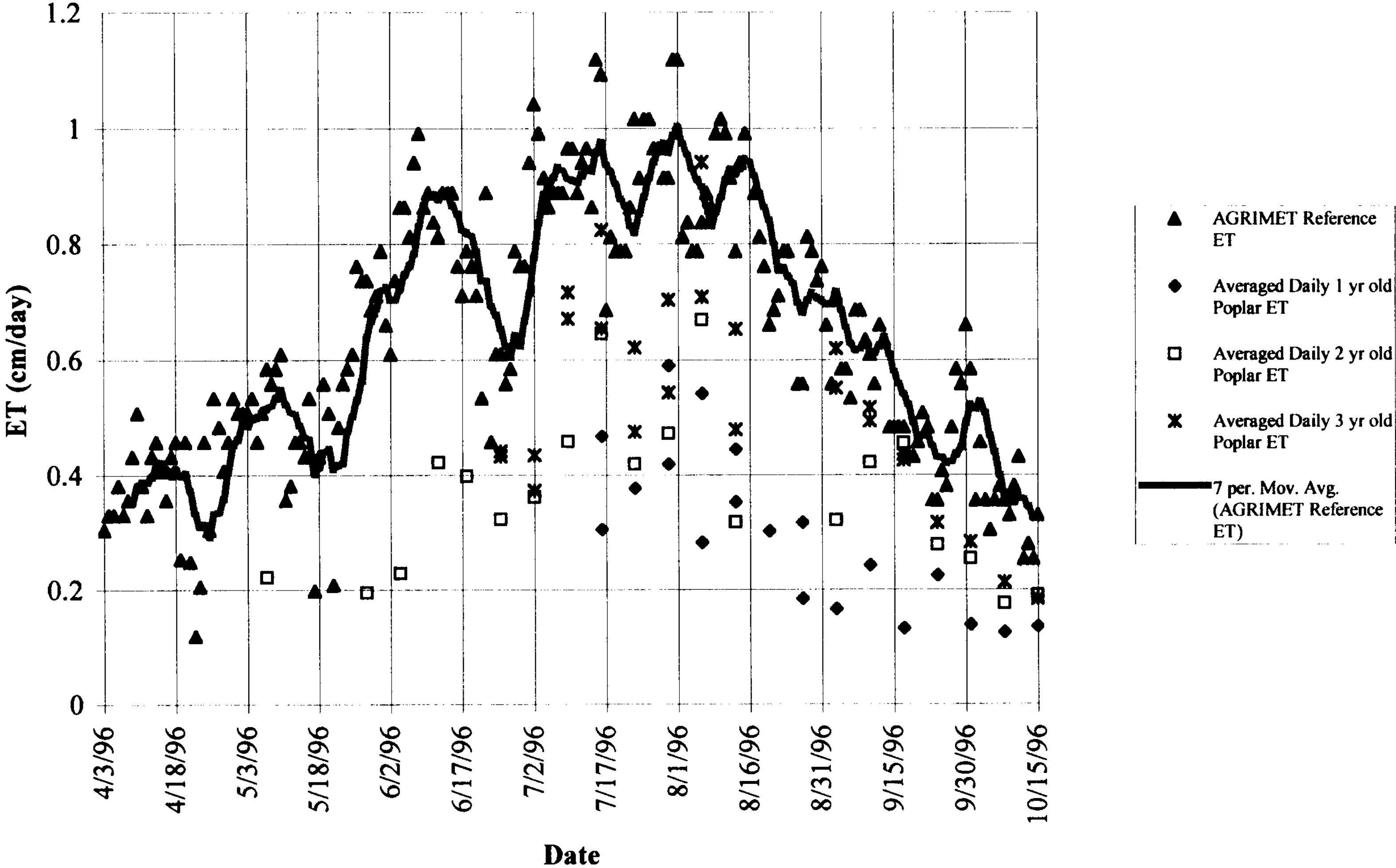


Figure 4.2.4 Hybrid Poplar and Alflalfa Reference ET from Boardman, OR AGRIMET Station (HERO)
April 1, 1997 - October 13, 1997

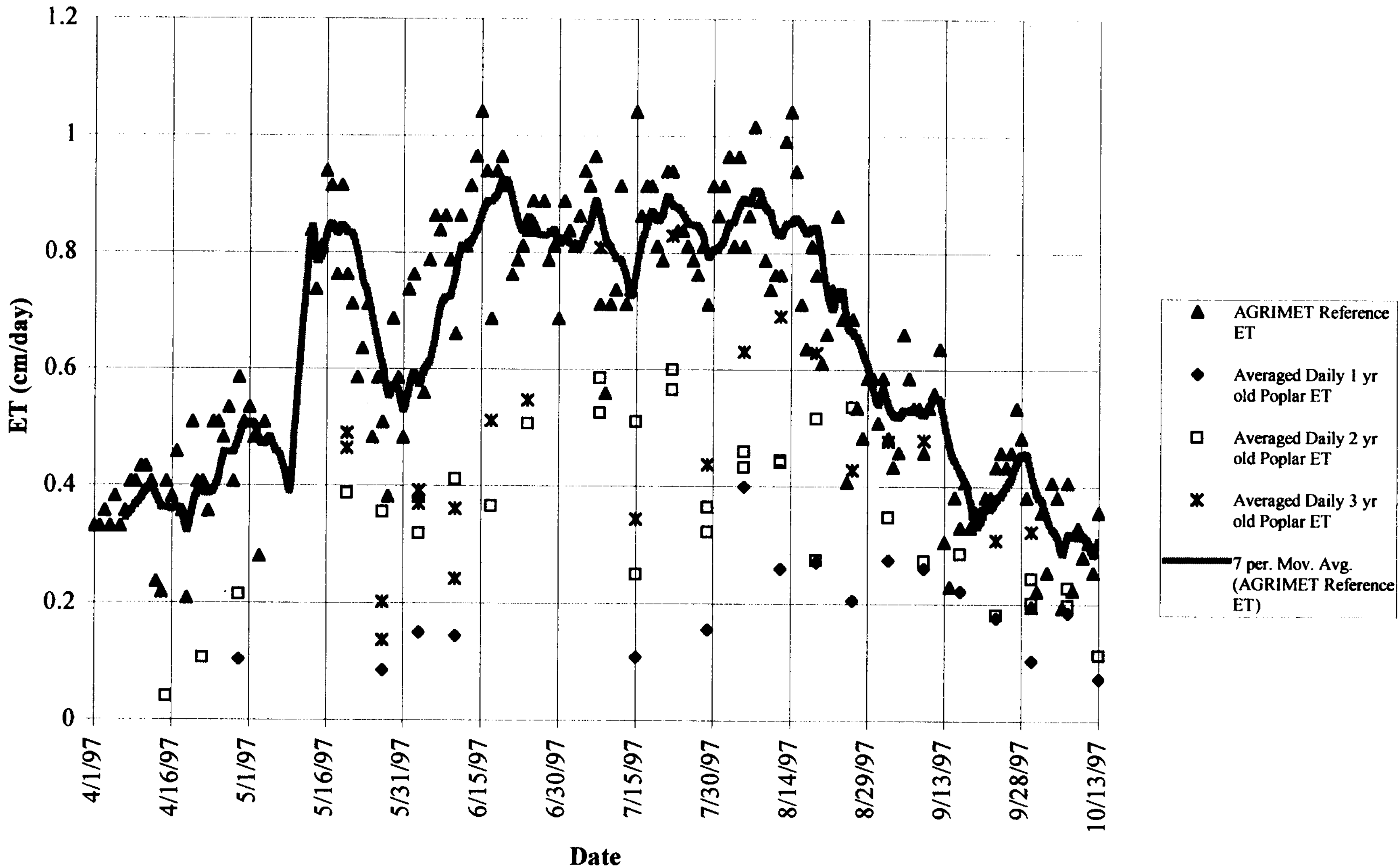


Table 4.2.1

Season, Crop, Age	Seasonal Average (cm/day)	Seasonal Maximum (cm/day)	Seasonal Minimum (cm/day)
1994			
Alfalfa Reference	0.7	1.2	0.2
1 Year Old Hybrid Poplars	0.3	0.5	0.1
1995			
Alfalfa Reference	0.6	1.0	0.1
1 Year Old Hybrid Poplars	0.3	0.5	0.1
2 Year Old Hybrid Poplars	0.5	0.8	0.2
1996			
Alfalfa Reference	0.6	1.1	0.1
1 Year Old Hybrid Poplars	0.3	0.6	0.1
2 Year Old Hybrid Poplars	0.4	0.7	0.2
3 Year Old Hybrid Poplars	0.5	0.9	0.2
1997			
Alfalfa Reference	0.6	1.0	0.2
1 Year Old Hybrid Poplars	0.2	0.4	0.1
2 Year Old Hybrid Poplars	0.4	0.6	0.1
3 Year Old Hybrid Poplars	0.5	0.8	0.1

*Seasonal average implies values averaged over the irrigation season approximately April 1-Oct. 15

Figures 4.2.1 through 4.2.4 show similar distributions of daily estimated hybrid poplar ET for each year of growth for each year. Generally, 3 year old estimates of daily ET are higher than two year old estimates which are then higher than 1 year old estimates. Isolated cases occur were this is not true, however. The reason for these occurrences could be explained by error in the neutron probe calibration yielding inaccurate changes in estimated soil water content, error in the drainage filtering estimation procedure allowing drainage to be computed as ET in the soil water balance equation or error introduced by making neutron probe measurements during or closely after irrigation applications which could yield locally decreased changes in estimated soil water content.

Peak hybrid poplar ET estimates occur between July 15th and August 8th for all ages of tree. Reference ET values consistently peaked during the month of July although isolated days occurred in mid-June and mid-August of 1997 where the reference ET was of a similar value as the seasonal maximum on July 15th. Evidence of the July peak in ET_{ref} can be observed in the seven-day moving averages in Figures 4.2.1 through 4.2.4. In every year except 1997 the seven-day moving average maximum occurred in July. The later half of the 1997 irrigation season was characterized by reductions in mean daily wind speed and mean net radiation.

4.3 Generalized Crop Curves for 3 years of Poplar Trees

Estimated mean crop curves for three years of growth of hybrid poplar trees have been constructed. A composite graph showing estimated crop curves for 1, 2 and 3 year old trees is given in Figure 4.3.1. Figures 4.3.2, 4.3.3 and 4.3.4 show crop coefficients and regressed crop curves with 95% prediction intervals for individual tree ages. The prediction interval indicates the range in which where there is a 95 % probability that the next value will occur. Table 4.3.1 provides tabulated weekly values of crop coefficients obtained from the regression equations. In each group of crop coefficients, a second order polynomial was regressed upon the weekly crop coefficients in order to create a crop curve. A second order polynomial was chosen because it represents the distribution of the crop coefficients throughout the season with special regards to the mid-season peak.

As can be seen in Figures 4.3.2-4.3.4 a large amount of scatter was present in the regression procedure. This scatter resulted in low r^2 values of 0.18, 0.28 and 0.45 for 1, 2 and 3 year-old trees, respectively. While a high degree of uncertainty is often common in the estimation of crop ET from the soil water balance method, these low r^2 values may also indicate that the chosen function for regression analysis may not appropriate. Wright (1982) and Jensen et al. (1990) suggest constructing crop curves by hand. Nevertheless, an analytical function was regressed in order to determine average crop coefficients throughout the irrigation season. The use of a simple function provides an easy means of calculating monthly and seasonal ET estimates.

Crop coefficients ranged from 0.1 to 0.45 for one year olds, 0.2 to 0.65 for two year olds and 0.1 to 0.75 for three year olds. Estimates of crop coefficients early in the irrigation season are not reliable due to the lack of data available at this time. The large range covered by the 95% prediction intervals reveals the uncertainty in this analysis.

Figure 4.3.1 Estimated Crop Curves for Three Years of Growth of Drip-Irrigated Hybrid Poplar Trees

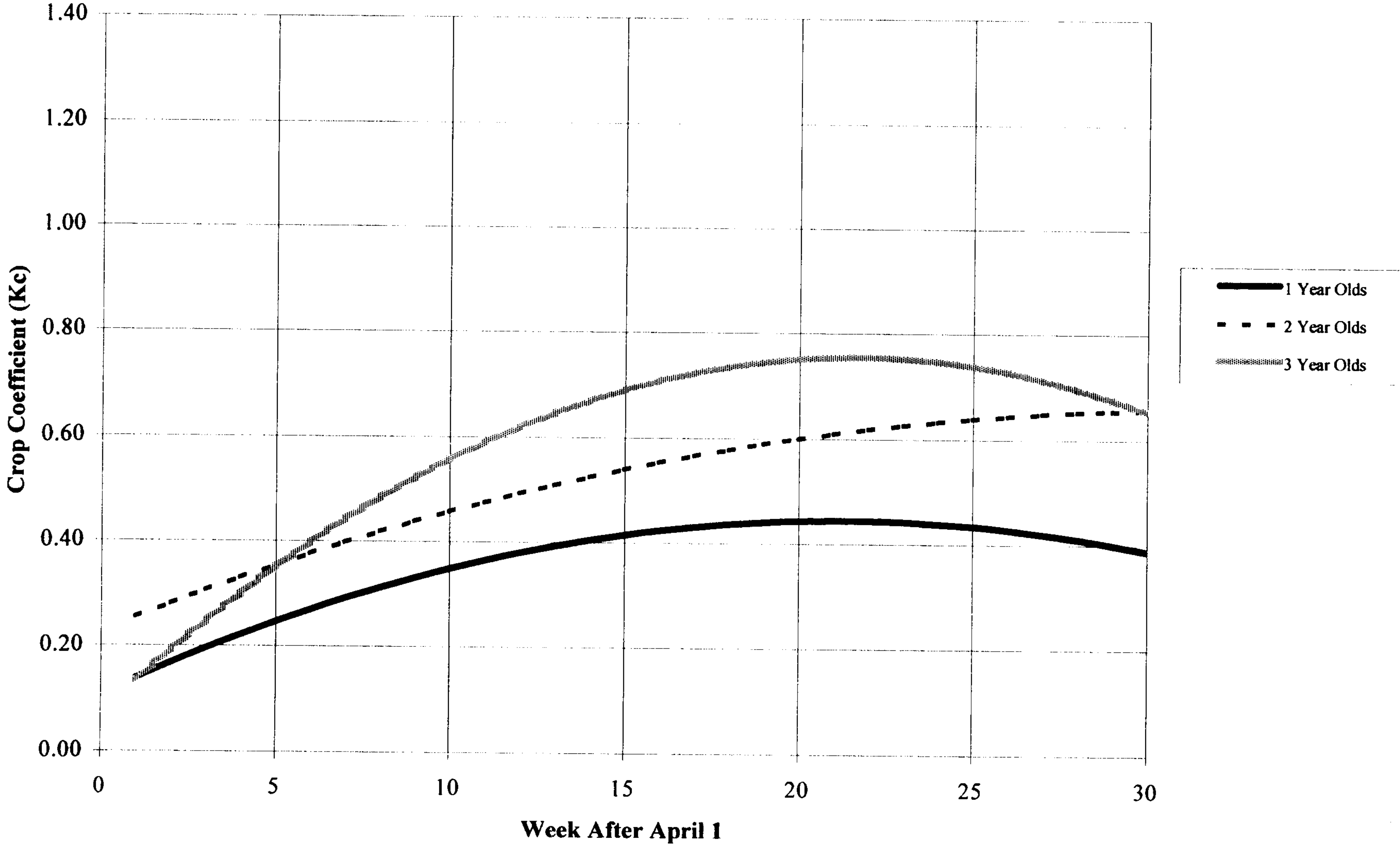


Figure 4.3.2 Crop Curve Estimate for 1 Year Old Hybrid Poplars

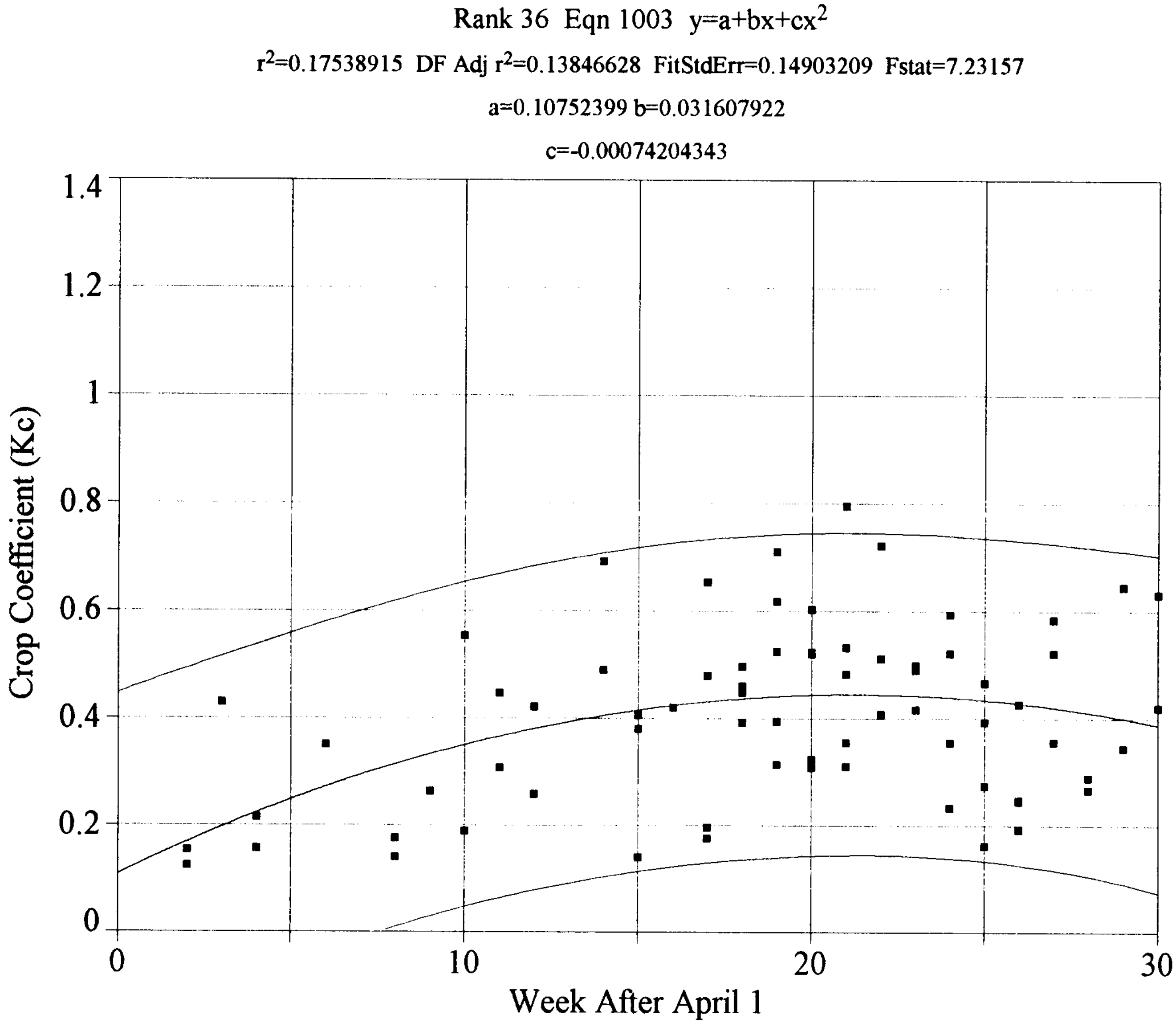


Figure 4.3.3 Crop Curve Estimate for 2 Year Old Hybrid Poplars

Rank 44 Eqn 1003 $y=a+bx+cx^2$

$r^2=0.28396104$ DF Adj $r^2=0.2518996$ FitStdErr=0.14196181 Fstat=13.48345

a=0.22882615 b=0.027092706

c=-0.00042699031

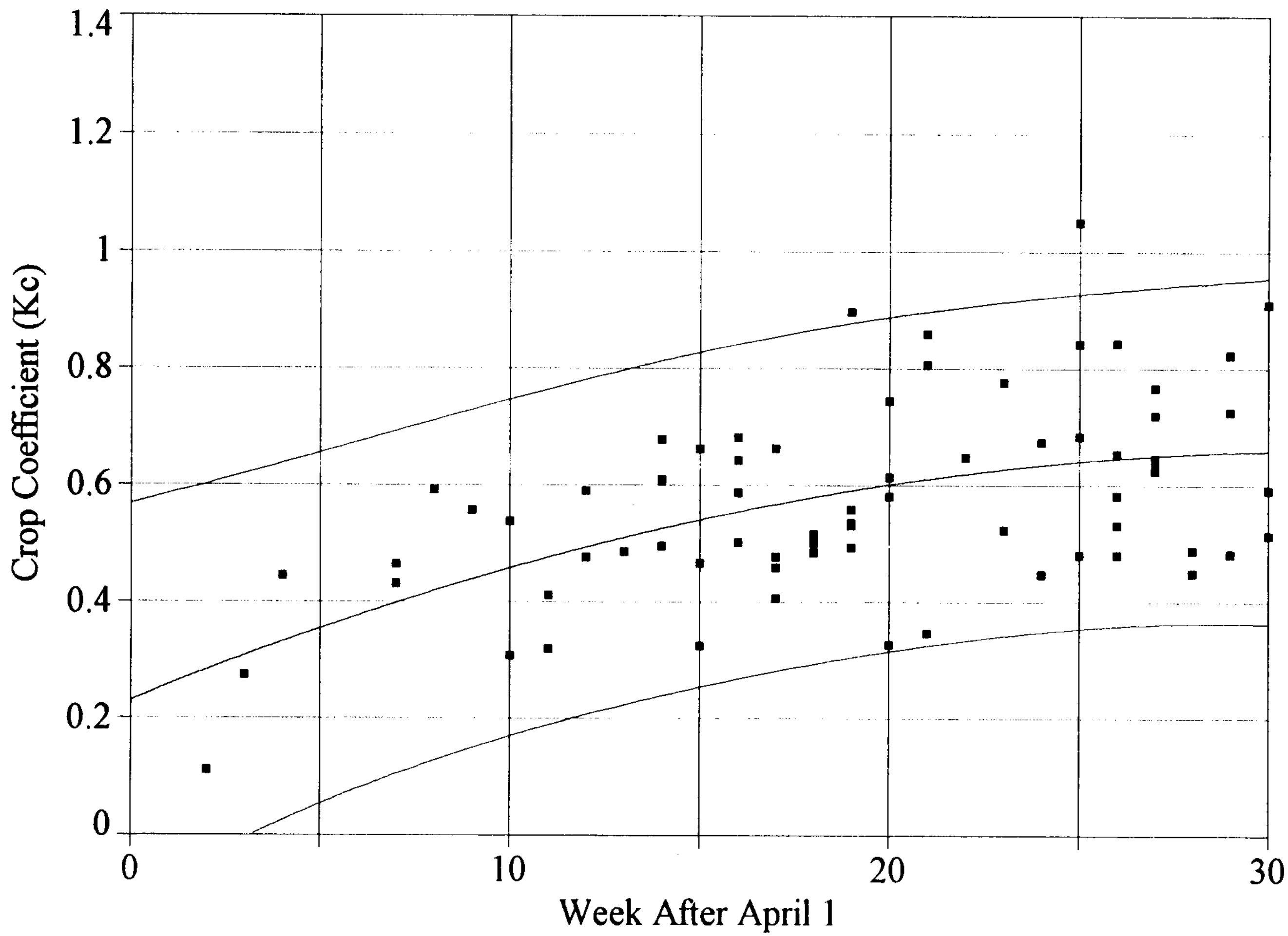


Figure 4.3.4 Crop Curve Estimate for 3 Year Old Hybrid Poplars

Rank 35 Eqn 1003 $y=a+bx+cx^2$

r^2=0.44673376 DF Adj r^2=0.4114189 FitStdErr=0.13911679 Fstat=19.378754

a=0.072204677 b=0.063075833

c=-0.0014574124

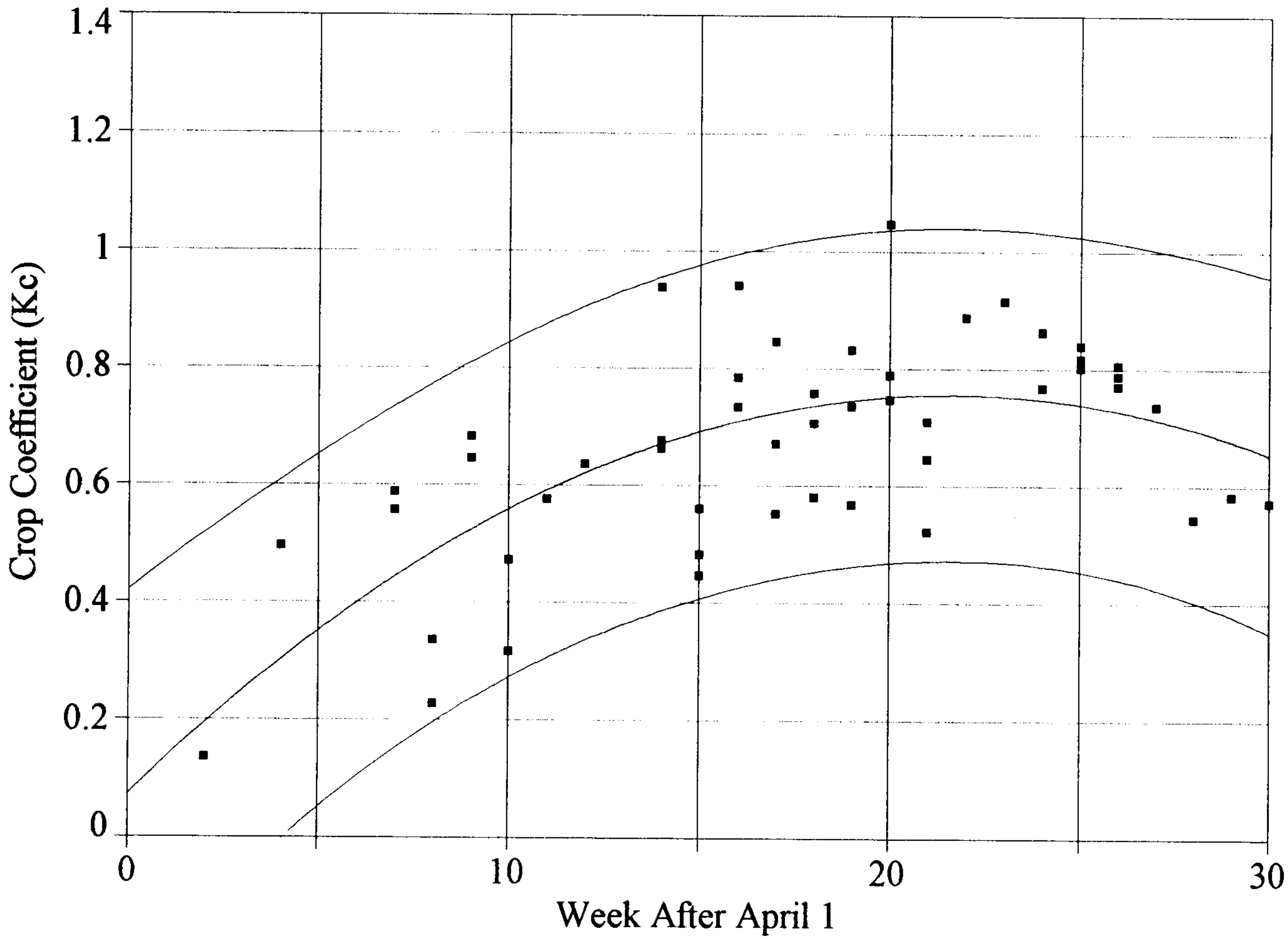


Table 4.3.1 Weekly Crop Coefficients For 1, 2 and 3 Year Old Hybrid Poplars

Week After April 1	1 Year Olds	2 Year Olds	3 Year Olds
1	0.14	0.26	0.13
2	0.17	0.28	0.19
3	0.20	0.31	0.25
4	0.22	0.33	0.30
5	0.25	0.35	0.35
6	0.27	0.38	0.40
7	0.29	0.40	0.44
8	0.31	0.42	0.48
9	0.33	0.44	0.52
10	0.35	0.46	0.56
11	0.37	0.48	0.59
12	0.38	0.49	0.62
13	0.39	0.51	0.65
14	0.40	0.52	0.67
15	0.41	0.54	0.69
16	0.42	0.55	0.71
17	0.43	0.57	0.72
18	0.44	0.58	0.74
19	0.44	0.59	0.74
20	0.44	0.60	0.75
21	0.44	0.61	0.75
22	0.44	0.62	0.75
23	0.44	0.63	0.75
24	0.44	0.63	0.75
25	0.43	0.64	0.74
26	0.43	0.64	0.73
27	0.42	0.65	0.71
28	0.41	0.65	0.70
29	0.40	0.66	0.68
30	0.39	0.66	0.65

Errors due to improper calibration in the neutron probe, spatial variability in rainfall and uncertainty as to the true quantity of drainage all contributed to the wide range of expected values. The spread in the prediction intervals (PI) is observed in each age of tree, indicating that uncertainty in the estimates is not likely to decrease with age. The uncertainty in estimated crop coefficients contributes to the overlapping of curves in Figure 4.3.1. Generally, the curves increase in height and curvature with age as would be expected but overlapping does occur between the 2 and 3 year old trees in the early season and in the late season.

Crop curves had peak values around weeks 20 and 21 (approximately August 5-12) for 1 and 3 year old trees, respectively. No maximum was observed in the regressed 2 year old function. Special note should be given to the fact that the peak in the crop curve does not correspond to a peak in crop water use. This is because the crop coefficient is the crop ET normalized by the reference crop ET. Therefore, depressed reference crop ET values caused by physiological constraints on the reference crop can yield higher values of crop coefficient for an unchanging value of crop ET. As pointed out previously (Section 4.2.2) crop ET estimates tended to peak between weeks 15 and 20, a few weeks earlier than the estimated peaks in the crop coefficient.

4.4 Monthly and Seasonal ET Results

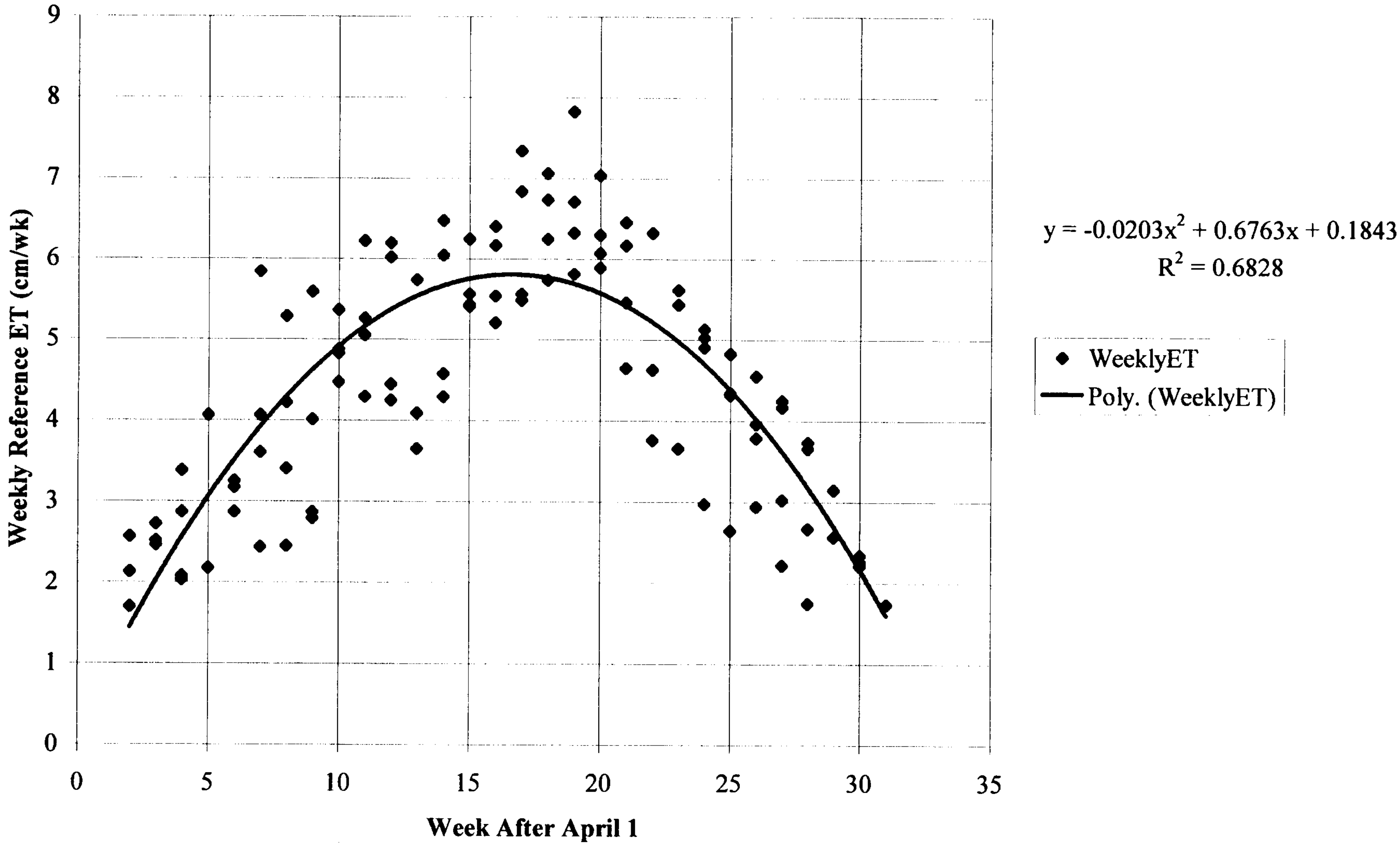
Monthly and seasonal hybrid poplar ET estimates have been made. Estimates of monthly and seasonal ET were made using the estimated crop curves from Section 4.3. Reference ET was compiled for April 1st through October 15th, 1994-1997 (Figure 4.4.1). Like the crop curves, a 2nd degree polynomial was regressed through the reference ET data. An r^2 value of 0.68 was obtained indicating a fairly good fit of the model to the data although the regressed trendline appears to underestimate peak ET_{ref} values. Reference ET and crop ET were calculated for each week of the year using the reference ET model and the crop curves, respectively. Once weekly ET was calculated it was possible to obtain monthly and seasonal estimates of hybrid poplar ET throughout the irrigation season.

Table 4.4.1

Month	Reference ET (cm/mo)	Age of Tree 1 Year Old	2 Year Old	3 Year Old
April	10.1	2.1	3.2	2.8
May	21.3	6.7	9.0	10.4
June	27.5	10.8	14.0	17.7
July	28.7	12.5	16.6	21.0
August	24.8	10.9	15.5	18.6
September	13.6	5.7	8.9	9.6
October	3.8	1.5	2.5	2.5
Seasonal (cm)	129.8	50.2	69.7	82.6
Seasonal (in)	51.1	19.8	27.4	32.5

Results of the monthly and seasonal ET analysis are shown in Table 4.4.1. 1 year old hybrid poplar ET ranges from 2.1 to 12.5 cm/month, 2 year old hybrid poplar ET ranges from 3.2 to 16.6 cm/month and 3 year old hybrid poplar ET ranges from 2.8 to 21.0 cm/month. In every age class the peak month of hybrid poplar ET is July. This model estimated peak is in good agreement with the peak estimated average daily ET values observed in Figures 4.2.1-4.2.4. The ET estimates for the month of October presented here only account for the first two weeks of the month. This was because irrigation and soil water monitoring stopped on approximately October 15th

Figure 4.4.1 Composite Weekly Reference ET from AGRIMET Station Near Boardman, OR 1994-1997

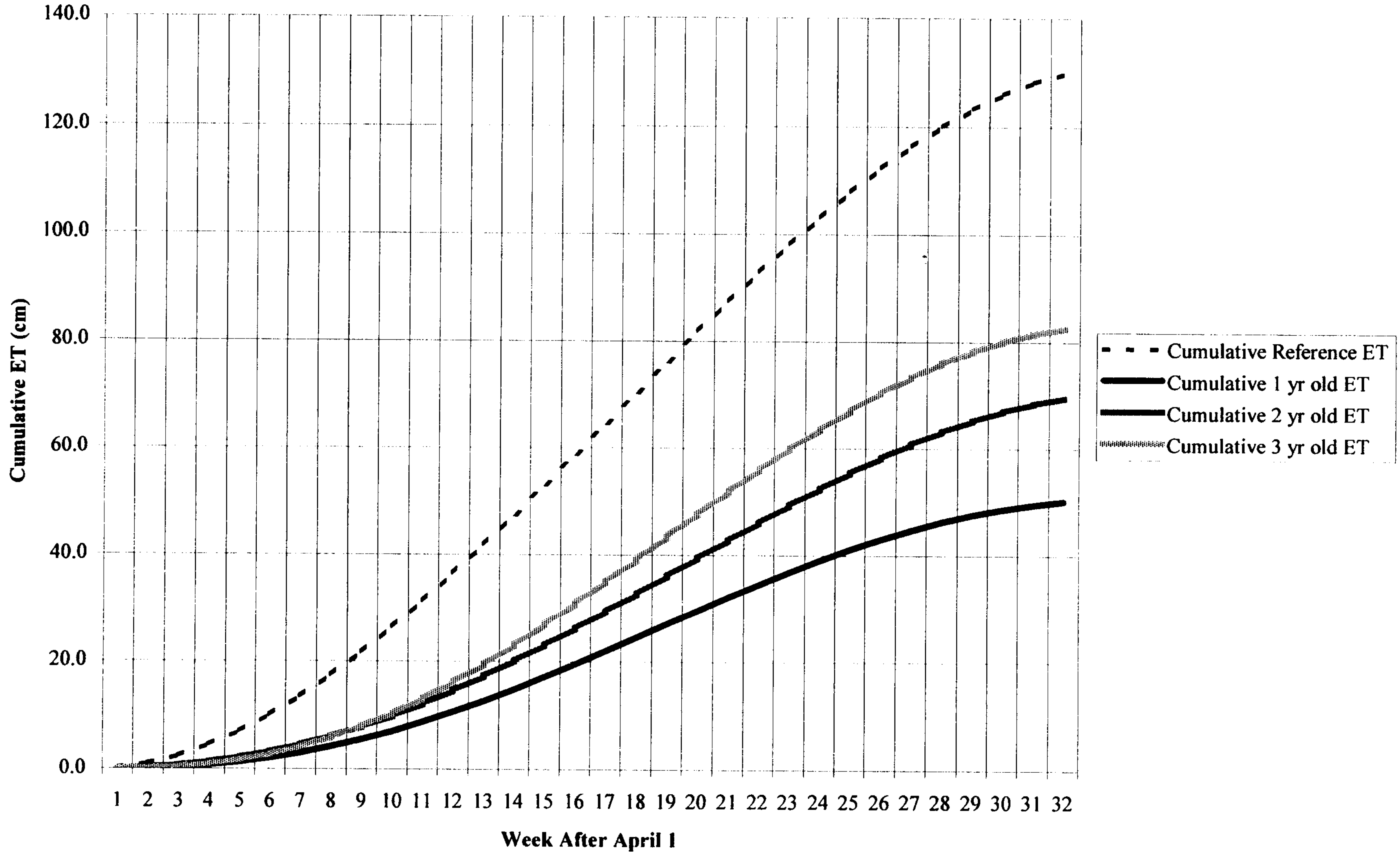


every year. Hence the estimates of monthly hybrid Poplar ET for October will be low.

It may also be expected that hybrid poplar ET estimates early in the season are likely to have a higher degree of error. This uncertainty is due to the fact that there were less transects available for ET analysis early in the year due to soil water drainage and significant precipitation.

Hybrid poplar ET lags significantly behind reference ET early in the irrigation season during April, May and June. Peak reference ET occurs during July at 28.7 cm/month. June reference ET is close behind at 27.5 cm/month. Hybrid poplar ET would appear to peak later than reference ET as August is the month with the second largest monthly ET behind July. Figure 4.4.2 graphically displays cumulative reference and hybrid poplar ET estimates as calculated by the regressed models. As in Table 4.4.1, Figure 4.4.2 shows that seasonal, alfalfa-computed reference ET is significantly greater than one, two or three year old hybrid poplar ET. The maximum rate of increase for each of the cumulative ET curves in Figure 4.4.2 represents the period of maximum ET. For the reference crop the maximum rate is expected the 16th week after April 1st or approximately the third week in July. Maximum hybrid poplar ET rates can be expected the 18th and 19th weeks after April 1st or around the first of August. Following these times of peak water use, cumulative ET for both the alfalfa reference and the hybrid poplars begins to slow.

Figure 4.4.2 Cumulative Reference and Estimated Hybrid Poplar ET near Boardman, OR



Seasonal hybrid poplar ET provided in Table 4.4.1 and Figure 4.4.2 shows a strong correlation with age. Seasonal water use for 1 year old, 2 year old and 3 year old hybrid poplars was 50.2 cm (19.7 in), 69.7 cm (27.4 in), 82.6 cm (32.5 in), respectively. All seasonal hybrid poplar ET estimates were significantly below seasonal reference ET at 129.8 cm (51.1 in). This depression of hybrid poplar crop ET below that of the reference ET does indicate significant controls acting on the poplars in their transfer of water from the soil to the atmosphere.

Table 4.4.2 shows the total applied water, consisting of irrigation and rainfall, for each phase for all four years. Due to missing data resulting from the removal of transects possessing significant drainage and/or precipitation of the soil water drainage estimation and weeks with significant precipitation it was impossible to calculate an annual water budget. Annual average applications can be compared to hybrid poplar ET estimates formulated using crop curves. On average, 7.7 cm (3.0 in) of rain can be expected during the irrigation season at Boardman, OR. Differences in rainfall totals during the same year at different sites indicate spatial variablility of rainfall.

The three-year old hybrid poplar ET estimate of 82.6 cm was surpassed by seasonal applied water equal to 91.4 cm indicating a possible over application of water. The surplus of water applied to three-year old trees was observed in weekly monitoring data during the 1996 and 1997 seasons as increases in transect soil water content. Two-year old, seasonal, hybrid poplar water use estimates of 69.7 cm compared closely to average seasonal applied water of 68.6 cm. One-year old

Table 4.4.2 Irrigation Application Totals

Year	Phase and Age	Irrigation (cm)	Irr + Rain (cm)	Rainfall (cm)	
1997					
	P1 (4 yr olds)	86.4	94.0	7.6	
	P2 (3 yr olds)	81.3	88.9	7.6	
	P3 (2 yr olds)	61.0	66.0	5.1	
	P4 (1 yr olds)	30.5	36.8	6.4	
1996					
	P1 (3 yr olds)	86.4	94.0	7.6	
	P2 (2 yr olds)	61.0	68.6	7.6	
	P3 (1 yr olds)	30.5	40.6	10.2	
1995					
	P1 (2 yr olds)	63.5	73.7	10.2	
	P2 (1 yr olds)	33.0	43.2	10.2	
1994					
	P1 (1 yr olds)	30.5	35.6	5.1	
Seasonal Averages			**1 yr olds**	**2 yr olds**	**3 yr olds**
	Mean Irrigation (cm)		30.5	61.0	83.8
	Mean Irr + Rain (cm)		38.1	68.6	91.4
	Average Rainfall (cm)	7.7			

estimates of hybrid poplar water use (50.2 cm) exceeded average seasonal applied water (38.1 cm) by approximately 12 cm.

The large difference in 1 year old seasonal water balance is most likely due to plant water use by an unintentional cover crop of wheat, crab grass and Russian thistle. This ground vegetation can thrive due to the lack of complete canopy cover in one-year old trees. Soil evaporation may also contribute to increased hybrid poplar ET estimates but this contribution is most likely small when compared to that of the cover crop.

4.5 Model Simulations and Optimization of Soil Water Retention Parameters

192 simulations were run in order to optimize two-dimensional irrigation application rates and soil water retention parameters α and n. Error surfaces consisting of the absolute volume error, the mean biased error and the mean absolute error were created. Each error surface for the three irrigation application rates are provided in Figures 4.5.1, 4.5.2 and 4.5.3.

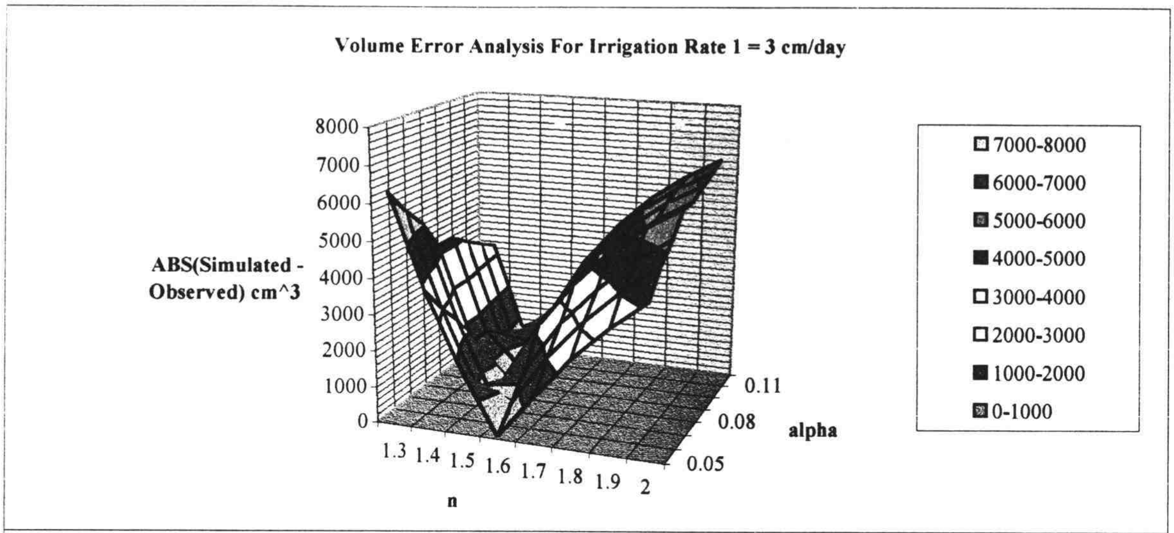
The absolute errors total transect water content in Figure 4.5.1 do not appear to be as sensitive to changes in α as they do to n. Error surfaces have a well defined trough. The presence of a trough as opposed to a "bowl-shaped" minima suggests that the absolute volumetric error is more sensitive to n than it is to α. The troughs are not perfectly smooth due to the size of the discretization of optimized parameters. Decreasing the interval between values of n, in this case, would smooth the trough in the error surface. For an irrigation application rate of 3 cm/day the minimum error corresponds to an n value of 1.6 that decreases to approximately 1.5 for increasing values of α. Optimized values of n increased very slightly at higher irrigation rates. No explanation is offered as to why this shift would occur. For modeling and calculation purposes though an *n* value of 1.6 should be appropriate. No other recommendations concerning the optimized values of α or the irrigation rate can be drawn from the error surfaces of absolute changes in volume.

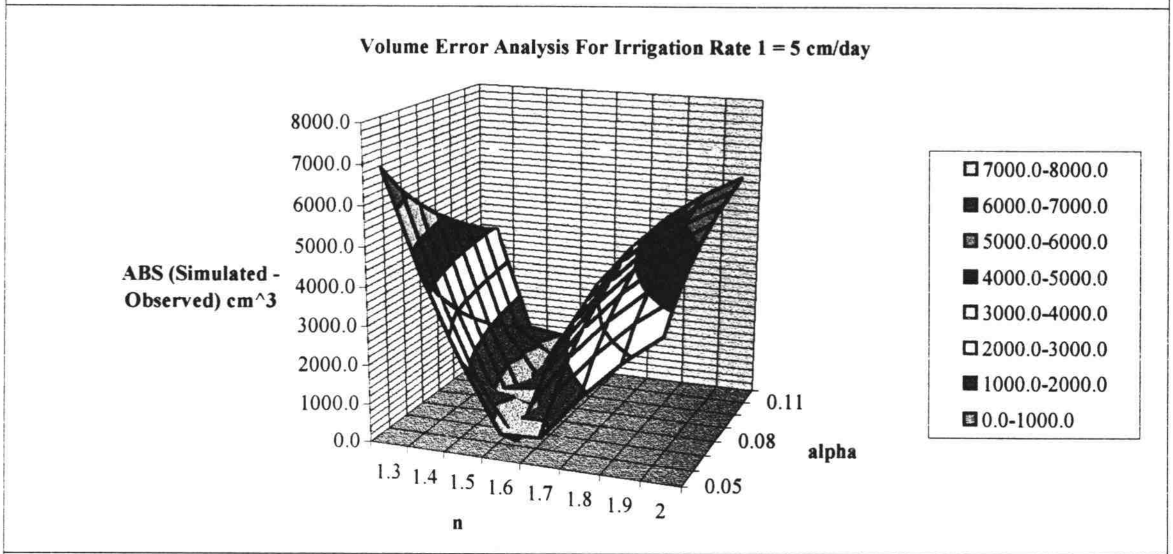
Figure 4.5.2 shows error surfaces of the mean biased error (MBE) for different values of α, *n* and irrigation application rates. These errors represent the spatial bias of the model, i.e. whether or not the model tends to under- (negative MBE's) or over-predict water contents (positive MBE's). A MBE of zero indicates a high spatial correlation of soil water content between simulated and measured water contents. MBE does not appear to be sensitive to changes in *n*. MBE does appear to posses a varying degree of sensitivity to α at the different irrigation application rates.

Changes in α at the 3 cm/day rate produce larger changes in MBE than changes at the 7 cm/day rate. For the given ranges of α and n, the MBE is mostly negative at the 3 cm/day rate and is mostly positive at the 7 cm/day rate. This is what would be expected as the 7cm/day rate applies more total water. Though all three application rates both over- and under-predict spatial water contents for the given range of parameters, the relative over- and under-predictions at 7 and 3 cm/day may indicate high and low estimates of the actual irrigation application rate, respectively.

Figure 4.5.3 shows the error surfaces of the mean absolute error (MAE). This error measure indicates the magnitude of the spatial error of the model. For each irrigation application rate the error surface decreases with decreasing values of α.

Figure 4.5.1 Absolute Error in Volume





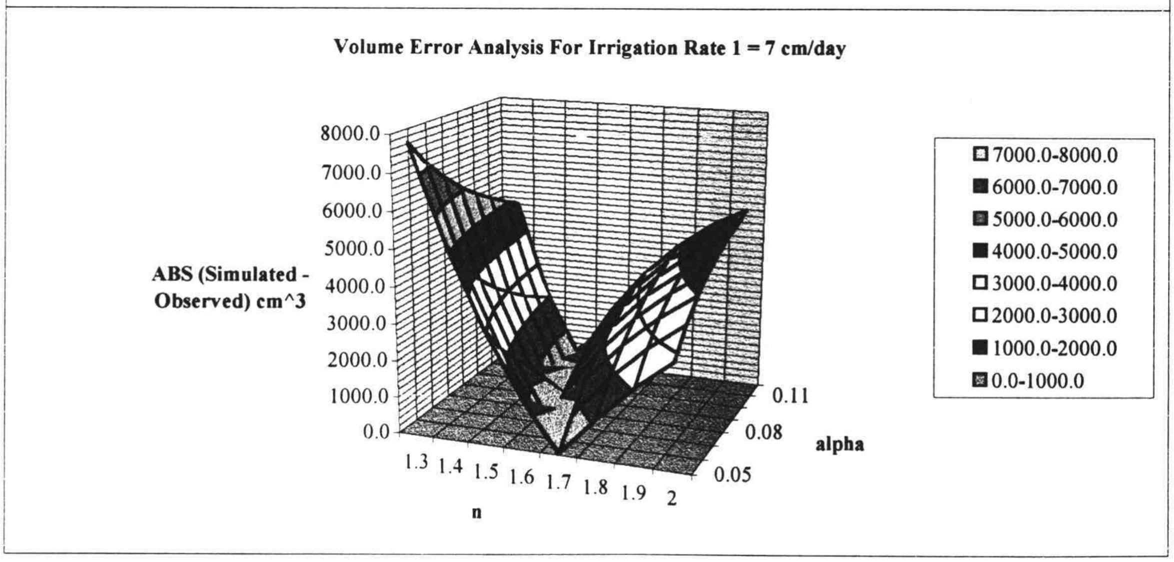
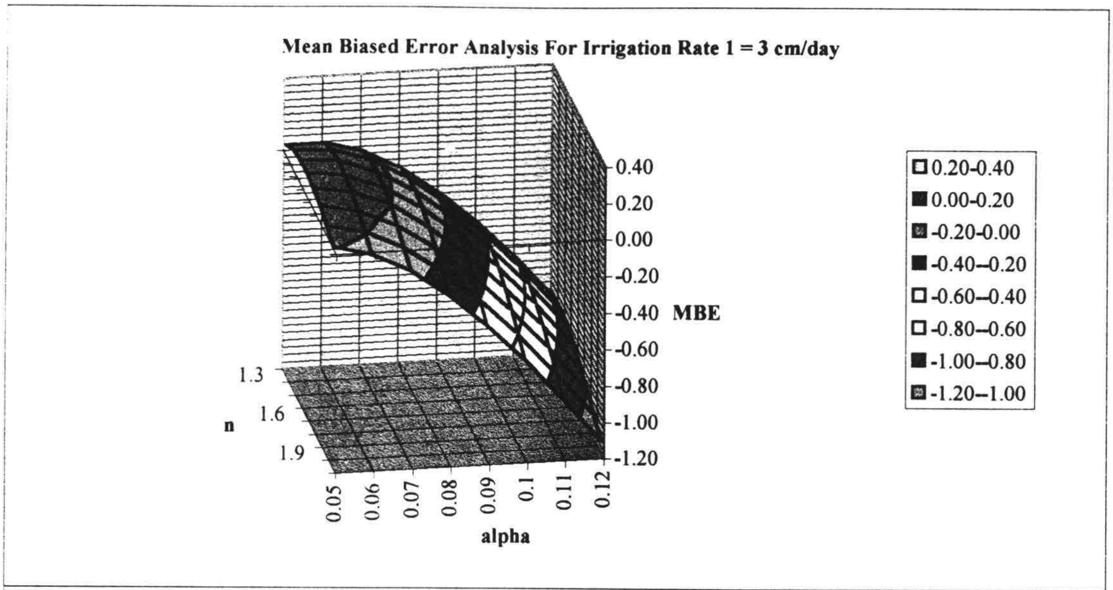
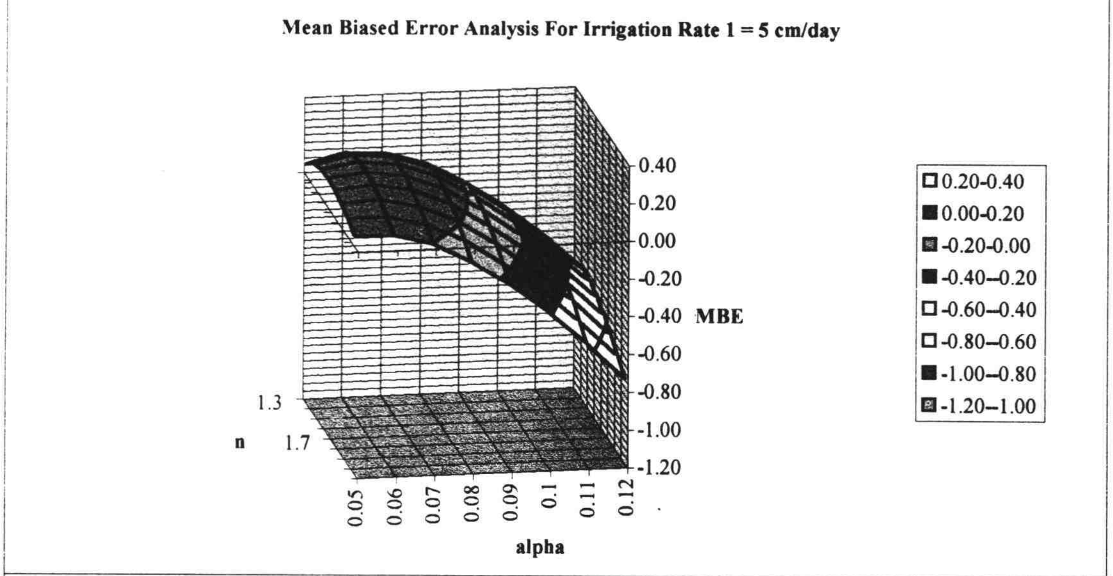


Figure 4.5.2 Mean Biased Error Surfaces





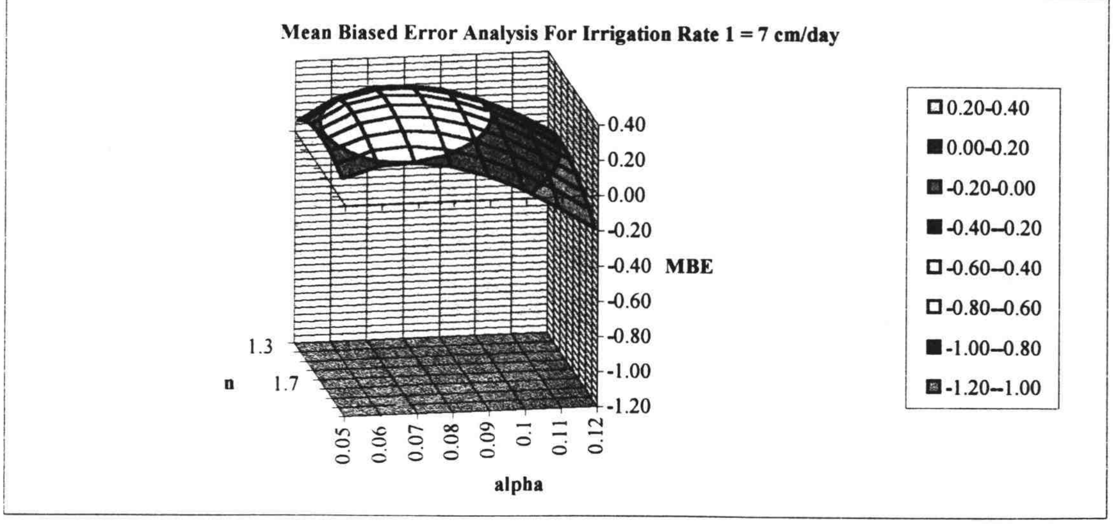
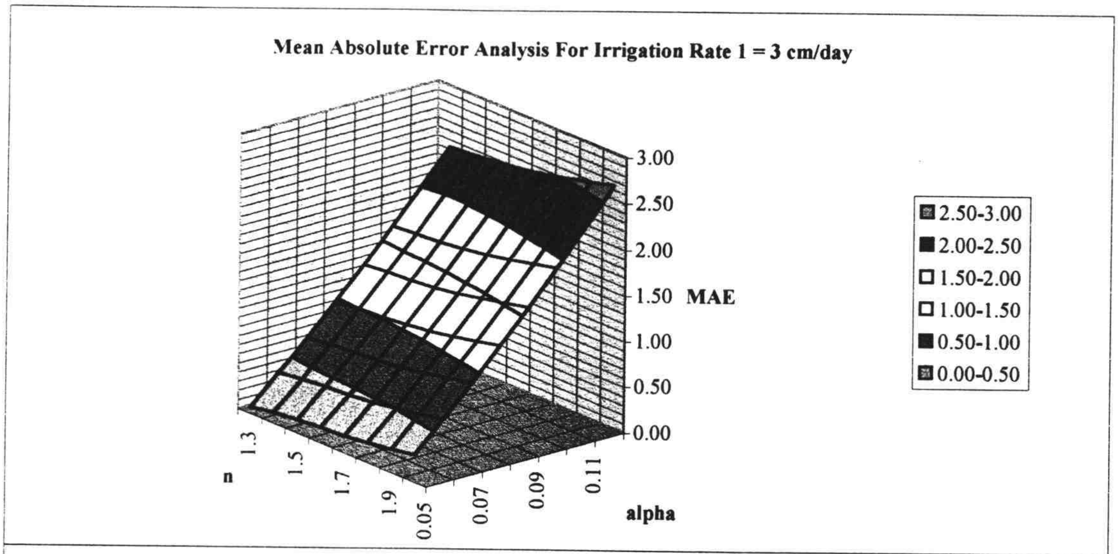
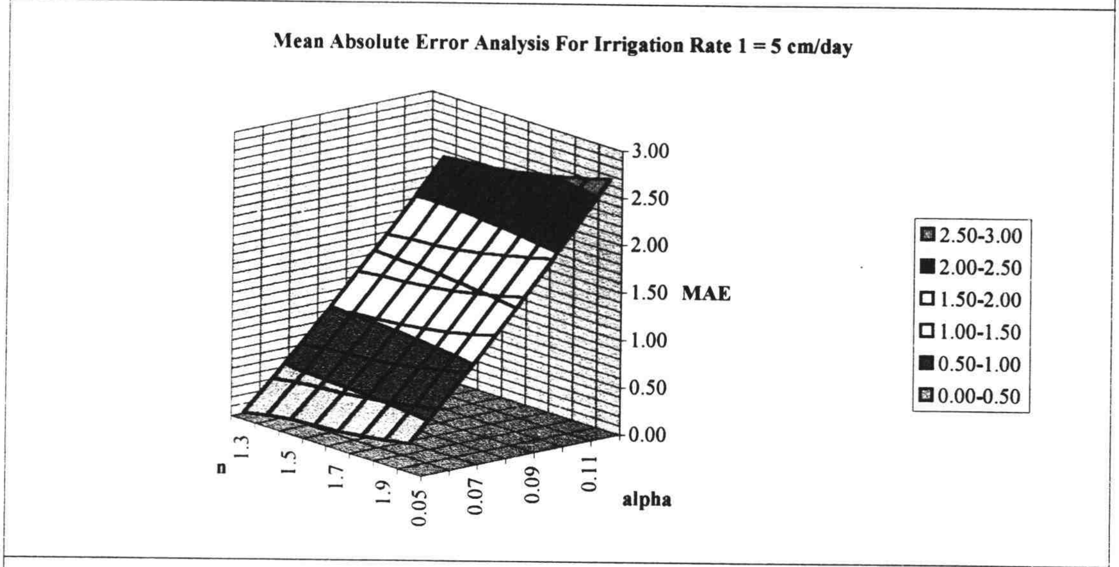
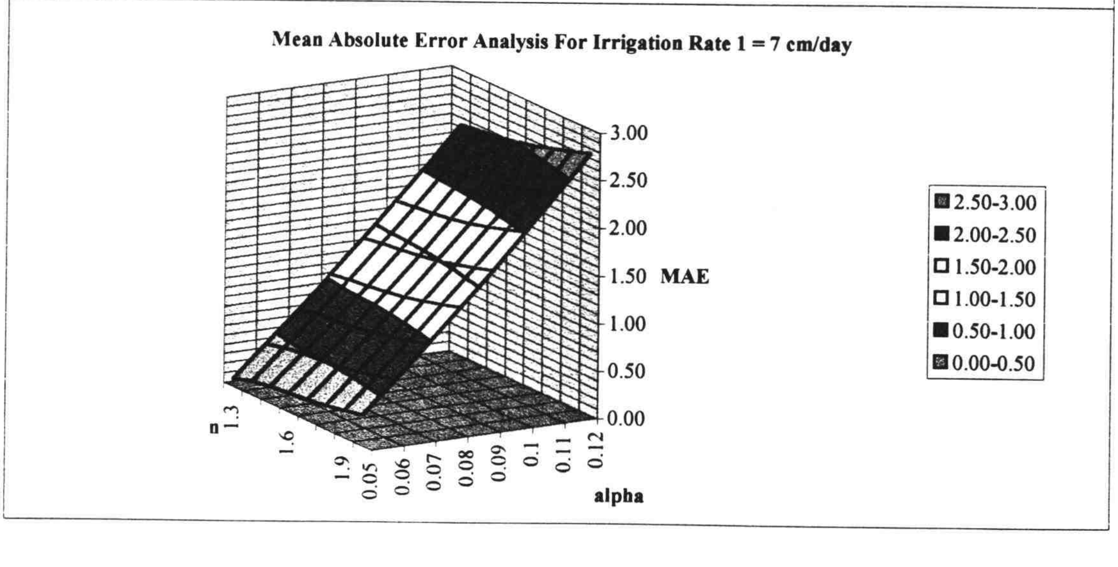


Figure 4.5.3 Mean Absolute Error Surfaces







The slope of the error surface is nearly constant at each application rate. A much smaller decrease in MAE was observed for decreasing values of n. These results indicate that the absolute error in spatial water content is relatively insensitive to changes in the irrigation application rate and to changes in n. This result would seem to be in partial contradiction to results obtained in Figure 4.5.2 where irrigation application did appear to have an effect on the total soil water content. No minima were obtained from the Mean Absolute Error analysis that would indicate optimized parameters.

No conclusive estimates of the optimized parameters could be made using these analyses. From the error surfaces it does appear that the total water balance, as shown by the Absolute Error in Volume surface, may be more sensitive to n than α while the opposite may be true for the spatial distribution of water content, as shown by MBE and MAE surfaces. It is doubtful that increasing the domain of the parameter space would yield error surfaces with minima indicating optimized parameters. This is because the outer most values in the n and α parameter domain do not correspond to typical values of sands and loamy sands as presented in the literature. The sensitivity of MBE to the irrigation application rates suggests possibly that more simulations run with a finer discretization of the application rate may yield better estimates of the rate.

Due to the difficulty encountered in parameter optimization no simulations were done to quantify or demonstrate the model's capability to simulate changing irrigation practices and variable environmental demands during different parts of the season. The results of the sensitivity analysis indicate a need for further optimization or data collection to ensure adequate representation of physical processes in this system. Other parameters such as the root sink function, root zone distribution, variability in K_{sat} or local soil heterogeneity may have a more significant influence on the errors determined in this analysis.

5 Conclusions and Discussion

5.1 Application of Hybrid Poplar ET Estimates

Estimated crop coefficients presented here for three years of growth of hybrid poplars represent mean crop coefficients. This is because crop coefficients could only be calculated on a weekly basis due to the soil moisture sampling and precipitation measurement frequency. At weekly intervals it is impossible to determine the contribution soil evaporation of rainfall to the calculated soil water balance. Evaporation of irrigation water in drip irrigation systems is limited to the wetted area surrounding emitters. The sum of the wetted area may or may not be a significant portion of the entire field area. Soil evaporation processes may be significant in one-year old plants where the canopy is not complete. It is doubtful that soil evaporation is significant in older tree stands under a fully enclosed canopy and it would be difficult to assess soil evaporation processes over the course of a week as the drip irrigation is near continuous.

Since the definition of a basal crop coefficient stipulates that surface evaporation be assumed to be equal to zero and there is a possibility that surface evaporation does contribute to some degree to the computed soil water balances, at least for the younger trees, the crop coefficients presented here are assumed to be mean or average crop coefficients. The second criteria for both mean and basal crop coefficients of a non-limiting amount of soil water was met by near continuous irrigation and a lack of any evidence of excessive soil water depletion. Soil water was managed at approximately 80% of field capacity.

Estimates of hybrid poplar ET calculated in this thesis (and hence, hybrid poplar crop coefficients) should provide an upper bound for actual crop ET. Two explanations can be provided to support this hypothesis. The first explanation involves comparing the weekly changes in soil water content at different times of the irrigation season. Specifically, instances occurred during irrigation monitoring, where soil water content increased from one week to the next. Ideally, near-continuous drip irrigation would be managed such that soil water contents remained at a constant level, neither increasing or decreasing from week to week. When increases in soil water content are observed it may be concluded that more water is being applied to the crop than is required or can be used by the crop. (It is necessary to separate the required water from the capable use because the requirement is established by the evaporative demand of the atmosphere and the plants stomatal response to that need while the capable use is established by the plants ability to transport a given quantity of water from the soil to the leaf surface in the absence of stomatal control.)

Increases in soil water content were occasionally observed in all ages of trees during expected peak water use periods. These weekly increases in soil water content indicate more water was supplied on a weekly basis than was consumed by the trees. Also, as shown in Section 4.4, Tables 4.4.1 and 4.4.2, average, seasonal applied water exceeded estimated water use in three-year old hybrid poplars by 8.8 cm. The seasonal water balance for two-year olds was nearly equal to zero indicating a low probability of over- or under-estimation of ET.

One-year old hybrid poplar ET estimates are most likely influenced by soil water consumed by an unintentional cover crop. As seen by comparing Tables 4.4.1 and 4.4.2, estimated crop ET can exceed total applied water. No signs of advanced moisture stress (e.g. senescence) or crop losses due insufficient soil water were reported by farm managers in one-year old hybrid poplars. One-year old hybrid poplar rows were tilled in an attempt to reduce soil water extraction by the unintentional cover crop. Since is impossible to manage invading species completely due to the risk in damaging drip lines a significant amount of vegetation did persist. It is most likely that plant water use by one-year old hybrid poplars alone would be less than that indicated by the derived crop model.

Qualitative observations of hybrid poplar leaf stress were documented by farm managers in two and three year old trees during periods of high evaporative demand (i.e. high reference ET). No large deficits in root zone soil water content have ever been observed during the four years of soil water monitoring. This is most likely because of the near-continuous drip irrigation that occurs during mid-summer. Though there is a significant amount of error in the soil water content estimation procedure used in this study, it may be that there is a limit to the rate at which the tree can transport water from the soil to the leaf surface. It is often assumed that when the leaf becomes water limited, stomata will close and leaf evaporation will be reduced to near zero. In discussions with poplar farm managers it has been suggested that attempts to increase productivity in hybrid poplars through selective breeding may severely impair stomatal control. If this is so and stomata remain open during high evaporative demand periods (or if cuticular ET is high) and there is in fact no significant reduction in soil water content then it may be that crop ET is transport limited to some value below the evaporative demand. This limitation may be a function of xylem volume among other physiological parameters. Since xylem volume is a function of stem diameter (via stem circumference) is not known whether older trees or other varieties of poplar with larger stem diameters may be similarly "transport limited."

Further support that the maximum hybrid poplar ET estimates may be constrained by the tree's capacity to transport water from the soil to the leaf surface is given by the fact that reference ET is almost always greater than estimated hybrid poplar ET. This implies that the atmosphere was capable of evaporating more water than was directly removed by the poplars as observed in the soil water changes.

The second reason why it is hypothesized that the calculated ET estimates presented here represent upper bounds is that some drainage may still be present in the assumed steady-state soil water transects used in the ET analysis. The drainage filtering procedure only provided a coarse estimation of drainage that was not mass-conservative. In effect, the estimated drainage only represents the capacity for drainage at the time of the soil water measurements. It was not actually determined that the estimated amount of water actually left the transect. In order to do this numerical simulation would have to be employed to implicitly solve for the drainage and the crop ET. If drainage was occurring in transects used in the ET analysis, some overestimation of ET would occur due to the inclusion of drainage. Also, the drainage criteria was set to 10% of the calculated ET + D. Therefore, if the drainage in the transect was computed to be greater than zero then an overestimation in crop ET up to 10% may directly result.

5.2 Comparison of Hybrid Poplar ET Estimates

Estimates of one, two and three year old hybrid poplar water use compare well with other general estimates provided by other workers. Seasonal, drip-irrigated, hybrid poplar ET estimates near Boardman, OR, ranged from 500 mm (20 in) to 700 mm (28), to 830 mm (33 in) for one, two and three-year old trees. These estimates are lower than the 1200 mm suggested by Pryor and Willing (1982). The most obvious reason for this difference is the large difference in latitude between Boardman, OR, at approximately 45°N and Australia at approximately 29°S, which results in an extended growing season for Australian trees.

FAO (1980) provided several different estimates of poplar water use for a few of the different climates situated around the Mediterranean. FAO estimates were only provided in maximum estimated plant water use per month. Estimates of peak, monthly, hybrid poplar ET from Boardman, OR at 125 mm/mo, 166 mm/mo and 210 mm/mo for one, two and three-year old trees, respectively, most closely compare to FAO estimates obtained in " hot Mediterranean climates" (125 mm/mo) or "interior deserts" (180 mm/mo).

Hybrid poplar estimates by Madison and Licht (1994) obtained at various sites throughout the U.S. displayed a wide range of values ranging from 51 mm/yr (2 in/yr) at age one to 2190 mm (86 in/yr) for five year old trees. Five-year old estimates from Madison and Licht are nearly two and one-half times the estimated water use from three-year old estimates at Boardman, OR. No data from five-year old trees was available from Boardman for comparison.

Regressed estimates of poplar ET seem to be in reasonable agreement with suggested values provided by other authors. The hybrid poplar ET estimates calculated by the soil water balance methods from Boardman, OR should also yield reasonable estimates of seasonal crop coefficients. These crop coefficients should be applicable to other climates similar to Boardman, OR and should yield similar hybrid poplar crop ET estimates for drip-irrigated hybrid poplars when multiplied by Kimberely-Penman reference ET values. If another reference ET estimating method is used such as the original Penman method (Penman, 1948, Doorenbos and Pruitt, 1977) or the Penman-Montieth method (Montieth, 1965) then adjustments to either the crop coefficients or the crop ET will need to be made (Wright, 1995).

Table 5.2.1 from Doorenbos and Pruitt (1977) provides approximate ranges of seasonal crop ET for a variety of crops. Hybrid poplar ET estimates of 500-830 mm/season for one-through three-year old trees compare well with other similar crops such as deciduous trees (700-1050 mm/season), orange trees (600-950 mm/season), avocados (650-1000 mm/season) and grapefruit (650-1000mm/season). The estimates from Doorenbos and Pruitt are approximate ranges across a range of climate types and management practices.

Table 5.2.1 (from Doorenbos and Pruitt, 1977)

Seasonal crop ET	Mm		mm
Alfalfa	600-1500	Onions	350-600
Avocado	650-1000	Oranges	600-950
Banana	700-1700	Potatoes	350-625
Baeans	250-500	Rice	500-950
Cocoa	800-1200	Sisal	550-800
Coffee	800-1200	Sorghum	300-650
Cotton	550-950	Soybeans	450-825
Dates	900-1300	Sugarbeets	450-850
Deciduous Trees	700-1050	Sugarcane	1000-1500
Flax	450-900	Sweet Potatoes	400-675
Grains	300-450	Tobacco	300-500
Grapefruit	650-1000	Tomatoes	300-600
Maize	400-750	Wvegetables	250-500
Oil seeds	300-600	Vineyards	450-900
		Walnuts	700-1000

5.3 Source of Error in Hybrid Poplar ET and Crop Curve Estimation

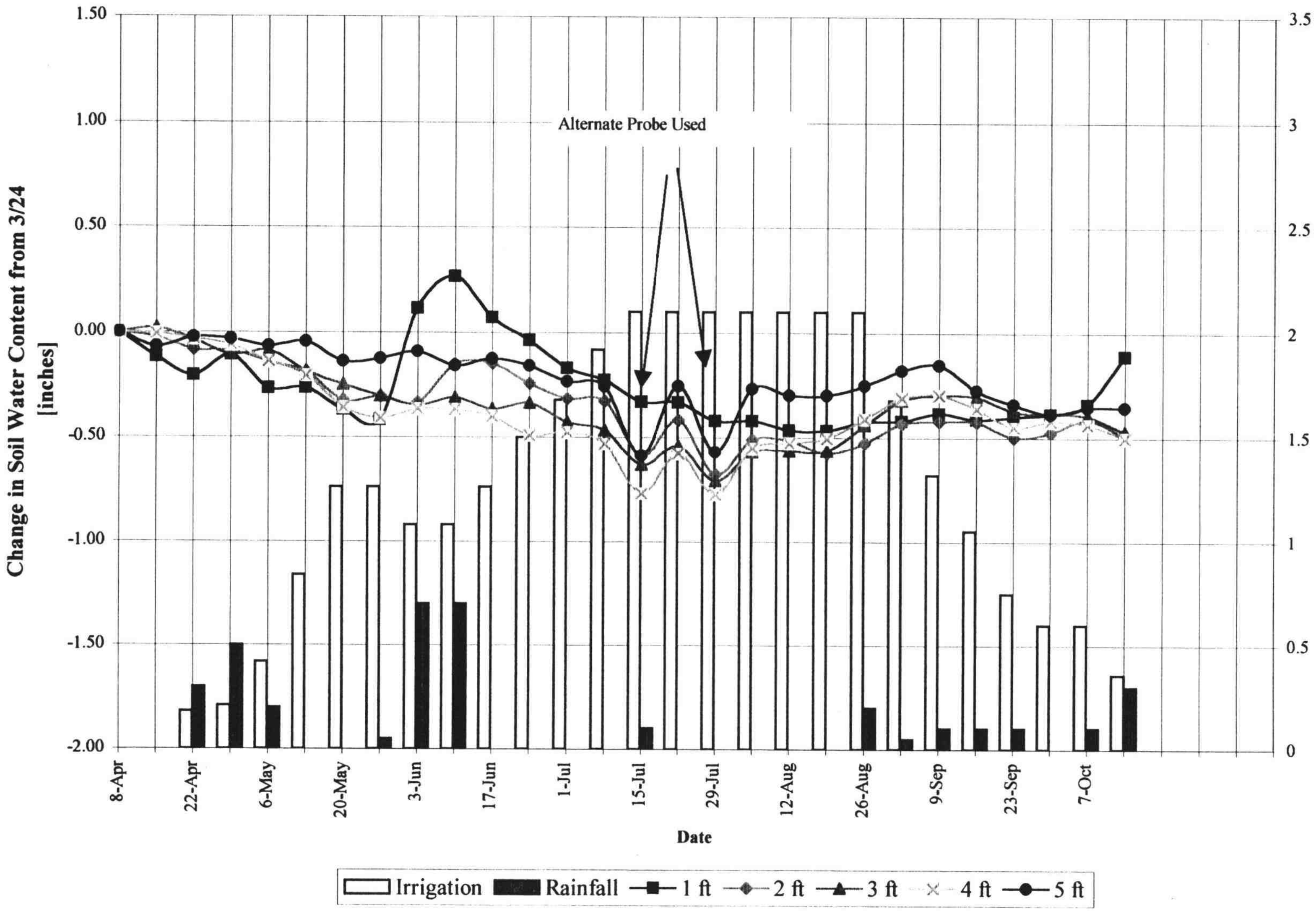
Several sources of error exist in the development of the presented ET estimates and crop curves. These sources of error contribute to the uncertainty in the evapotranspiration analysis. One of these sources of error is the uncertainty in the neutron probe calibration procedure. A discussion of factors influencing the error in neutron probe measured soil water content was provided in Section 3.2.2. Calibration of the neutron probe was carried out by IRZ consulting. The calibration coefficients were obtained by combining probe readings and gravimetric soil water content samples from a variety of locations in the same region but not limited to the poplar plantation. This will result in a calibration equation that should perform generally well throughout the entire region but may produce significant errors in local estimates. Since local estimates and their accuracy are of prime concern in this analysis, the lack of locally calibrated estimates will yield some error.

Evidence of calibration error can be found in neutron probe monitoring data. Figure 5.3.1 shows the changes in soil water content for a particular monitoring tube during 1997. The two weeks, July 15^{th} and 29^{th}, are easily discernable as the two weeks where the alternate probe was used. Such a difference in the change in soil water content between the two probe estimates yields uncertainty as to which calibration is correct. Without extensive calibration data it is impossible to quantify the amount of error in either probe. Due to soil variability each site may require an individual calibration in order to provide accurate soil water content and hence changes in soil water content estimates.

The interpolation procedure used in determining the two-dimensional soil water transect will also introduce error into the analysis. This error is introduced by the estimation of the soil water content between measurement points. The two-dimensional interpolation procedure assumes the gradient from one measurement point to another is of a particular form, in this case bi-linear. In fact, the actual transition between point estimates may be far from bi-linear. Since it impossible to measure the actual continuous distribution of soil water content a certain amount of error will have to be accepted. Geostatistical analysis may provide a better estimate of this distribution.

Error in the soil water balance exists due to non-standard soil moisture sampling times. Irrigation applications were not scheduled in cooperation with neutron probe soil water measurements. This means an error in the water balance will be introduced by taking the soil moisture readings during, closely before or closely after an irrigation session. The proximity to an irrigation application could yield locally

Figure 5.3.1 Phase 1 - Paired Site #3 - Tube 2 Ellum Soil



decreased changes in soil water content from week to week. Errors in the soil water balance from non-standard sampling times should cancel from throughout the course of the season but the change in soil water content, and thus the calculated crop coefficient, for a given week may be under- or over-estimated.

Error was introduced into the drainage analysis by assuming a single soil water retention function across the entire farm. Soil sampling across the farm revealed marked changes in soil texture and structure at different locations and at different depths. By not accounting for this variability in soil water retention processes, drainage calculations at specific sites may have been over- or under estimated. This error would lead to both the inclusion of transects having significant drainage and exclusion of transects not having significant drainage. Subsequently, crop coefficients may not be completely representative of actual hybrid poplar ET values, especially in the early season when more drainage was occurring.

The assumption that the crop curve obtained here is fully represented by a second-degree polynomial will introduce error. There is no physical significance to the use of a second-degree polynomial other than that it provides a mid-season peak value estimate with lower estimates at the beginning and end of the season. The values of the coefficients are only shape factors of the regressed curve and individually have no physical significance. Other authors have provided methods by which seasonal crop curves may be developed. Doorenbos and Pruitt (1977) suggest a piecewise fit by hand technique that is intended to capture physiological growth phases of the crop influencing plant water use. Detailed physiological information such as bud-break date, time of full canopy coverage, and leaf senescence are required, however. Not all of these biological parameters could be obtained for this study.

5.4 Discussion of Parameter Estimation Using HYDRUS-2D

The optimization procedure did not yield conclusive estimates of α, n or the irrigation application. The error surfaces of absolute total volume error suggest that n may be close to 1.6. The error surfaces of MBE suggest that the two-dimensional irrigation application rate may be less than 7 cm/day but greater than 3 cm/day. No results indicated any optimized values of α. Ideally, all three error analyses would have indicated optimized values of the parameters by yielding an error surface minima or zero error estimate at a specific point in parameter space in the case of the MBE surface.

This lack of ability to optimize the intended parameters indicates that other physical factors, possibly incorrectly initialized, are contributing to the error in these analyses. Due to the non-linearity of the retention function and the solution of the governing equation, different physical processes may have a significantly different influence on the water flow solution under different conditions. For example, though α and n are integral parts of the soil water retention function, which establishes the calculated pressure gradient across the soil profile, errors in the estimation of K_{sat} can have a significant effect on water flow at some soil-water potential gradients but then not as much at others. Depending on the shape of the retention function and the magnitude of K_{sat}, error in K_{sat} may only be significant during near saturated conditions, where soil water fluxes are relatively large. Similar discussions can be raised concerning the uncertainty in estimating the root sink function and the root uptake intensity. For this experiment, there are too many uncertain parameters to adequately implement the HYDRUS-2D numerical simulation model.

6. Recommendations

The data in this experiment were not originally intended for developing crop water use requirements. The monitoring program was established to assist in the transfer of water rights as outlined in Section 1.2.1. A soil water balance experiment, designed to determine hybrid poplar crop water use would improve the quality of the estimates presented. A detailed experiment must include site specific calibration of the neutron probe to reduce calibration errors. Precipitation data should be collected at every soil water monitoring site to remove error introduced by spatial variation of precipitation processes. Detailed soil physical characterization should be performed for each monitoring site in order to calculate the most accurate soil water retention function possible.

Sampling of soil water contents should be done continuously or more often during high ET demand to determine if soil water is a limiting factor in daily hybrid poplar ET. If soil water is not limiting and there is truly an absence of stomatal control in hybrid poplars then it could be that hybrid poplar ET is "transport limited" as discussed in Section 5.1. Transport limitation, if present, should be correlated with other physiological parameters such as xylem volume, stem diameter and tree height.

The most reliable method of ET estimation has been to incorporate the use of a sensitive weighing lysimeter. A recording, weighing lysimeter could account for water applications and hybrid poplar ET on less than a diurnal scale. It would then be possible to obtain a true mass balance by removing errors due to drainage, precipitation variability, non-uniformity in irrigation applications and errors in the calibration of the neutron probe. Using a weighing lysimeter it should be possible to obtain basal crop coefficients by removing the effects of wet soil evaporation due to precipitation. In a well managed lysimeter experiment it should also be possible to calculate the contributions of cover crop ET to the one-year old hybrid poplar estimates.

An eddy correlation system (ecor) could also provide more accurate estimates of hybrid poplar ET than using the neutron probe soil water balance. Actual crop ET is directly measured using ecor systems. No drainage estimation or soil physical characterization would be needed which would result in a reduction of error. Using an ecor system, it should be possible to obtain both mean and basal crop coefficients.

Performing drainage calculations and ET estimates in an iterative procedure for each site would improve the accuracy of the ET estimates by ensuring that mass is conserved within each transect. A numerical, physical simulation model such as HYDRUS-2D could be implemented for such a procedure. Extensive soil physical characterization would be required to obtain sufficient model representation of field conditions.

The contributions of the cover crop to one-year old hybrid poplar ET should be examined in order to obtain more accurate estimates of crop ET. A large difference between the seasonal estimated ET and applied water suggests a contribution of the cover crop to the one-year old estimates. Farm managers periodically tilled the soil between emitter lines to suppress cover crop growth. Though the one-year old estimates obtained are valid for the fields in Boardman, OR , it may be difficult to transfer these estimates to other sites with different cover crops or cover crop management practices. Ideally, the water used by the hybrid poplars alone would provide the most convenient estimates to transfer to other sites.

In order to implement a numerical simulation model such as HYDRUS-2D a thorough site characterization must be performed. Uncertainty, in the absolute values and relative effects of soil physical and root system parameters will yield poor simulation results. The use of a two dimensional model to simulate a truly three dimensional process may also be a significant factor contributing to the failure of this simulation experiment. A three-dimensional unsaturated zone model may be required to perform simulation in this field unless further techniques for transforming application rates into a two-dimensional framework can be developed. Farm managers and irrigation researchers requiring predictive estimates of irrigation and evapotranspiration processes should insist on thorough site characterization and well designed model calibration experiments to insure reliable numerical simulation results.

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APPENDIX

Table A.1 Summary of Statistics and Ranking of Methods for Monthly Estimates of E_t at All Locations[1]

Rank (1)	Method (2)	All Months %[2] (3)	All Months SEE[3] (4)	All Months b[4] (5)	All Months r[5] (6)	All Months ASEE[6] (7)	Peak Month % (8)	Peak Month SEE (9)	Peak Month b (10)	Peak Month r (11)	Peak Month ASEE (12)	Weighted SEE[7] (13)
1	Penman-Monteith	101	0.36	1.00	0.99	0.36	97	0.52	1.03	0.99	0.47	0.40
2	1982 Kimberly-Penman	107	0.53	0.95	0.98	0.49	107	0.79	0.98	0.96	0.73	0.59
3	FAO-PPP-17 Penman	111	0.66	0.93	0.97	0.56	105	0.72	0.99	0.97	0.72	0.66
4	Penman (1963)	106	0.57	0.99	0.97	0.57	99	0.95	1.07	0.96	0.81	0.67
5	Penman (1963), VPD #3	113	0.67	0.93	0.97	0.57	105	0.77	1.00	0.98	0.77	0.68
6	1972 Kimberly-Penman	112	0.74	0.93	0.96	0.67	102	0.72	1.03	0.97	0.70	0.72
7	FAO-24 Radiation	114	0.73	0.91	0.97	0.59	110	0.86	0.95	0.96	0.73	0.73
8	FAO-24 Blaney-Criddle	108	0.66	0.95	0.96	0.64	106	0.98	0.98	0.94	0.97	0.76
9	FAO-24 Penman ($c = 1$)	121	0.91	0.88	0.96	0.65	111	0.84	0.95	0.96	0.76	0.82
10	Jensen-Haise	85	0.84	1.11	0.95	0.71	83	1.44	1.15	0.92	1.06	0.95
11	Hargreaves et al. (1985)	108	0.88	1.00	0.93	0.86	101	1.47	1.07	0.87	1.39	1.05
12	Busginer-van Bavel	121	1.10	0.87	0.92	0.90	110	1.19	0.97	0.91	1.16	1.08
13	FAO-24 Corrected Penman	127	1.16	0.82	0.96	0.65	122	1.53	0.86	0.93	1.00	1.10
14	FAO-24 Pan	100	0.92	0.94	0.92	0.88	95	1.58	1.03	0.82	1.57	1.11
15	SCS Blaney-Criddle	101	1.16	0.99	0.87	1.15	103	1.31	1.05	0.89	1.26	1.20
16	Christiansen pan	92	0.95	1.03	0.91	0.94	88	1.88	1.11	0.78	1.73	1.21
17	Pan evaporation	118	1.34	0.82	0.92	0.87	113	1.82	0.88	0.83	1.56	1.35
18	Turc	90	1.30	1.20	0.89	1.07	85	2.26	1.31	0.84	1.49	1.46
19	Priestley-Taylor	85	1.29	1.22	0.90	1.02	86	2.34	1.28	0.78	1.72	1.48
20	Thornthwaite	79	1.68	1.24	0.78	1.47	79	2.69	1.41	0.79	1.70	1.84

[1] All equation estimates have been adjusted for the reference crop of the lysimeter.
[2] Average percentage of lysimeter measurements.
[3] Standard error of estimate for E_t estimates in mm d^{-1} that have not been adjusted by regression.
[4] Regression coefficient (slope) for regression through the origin of lysimeter versus equation estimates.
[5] Correlation coefficient for regression through the origin of lysimeter versus equation estimates.
[6] Standard error of estimate for E_t estimates in mm d^{-1} that have been adjusted by regression through the origin.
[7] Weighted standard error of estimate calculated as 0.7(0.67(Col. 4)+0.33(Col. 7)) + 0.3(0.67(Col. 9)+0.33(Col. 12)).

Table A.2 Crop Coefficient (Kc) for Field and Vegetable Crops for Different Stages of Crop Growth and Prevailing Climatic Conditions (from Doorenbos and Pruitt, 1977)

Crop	Humidity		RHmin >70%		RHmin <20%	
	Wind m/sec		0-5	5-8	0-5	5-8
	Crop stage					
All field crops	initial	1	Use Fig. 7 by interpolation			
"	crop dev.	2				
Artichokes (perennial-clean cultivated)	mid-season	3	.95	.95	1.0	1.05
	at harvest or maturity	4	.9	.9	.95	1.0
Barley		3	1.05	1.1	1.15	1.2
		4	.25	.25	.2	.2
Beans (green)		3	.95	.95	1.0	1.05
		4	.85	.85	.9	.9
Beans (dry) Pulses		3	1.05	1.1	1.15	1.2
		4	.3	.3	.25	.25
Beets (table)		3	1.0	1.0	1.05	1.1
		4	.9	.9	.95	1.0
Carrots		3	1.0	1.05	1.1	1.15
		4	.7	.75	.8	.85
Castorbeans		3	1.05	1.1	1.15	1.2
		4	.5	.5	.5	.5
Celery		3	1.0	1.05	1.1	1.15
		4	.9	.95	1.0	1.05
Corn (sweet) (maize)		3	1.05	1.1	1.15	1.2
		4	.95	1.0	1.05	1.1
Corn (grain) (maize)		3	1.05	1.1	1.15*	1.2
		4	.55	.55	.6 *	6
Cotton		3	1.05	1.15	1.2	1.25
		4	.65	.65	.65	.7
Crucifers (cabbage, cauliflower, broccoli, Brussels sprout)		3	.95	1.0	1.05	1.1
		4	.80	.85	.9	.95
Cucumber		3	.9	.9	.95	1.0
Fresh market		4	.7	.7	.75	.8
Machine harvest		4	.85	.85	.95	1.0
Egg plant (aubergine)		3	.95	1.0	1.05	1.1
		4	.8	.85	.85	.9
Flax		3	1.0	1.05	1.1	1.15
		4	.25	.25	.2	.2
Grain		3	1.05	1.1	1.15	1.2
		4	.3	.3	.25	.25
Lentil		3	1.05	1.1	1.15	1.2
		4	.3	.3	.25	.25
Lettuce		3	.95	.95	1.0	1.05
		4	.9	.9	.9	1.0
Melons		3	.95	.95	1.0	1.05
		4	.65	.65	.75	.75
Millet		3	1.0	1.05	1.1	1.15
		4	.3	.3	.25	.25

Crop	Humidity		RHmin >70%		RHmin <20%	
	Wind m/sec		0-5	5-8	0-5	5-8
Oats	mid-season	3	1.05	1.1	1.15	1.2
	harvest/maturity	4	.25	.25	.2	.2
Onion (dry)		3	.95	.95	1.05	1.1
		4	.75	.75	.8	.85
(green)		3	.95	.95	1.0	1.05
		4	.95	.95	1.0	1.05
Peanuts (Groundnuts)		3	.95	1.0	1.05	1.1
		4	.55	.55	.6	.6
Peas		3	1.05	1.1	1.15	1.2
		4	.95	1.0	1.05	1.1
Peppers (fresh)		3	.95	1.0	1.05	1.1
		4	.8	.85	.85	.9
Potato		3	1.05	1.1	1.15	1.2
		4	.7	.7	.75	.75
Radishes		3	.8	.8	.85	.9
		4	.75	.75	.8	.85
Safflower		3	1.05	1.1	1.15	1.2
		4	.25	.25	.2	.2
Sorghum		3	1.0	1.05	1.1	1.15
		4	.5	.5	.55	.55
Soybeans		3	1.0	1.05	1.1	1.15
		4	.45	.45	.45	.45
Spinach		3	.95	.95	1.0	1.05
		4	.9	.9	.95	1.0
Squash		3	.9	.9	.95	1.0
		4	.7	.7	.75	.8
Sugarbeet		3	1.05	1.1	1.15	1.2
		4	.9	.95	1.0	1.0
	no irrigation last month	4	.6	.6	.6	.6
Sunflower		3	1.05	1.1	1.15	1.2
		4	.4	.4	.35	.35
Tomato		3	1.05	1.1	1.2	1.25
		4	.6	.6	.65	.65
Wheat		3	1.05	1.1	1.15	1.2
		4	.25	.25	.2	.2

A.3 Soil Water Retention Curves