AN ABSTRACT OF THE THESIS OF

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The application of the widely used Penman-Monteith evapotranspiration equation to hybrid poplar trees is impossible without a valid surface resistance. The increase in applications of drip-irrigated hybrid poplar trees for wood chip stock and veneer production, as well as bioremediation, constitutes a need for estimating the evapotranspiration of these trees. To the author's knowledge, there are no published estimates of surface resistance for poplar trees.

Six years of weekly soil moisture content for drip-irrigated, hybrid poplar trees were used in a water balance to compute evapotranspiration. The weekly data were adjusted with reference evapotranspiration data to compute a daily evapotranspiration. Only data that represent fully leaved hybrid poplars are used in this study and the data were screened for the effects of drainage. Additional parameters applied in this study include solar radiation, temperature, wind speed and relative humidity taken at a nearby AGRIMET Weather Station.

The results of this study indicate that surface resistance values cannot be described as a function of meteorological data within the constraints of the current experiment design. The graph of poplar evapotranspiration versus surface resistance shows that for a given evapotranspiration there can be multiple r_s values. This scatter is the influence of parameters other than r_s within the Penman-Monteith model. The use of an instrument to directly measure the surface resistance is recommended in further studies.

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Penman-Monteith Surface Resistance for Hybrid Poplar Trees

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Dana Anthony Butler

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Penman-Monteith Surface Resistance for Hybrid Poplar Trees

1. Introduction

The purpose of this thesis is to determine the surface resistance of drip-irrigated hybrid poplar trees. The surface resistance is also known as the stomatal resistance. The stomata are openings in the leaf surface that control the release of water vapor. The release of water vapor is necessary to allow for the dissolution of CO_2 so that it can enter the plant tissue (Dingman, 1994). Plants require CO_2 to make carbohydrates and thus survive. The determination of surface resistance values will provide a means for the direct calculation of evapotranspiration through the Penman-Monteith equation. Evapotranspiration is the amount of water lost through evaporation from the soil surface and the transpiration from the plant's leaves. Evapotranspiration data are imperative to appropriate and efficient irrigation. This thesis is built upon earlier work by Gochis (Gochis, 1998).

The study by Gochis used three years of drip-irrigated hybrid poplar tree soil moisture data to calculate crop coefficient values. Crop coefficient values account for all of the physiological differences between a reference crop and the crop of interest. A crop curve relating crop coefficients to day of year is useful for estimating plant evapotranspiration. A direct calculation of the evapotranspiration using the Penman-Monteith equation should prove more accurate than application of a crop coefficient to reference ET. The Penman-Monteith method has several parameters that are used to characterize the plant and individually account for the physiological differences.

Accuracy in the determination of evapotranspiration is important for irrigation scheduling.

This study uses six years of drip-irrigated hybrid poplar soil moisture data and the Penman-Monteith equation to calculate the surface resistance of hybrid poplar trees. The Penman-Monteith equation is physically based and when solving for the surface resistance, mean daily temperature, evapotranspiration, net solar radiation, relative humidity and wind speed data are the required inputs. The other variables in the Penman-Monteith equation can be calculated from this information.

Hybrid poplar trees are widely used in the wood products and bioremediation industries. The decline of economically available timber supplies has increased the popularity of hybrid poplar farms (Eaton and Finley, 1996). The use of hybrid poplars for bio-remediation of heavy metals and the uptake of nitrogen and phosphorous rich treated wastewater are now commonplace (Jordahl, et al., 1997). This study uses irrigation and rainfall data from the Potlatch Hybrid Poplar Farm for analysis.

Calculation of crop coefficients and other methods for estimating drip-irrigated hybrid poplar tree evapotranspiration have been studied. However to the author's knowledge, there has been no published data on the surface resistance of these trees. This thesis will provide surface resistance estimates for six years growth of drip-irrigated hybrid poplar trees grown on the Columbia River Plateau near Boardman, Oregon.

2. Literature Review

2.1 Overview of Poplar Trees

As the wood products industry in the Pacific Northwest continues to suffer from raw material supply problems, interest in experimenting with hybrid poplars is certain to increase (Leavengood, 1997). *Populus* is a deciduous genus of broadleaved trees of some 40 species found naturally in the Northern Hemisphere. Only about 10 of these species are of importance to major timber producers (Pryor and Willing, 1982). Hybrids are crosses between different species in the genus *Populus*. This genus is made up of 25 species including black cottonwood, eastern cottonwood, quaking aspen, balsam poplar, white poplar, European black poplar and Lombardy poplar (Leavengood, 1997). Poplar wood is white, has a suitable density for wood products, an even texture, and is without taste or odor (Pryor and Willing, 1982). *Populus* is within the family Silcaceae together with *Salix*, the willows, and the monotypic genus, *Chosenia*, of eastern Asia (Pryor and Willing, 1982). Table 2.1 details the genus divided into sections (Pryor and Willing, 1982). Hybridizing can take place between 2 to 4 species. Species within each section, (see table 2.1), will interbreed (Pryor and Willing, 1982).

Table 2.1 Poplar Species. (from Pryor and Willing, 1982)

Section	Common Name	Important Species
1 Leuce	White Poplar	alba
	Aspen	tremula
		tremuloides
		grandidentata
2 Aigeiros	Black Poplar	nigra
	Cottonwood	deltoides
3 Tacamahaca	Balsam Poplar	trichocarpa
		yunnanensis
		maximowiczii
4 Leucoides	Swamp Cottonwood	heterophylla
		ciliata
5 Turanga		euphratica

Poplar clonal growing stock is produced from the cultivation of stem cuttings allowing for extensive development of crosses that yield superior plant material (Pryor and Willing, 1982). The most important characteristics are rate of growth, stem and branch form, leaf bud dormancy relationship to day length, disease resistance and stability against wind (Pryor and Willing, 1982). The two factors that markedly affect the value of poplar wood are the wood density and tension wood. Wood density is the relationship of oven-dry weight to green volume. Green volume is the volume of the wood before it is oven dried. Density is strongly correlated with the strength of the timber and the amount of woody material present in a stem of a given volume. Tension wood results from a response by the stem to tension forces within it during growth. Leaning stems

develop higher tension on the upper side. Leaning develops on outside rows by trees reaching for light or elsewhere due to accidental causes. Tension wood does not peel easily to make good veneer (Pryor and Willing, 1982).

Short-rotation wood-crop (SRWC) tree plantations are those intensively managed using agronomic techniques such as site preparation, fertilization, irrigation and weed control to maximize biomass production over very short rotation lengths, typically 4-8 years (Lortz et al., 1994). The new hybrid poplar plantations in the Pacific Northwest were established to supply pulp and paper mills (Leavengood, 1997). Hybrid poplar trees are also used in laminated strand lumber, oriented strand lumber, veneer for plywood, solid-sawn products and fiber products (Leavengood, 1997).

2.2 Overview of Penman Monteith Equation

Accuracy in evapotranspiration estimates is crucial to irrigation management and design. Penman's combination of energy balance and aerodynamic equations provides a means for estimating theoretical values of evapotranspiration based on readily available meteorological data (Allen, 1986; FAO 56). The Penman-Monteith evapotranspiration equation is a physically based model that uses surface and aerodynamic resistances to parameterize water vapor transfer from the canopy to the atmosphere (Stockle, 1996). A paper written in

1989 by Allen et al., compared evapotranspiration data computed by the Penman-Monteith equation and other forms of the Penman equation to actual lysimeter measured data at eleven international sites. (Table 2.2) The Penman-Monteith method and a Penman equation with a variable wind function provided the best estimates of reference ET across the sites (Allen, et al., 1989). Standard errors for the evapotranspiration estimates varied for early, mid and late season as well as for humid and arid regions. The Penman-Monteith combination equation has been determined as the best method for estimating actual evapotranspiration for the reference crop (Smith et al., 1996; Allen et al., 1989; Jensen et al., 1990, Rana et al., 1996; FAO 56, 1998).

The Food and Agricultural Organization (FAO) Irrigation and Drainage paper 56, titled "Crop Evapotranspiration, Guidelines for computing crop water requirements" is the result of a collaboration of experts who met in May 1990 to review FAO methodologies on crop water requirements. The Penman-Monteith combination method was recommended to be the new standard for reference evapotranspiration (FAO 56, 1998). The Penman combination evapotranspiration equation combined with the aerodynamic and canopy resistance equations developed by Monteith is the basis of the Penman-Monteith equation (Allen, 1986).

Table 2.2 A comparison of ET methods. (from Smith et al., 1996)

LOCATIONS	HUMID			ARID		
Performance Indicator	**Rank**	**Over Estimate**	**Std. Error**	**Rank**	**Over Estimate**	**Std. Error**
COMBINATION METHODS						
Penman-Monteith	1	4%	0.32	1	-1%	0.49
FAO-24 Penman (c=1)	14	29%	0.93	6	12%	0.69
FAO-24 Penman (corrected)	19	35%	1.14	10	18%	1.10
FAO -PPP-17 Penman	4	16%	0.67	5	6%	0.68
Penman (1963)	3	14%	0.60	7	-2%	0.70
Penman 1963, VPD #3	6	20%	0.69	4	6%	0.67
1972 Kimberley Penman	8	18%	0.71	8	6%	0.73
1982 Kimberley Penman	7	10%	0.69	2	3%	0.54
Businger-van Bavel	16	32%	1.03	11	11%	1.12
RADIATION METHODS						
Priestley Taylor	5	-3%	0.68	19	-27%	1.89
FAO-Radiation	11	22%	0.79	3	6%	0.62
TEMPERATURE METHODS						
Jensen-Haise	12	-18%	0.84	12	-12%	1.13
Hargreaves	10	25%	0.79	13	-9%	1.17
Turc	2	5%	0.56	18	-26%	1.88
SCS Blaney-Criddle	15	17%	1.01	15	-16%	1.29
FAO Blaney-Criddle	9	16%	0.79	9	0%	0.76
Thornwaite	13	-4%	0.86	20	-37%	2.40
PAN EVAPORATION METHODS						
Class A Pan	20	14%	1.29	17	21%	1.54
Christiansen	18	-10%	1.12	16	-6%	1.41
FAO Class A	17	-5%	1.09	14	5%	1.25

The general form of the original Penman equation (Allen, 1986) is:

$$E_t = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma}E_a \qquad (1)$$

E_t evapotranspiration [mm/d]

Δ slope of the saturation vapor pressure-temperature curve calculated at mean air temperature [mb/°K]
γ psychrometric constant [mb/°K]
R_n net long-wave and short-wave radiation [mm/d] water equivalent
G heat flux in the soil [mm/d] water equivalent
E_a aerodynamic vapor transport term [mm/d]

where, $E_a = f(u)(e_a - e_d)$ (2)

$f(u)$ either an empirically or theoretically derived wind function
e_a saturation vapor pressure, [mb] at height z above ground surface
e_a evaluated at either the mean air temperature or as the average of the saturation vapor pressures at the maximum and minimum air temperatures
e_d saturation vapor pressure, [mb] at the dew point temperature

$f(u) = 0.263(a_w + b_w u)$ (3)

u wind speed at 2 m elevation [m/s]
a_w empirical coefficient, Penman (1948, 1963) suggests 1.0 for grass
b_w empirical coefficient, Penman (1948, 1963) suggests 0.537 for grass

$R_n = (1-\alpha)R_s - \sigma T_a^4 (0.56-0.092(e_d)^{0.5})(0.10 + 0.90\ n/N)$ where, (4)

R_s incident short-wave solar radiation, [mm/d] water equivalent
α surface albedo
σ Stefan-Boltzman constant, 2×10^{-9} mm day^{-1} [°K^{-4}]
T_a mean air temperature [°K]
n/N ratio of actual to possible hours of sunshine

$G = (T_a - T_p)c_s$ (5)

T_a mean daily air temperature [°K]
T_p mean air temperature for the preceding three days [°K]
c_s empirical specific heat coefficient for the soil surface

Wright (1982), Jensen (1974), Monteith (1965), and Brutsaert (1982) among others varied empirical terms and continued to improve the accuracy of the Penman equation. Monteith (1965) incorporated canopy and aerodynamic resistances into the Penman combination equation and the equation became known as the Penman-Monteith equation. This equation is given as,

$$E_t = \frac{\Delta}{\Delta + \gamma^*}(R_n - G) + \frac{\gamma^*}{\Delta + \gamma^*} E_a \quad (6)$$

where E_t, R_n, G, and E_a have units of mm/d

$$\gamma^* = \gamma(1 + r_c/r_{av}) \tag{7}$$

r_c canopy/stomatal/surface resistance parameter [s/m]
r_{av} aerodynamic resistance to water vapor [s/m]

$$r_{av} = \frac{\left[\ln\left(\frac{z_m - d}{z_{om}}\right)\right]\left[\ln\left(\frac{z_h - d}{z_{ov}}\right)\right]}{k^2 u_z} \tag{8}$$

z_m height of wind speed measurements [m]
d zero plane displacement of wind profile [m]
z_h height of air temperature and humidity measurements [m]
u_z wind speed at height z [m/s]
z_{om} surface roughness length for transport of momentum [m]
z_{ov} surface roughness length for transport of vapor [m]
k von Kármán constant of proportionality [0.41]

$$E_a = \frac{\rho c_p (e_a - e_d)}{\lambda \gamma r_{av}} (8.64x10^7) \tag{9}$$

ρ density of air [g/cm^3]
c_p specific heat of air at constant pressure (0.24 cal g^{-1} $^oK^{-1}$)
λ latent heat of vaporization [cal/g]
γ psychrometric constant [mb/ ^oK]

$$\lambda = 595 - 0.51(T_a\text{-}273.16) \tag{10}$$

$$r_c = \frac{(500 - 0.85R_n)}{LAI} \tag{11}$$

LAI leaf area index

The Penman combination and the Penman-Monteith equation are designed to yield a reference crop evapotranspiration. The common method for estimating crop evapotranspiration is to multiply a crop coefficient, K_c, times the reference crop evapotranspiration (Allen et al., 1989; Gochis, 1998). The K_c coefficient takes

into account all of the physiological differences between the reference crop and the crop of interest (FAO 56, 1998). The FAO 56 Penman-Monteith equation (Chapter 3.3) combines several of the steps above. The succinct equation is:

Penman – Monteith equation (FAO 56, p.19)

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a C_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \tag{12}$$

λ	latent heat of vaporization [MJ kg^{-1}]
λET	latent heat flux density of evaporation [MJ $m^{-2}d^{-1}$]
R_n	net radiation flux density at surface [MJ $m^{-2}d^{-1}$]
G	soil heat flux [MJ $m^{-2}d^{-1}$]
ρ_a	atmospheric density [kg m^{-3}]
C_p	specific heat of moist air [kJ kg^{-1} $^0C^{-1}$]
e_a	actual vapor pressure [kPa]
e_s	saturation vapor pressure [kPa]
r_a	aerodynamic resistance [s m^{-1}]
Δ	slope of the saturation vapor curve [kPa $^0C^{-1}$]
γ	psychrometric constant [kPa $^0C^{-1}$]
r_s	surface/stomatal resistance [s m^{-1}]

Solving for r_s

$$r_s = r_a \left(\frac{\Delta(R_n - G) + \rho_a C_p \dfrac{(e_s - e_a)}{r_a} - \lambda ET\Delta}{\lambda ET\gamma} - 1\right) \tag{13}$$

aerodynamic resistance, r_a, can be computed as

$$r_a = \frac{\ln \frac{z_m - d}{z_{om}} \ln \frac{z_h - d}{z_{oh}}}{k^2 u_z} \quad (14)$$

z_m height of wind speed measurements [m]
d zero plane displacement of wind profile [m]
z_h height of air temperature and humidity measurements [m]
z_{om} roughness parameter for momentum [m]
z_{oh} roughness parameter governing transfer of heat and vapor scalars [m]
k von Kármán constant (0.41)
U_z measured wind speed at z_m height [m s^{-1}]

z_m 2 m at AgriMet weather station

$d = 2/3$ h (Allen et al., 1989)

$z_{om} = h/8.15$ (Allen et al., 1989)

$z_{oh} = 0.1\ z_{om}$ (Allen et al., 1989)

h crop height (m) (Estimated by Potlatch Poplar Farm manager Jake Eaton)

1-yr old trees: $h_1 = 3.66$ m
2-yr old trees: $h_2 = 8.54$ m
3-yr old trees: $h_3 = 12.20$ m
4-yr old trees: $h_4 = 15.85$ m
5-yr old trees: $h_5 = 19.51$ m
6-yr old trees: $h_6 = 22.56$ m

$$\Delta = \frac{4098\left[0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right)\right]}{(T + 237.3)^2} \quad (15)$$

Δ slope of saturation vapor curve [kPa $^0C^{-1}$]
T mean daily temperature [^0C]

$$R_n = R_s - R_{nl} \quad (16)$$

R_s incoming solar radiation measured at the HERO AgriMet station [langley]
1 langley = 4.1868 x 10^{-2} MJ $m^{-2}d^{-1}$

$$R_{nl} = \sigma(T_{mean})(0.34 - 0.14\sqrt{e_a})\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \quad (17)$$

R_{nl} Net outgoing long wave radiation [MJ $m^{-2}d^{-1}$]
σ Stefan-Boltzman constant [4.903 10^{-9} MJ K^{-4} $m^{-2}d^{-1}$]
T_{mean} mean absolute temperature during the 24-hr period [K^4] [K = ^{0}C + 273.16]
e_a actual vapor pressure [kPa]
R_s/R_{so} relative shortwave radiation
R_s measured shortwave radiation [MJ $m^{-2}d^{-1}$]
R_{so} calculated clear sky radiation [MJ $m^{-2}d^{-1}$]

$$R_{so} = (0.75 + 2\ 10^{-5}z)R_a \quad (18)$$

z weather station elevation (182.9 m)
R_a extraterrestrial radiation [MJ $m^{-2}d^{-1}$]

$$R_a = \frac{24(60)}{\pi}G_{sc}d_r[\omega_s \sin(\varphi)\cos(\delta)\sin(\omega_s)] \quad (19)$$

G_{sc} solar constant = 0.0820 MJ $m^{-2}min^{-1}$
d_r inverse relative distance Earth-Sun
ω_s sunset hour angle [rad]
φ latitude [rad]
δ solar declination [rad]

$$d_r = 1 + 0.33\cos\left(\frac{2\pi}{365}J\right) \quad (20)$$

J Day of Year (Table 2.5, FAO 56)

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \quad (21)$$

$$\varphi = 45.47.56 \text{ [decimal degrees]}\ \frac{\pi}{180} = 0.799012 \text{ [radians]} \quad (22)$$

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right) \quad (23)$$

G soil heat flux [MJ $m^{-2}d^{-1}$] on a daily basis is relatively small and may be ignored, thus $G = 0$

$$\rho_a = \frac{1000P}{T_{Kv}R} \text{ [kg m}^{-3}\text{]} \quad (24)$$

R specific gas constant = 287 [J kg^{-1}K^{-1}]

$$\rho_a = 3.486\frac{P}{T_{Kv}} \text{ [kg m}^{-3}\text{]} \quad (25)$$

T_{Kv} virtual temperature [K]

$$T_{Kv} = T_K(1 - 0.0378\ \frac{e_a}{P})^{-1} \quad (26)$$

T_K absolute temperature

$$T_K = 273.16 + T[^0\text{C}] \quad (27)$$

e_a actual vapor pressure [kPa]

$$P = P_o\ (\frac{T_{Ko} - \alpha_1(z - z_o)}{T_{Ko}})^{\frac{g}{\alpha_1 R}} \quad (28)$$

P atmospheric pressure at elevation z [kPa]
P_o atmospheric pressure at sea level = 101.3 [kPa]
z elevation [m] = 182.9 m
z_o elevation at reference level [m] = 0
g gravitational acceleration = 9.807 [m s^{-2}]
R specific gas constant = 287 [J kg^{-1}K^{-1}]
α_1 constant lapse rate moist air = 0.0065 [K m^{-1}]
T_{Ko} temperature [K] at elevation z_o

C_p specific heat at constant pressure = 1.013 x 10^{-3} [MJ kg^{-1} ^{0}C^{-1}]

$$e_s = e^o(T_{mean}) \quad (29)$$

e_s saturation vapor pressure [kPa]
$e^o(T_{mean})$ saturation vapor pressure function [kPa]

$$e^o(T_{mean}) = 0.6108 \exp\ [\frac{17.27T}{T + 273.3}] \quad (30)$$

T mean daily temperature [^{0}C]

$$e_a = \frac{RH}{100}[\ e^o(T_{mean})\ ] \quad (31)$$

e_a actual vapor pressure [kPa]
RH mean measured relative humidity [%]

$$\lambda = 2.501 - (2.361 \times 10^{-3})T \quad (32)$$

λ latent heat of vaporization [MJ kg^{-1}]
T mean daily temperature [^{0}C]

ET calculated from water balance [mm/d]

$$\gamma = \frac{C_p P}{\varepsilon \lambda} = 0.00163\ \frac{P}{\lambda} \quad (33)$$

γ psychrometric constant [kPa $^0C^{-1}$]
P atmospheric pressure [kPa]
ε ratio molecular weight of water vapor/dry air = 0.622

2.3 Water Balance Method to Calculate Evapotranspiration

The water balance equation for a soil profile is:

$$\Delta S = P - ET - D - R \quad \text{where,} \quad (34)$$

ΔS change in soil profile water storage [mm]
P precipitation [mm]
ET evapotranspiration [mm]
R runoff [mm]
D deep percolation [mm]

Solving for ET

$$ET = -\Delta S + P - D - R \quad (35)$$

The water balance method for estimating evapotranspiration is widely used since it is less expensive than lysimeter and other evapotranspiration measuring methods (Evett et al., 1993). Precise weighing lysimeters are extremely accurate devices for measurement of evapotranspiration, however they greatly disturb the soil profile, interrupt deep percolation, have heat flux distortions from the steel walls and typically cost more than $65,000 (Evett et al., 1993).

Application of neutron probes is a common way to measure soil water content that is inexpensive compared to lysimeters (Evett et al., 1993). The use of neutron scattering for water balance studies has been documented as being imprecise for measurements near the surface (Evett et al., 1993). In a 16-day experiment developing a water balance using neutron probes and comparing the data with lysimeter data, Evett et al. (1993) discovered neutron probe measurements to be in error by 3.6 mm. In another experiment, Evett et al. (1993) coupled TDR probes for surface measurements with neutron scattering probes for measurements at depth and the water balance was determined to be within 0.7 mm of the lysimeter reading (Evett et al., 1993). The amount of error is significantly reduced when TDR probes for surface measurements are used.

It has been discovered that much of the error associated with using neutron probes for soil water balance occurs when the probe does not extend below the depth of wetting due to irrigation (Evett et al., 1993). In the analysis presented in

this thesis, the probes extend to a depth of 1.52 m and the wetting front does not extend beyond 0.92 m.

In an analysis of error performed by Haverkamp et al., (1984) the estimated variance was comprised of two terms, the instrument and the soil calibration components. It has been shown that the source of error associated with the neutron probe can be reduced by increasing the number of count replications at each sampling point, or the counting time, or both (Haverkamp et al., 1984; Carrijo and Cuenca, 1992). The instrument component of standard error as function of soil layer thickness and number of reading for which $var(\theta) = 1.106603 \times 10^{-5}$ decreased by 80 – 90% when four additional readings were taken for each depth (Carrijo and Cuenca, 1992).

Haverkamp et al. (1984) found that the soil calibration component represents the major contribution to the total variance of an individual water content estimate. Using an unbiased technique, like the least squares technique, notably decreases the total variance of water contents and soil water storage (Haverkamp et al., 1984).

In a study by Evett and Steiner (1995), two models of neutron scattering gauges were used (three gauges of each). Both models of neutron scattering gauges were calibrated vs. volumetric soil water content with coefficients of determination (r^2) ranging from 0.97 to 0.99 and root mean squared errors <0.012 m^3m^{-3} water content. The average 95% confidence interval on predictions ranged from 0.0153 to 0.0161 m^3m^{-3} (Evett and Steiner, 1995). Data presented by Evett and Steiner

(1995) and Carrijo and Cuenca (1992) indicate that the neutron probe can be used effectively for hydrologic balance studies and this technique was applied to this study.

3. Data and Methods

3.1 Data Collection

3.1.1 Potlatch Hybrid Poplar Farm Data

Soil moisture data were collected at the Potlatch Poplar Farm in Northeast Oregon near Boardman. The Potlatch Poplar Farm covers approximately 9105.46 ha and has six phases of hybrid poplar tree growth with ages ranging from 1-yr to 6-yr old (Eaton and Finley, 1996). The Potlatch Poplar Farm is located at 119031'46" 45047'56" N and an elevation of 182.93 m above sea level. The farm is located in the high desert near the Columbia River. The Columbia River provides a reliable source of irrigation water. The growing season has 190 frost-free days. The soil types are sandy loams consisting of primarily Quincy soil with some Irrigon soil found in Phase 1 and Phase 2 trees.

The trees are the result of a rigorous clonal testing program. The trees are mass propagated at contract stool beds, then processed and stored for spring planting (Eaton and Finley, 1996). The field is leveled, the soil is ripped and a pre-emergent herbicide is used to prepare the site. After the planting is completed,

herbicides are applied as well as cultivation and pest monitoring (Eaton and Finley, 1996).

Oregon law mandates that irrigation water must be applied to the land specified in the originally granted water rights agreement. In an effort to comply with Oregon Law, but also to expand acres of tree growth, the Potlatch Corporation and the Oregon State Board of Water Resources developed a new plan. The plan consists of a relocation of unirrigated acres. The Potlatch Corporation currently irrigates with a drip irrigation system. The drip irrigation system leaves a 0.61 m dry zone in the middle of the tree rows. The new plan takes this unirrigated area and moves the water rights to a new area on the farm. The plan included a rigorous monitoring program of the 0.61 m dry zone to be completed by the Hydrologic Science Team (HST) of Oregon State University (OSU) and Hydrologic Engineering, Inc. (HEI).

The data used in this thesis has been created for the monitoring program. A different method would have been created if the funding was for this thesis topic by itself. The data used here within are the best available data and every effort has been exercised to maintain quality assurance.

3.1.2 Soil Moisture Data

HST and HEI used neutron probe measurements to monitor the soil moisture content. The neutron probe uses a radioactive source to emit fast moving neutrons. The radioactive material discharges excited or high-energy neutrons through the access tube that bounce off or collide with hydrogen atoms. As a neutron bounces off a hydrogen atom, the neutron's speed is reduced and the number of slow moving neutrons is counted. The information is collected by a microprocessor that has been calibrated to count the number of returning neutrons per unit of time. That number can be translated into the amount or concentration of water in the soil. A higher reading corresponds with a higher moisture content (Evett et al., 1993).

Each of the six years of tree growth is labeled as a phase. Phase 1 are the 6-year-old trees, Phase 2 are the 5-year-old trees, Phase 3 are the 4-year-old trees, Phase 4 are the 3-year-old trees, Phase 5 are the 2-year-old trees and Phase 6 are the 1-year-old trees. The trees are grown along emitter lines. The emitter lines are spaced 3.05 m apart with emitters on each line spaced 1.22 m apart. Monitoring transects consist of six neutron probe access tubes with the exception of Phase 2 Transect 1. Phase 2 Transect 1 is a larger transect with 11 neutron probe access tubes. All of the neutron probe access tubes are aluminum tubes spaced 0.61 m apart and are 1.50 m deep. Neutron probe counts are read at 0.30 m intervals from 0.30 m to 1.50 m. Thirty readings are taken for each transect. Phase 2 Transect 1

has fifty-five readings taken for the entire transect. Phase 1, Phase 2 and Phase 3 have two monitoring transects. Phase 4, Phase 5 and Phase 6 have one monitoring transect. Neutron probe counts are taken weekly over the entire irrigation season, usually from April 1 to October 15. According to the plan, the 0.61 m space between the third and fourth access tubes is labeled as the dry zone.

The data consist of five years of evapotranspiration data for 1-year-olds, five years for 2-year-olds, four years for 3-year-olds, three years for 4-year-olds, two years for 5-year-olds and one year for 6-year-olds. Soil moisture data for the one-year olds in 1999, Phase 6, were measured with a Troxler probe. The new instrument contains new unquantifiable errors that makes the grouping of these data with the other one-year-old data impossible.

IRZ Consulting of Hermiston, Oregon completed the fieldwork portion of this plan. On a weekly basis, a field technician from IRZ Consulting visited the Potlatch Poplar Farm and collected soil moisture data using the neutron probe. Neutron probe counts were submitted electronically to the Hydrologic Science Team for calculation of soil water content and soil water content change.

Neutron probe counts were converted to percent soil moisture with the following calibration equation provided by IRZ Consulting:

$$\theta = a + n \cdot b \tag{36}$$

where a and b have the following values:

$$a = 0.315354$$

$$b = 0.0001669$$

θ is the soil moisture content (cm^3/cm^3) and n is the neutron probe count. The percent soil moisture content was multiplied by the (volume of the transect of interest/area of the transect of interest) to get an equivalent depth of water (cm) in the transect per 30.48 cm.

3.1.3 Irrigation Data

Potlatch Corporation provided irrigation data in hours of irrigation per phase per week. A sophisticated computerized irrigation system provides assured hours of irrigation. Irrigation cycles depend on the time of year and the age class of trees. Irrigation begins with one 2-3 hour set every third day. In the peak of the summer irrigation cycles are either two sets for four hours or three sets for three hours (Eaton, personal communication). The water delivery system is designed to operate at 757 m^3/min (Eaton and Finley, 1996). Irrigation of the hybrid poplar trees was through a drip irrigation system. The drip emitters apply 0.003 m^3 of water per hour at the operating pressure. Irrigation was computed using the number of hours the water was pumped to a certain phase. A volume of water can be found by multiplying the number of hours of irrigation by the application rate. This volume divided by the area of irrigated acres yields the depth of water applied in inches per week. The depth was multiplied by 2.54 to yield an irrigation depth in centimeters (See Table 3.1).

Table 3.1 Example of Irrigation Data

(* represents proprietary information.)

June 19**	(cm)					
Location	5/27-6/2	6/3-6/9	6/10-6/16	6/17-6/23	6/24-6/30	Total
Phase *	2.74	3.96	3.81	4.88	4.72	20.12
Phase *	2.74	3.96	3.81	4.88	4.65	20.04
Phase *	1.83	2.90	2.74	3.81	3.66	40.16
Phase *	1.83	2.90	2.59	3.20	3.20	13.72
Phase *	0.84	0.91	0.91	1.37	1.07	5.11

3.1.4 Rainfall Data

Rainfall was measured in open catch can type rain gauges. The gauges have a layer of oil to prevent evaporation. Rainfall was measured in inches per week and converted to centimeters per week. There was at least one rain gauge per phase. The rainfall over an entire phase is considered uniform. The Potlatch Corporation provided rainfall data (See Table 3.2).

Table 3.2 Example of Rainfall Data

(* represents proprietary information.)

June 19**	(cm)					
Location	5/27-6/2	6/3-6/9	6/10-6/16	6/17-6/23	6/24-6/30	Total
Phase *	0.51	0.25	0.00	0.00	0.13	0.89
Phase *	0.38	0.25	0.00	0.00	0.13	0.76
Phase *	0.38	0.25	0.00	0.00	0.13	0.76
Phase *	0.25	0.25	0.00	0.00	0.13	0.64
Phase *	0.25	0.25	0.00	0.00	0.13	0.64

3.1.5 AgriMet Weather Data

The weather inputs for the Penman-Monteith equation were measured at the Agricultural Meteorology monitoring network (AgriMet) station located at the Hermiston Agricultural Research Extension Center (HERO). The HERO AgriMet station is located approximately five miles north of the Potlatch Poplar Farm. The mean daily temperature, mean daily relative humidity, cumulative incoming solar radiation and average daily wind speed above a reference crop were used for this analysis. The AgriMet network uses the following equipment (USBR,1999):

Table 3.3 AgriMet Weather Equipment

Equipment	Manufacturer
Data Logger Model CR10X	Campbell Scientific, Inc.
GOES Transmitter Model TGT-1	Telonics, Inc.
Data Collection Platform Model 8004	Sutron, Inc.
Data Collection Platform Model VX-1100	Vitel, Inc.
Yagi Antenna, Model 5000-0080	Sutron, Inc.
Top Hat Antenna Model V2TH	Vitel, Inc.
10 Watt Solar Panel Model MSX-10	Solarex, Inc.
Solar Panel Regulator Model JL-2	Vitel, Inc.
31-PHD Workaholic Battery	Interstate Batteries, Inc.
Station Tripod	U.S. Bureau of Reclamation
NEMA 4-E Enclosure Model A-24 H20 CLP	Hoffman, Inc.
Sensors	**Manufacturer**
Pyranometer Model LI-200SB	Licor, Inc.
Wind Monitor Model 05103	RM Young, Inc.
Air Temperature Thermistor Model 44030	YSI, Inc.
Relative Humidity Sensor Model HMP 35A/45D	Vaisala, Inc.
Temperature/RH Radiation Shield Model 41002P	RM Young, Inc.
Tipping Bucket Precipitation Gage Model 6011A/6010	Qualimetrics, Inc.
Universal Storage Precipitation Gage	Belfort, Inc.
Soil Temperature Thermistor Model 44030	YSI, Inc.
Leaf Wetness Sensor Model 237	Campbell Scientific, Inc.
Evaporation Pan	Novalynx, Inc.

On several occasions either wind speed, temperature, solar radiation or relative humidity data from the AgriMet station were unavailable and those days were not included in this analysis. Table 3.4 shows the percentage of days that were used in this analysis in comparison to the total possible number of days.

Table 3.4 Percentage of Days Used for Each Age Group

	One Yr. Old	Two Yr. Old	Three Yr. Old	Four Yr. Old	Five Yr. Old	Six Yr. Old
Days not Used	115	81	29	34	6	5
Total Days	852	852	679	512	342	172
% Used	86.50	90.49	95.73	93.36	98.25	97.09

3.2 Hybrid Poplar Evapotranspiration Computation on a Weekly Basis

3.2.1 Soil Water Balance

The evapotranspiration of a transect has been found by performing a soil water balance. The soil water balance for this study is shown by equation 37.

$$ET = IR + R - \Delta \quad \text{where,} \tag{37}$$

ET	evapotranspiration of a transect on a weekly basis (cm)
IR	applied depth of irrigation water on a weekly basis (cm)
R	rainfall depth on a weekly basis (cm)
Δ	$\theta_1 - \theta_2$ (cm)

Table 3.1 and Table 3.2 show examples of the applied depth of irrigation water and the rainfall data. These data are used as the IR and R inputs into equation 37.

The soil moisture data described in Chapter 3.1 are used to determine a change in soil moisture content on a weekly basis. The soil moisture readings can be converted to an equivalent volume of water by taking the percent soil moisture content and multiplying it by the volume of soil that the reading represents. The soil moisture readings were averaged at the 0.30 m, 0.61 m, 0.92 m, 1.22 m and 1.52 m levels for each tube in the transect. The summation of the water contents for each of these levels is the total volume of water in the entire transect. The total volume of water was divided by the area of the transect to yield a depth of water in

cm. The change in the depth of water from one week to the next plus the irrigation and rainfall data yields the evapotranspiration. Table 3.5 is an example of the spreadsheet used to calculate ET values from the measured data using equation 37.

Table 3.5 Spreadsheet of ET calculation for six-year-old hybrid poplar trees.

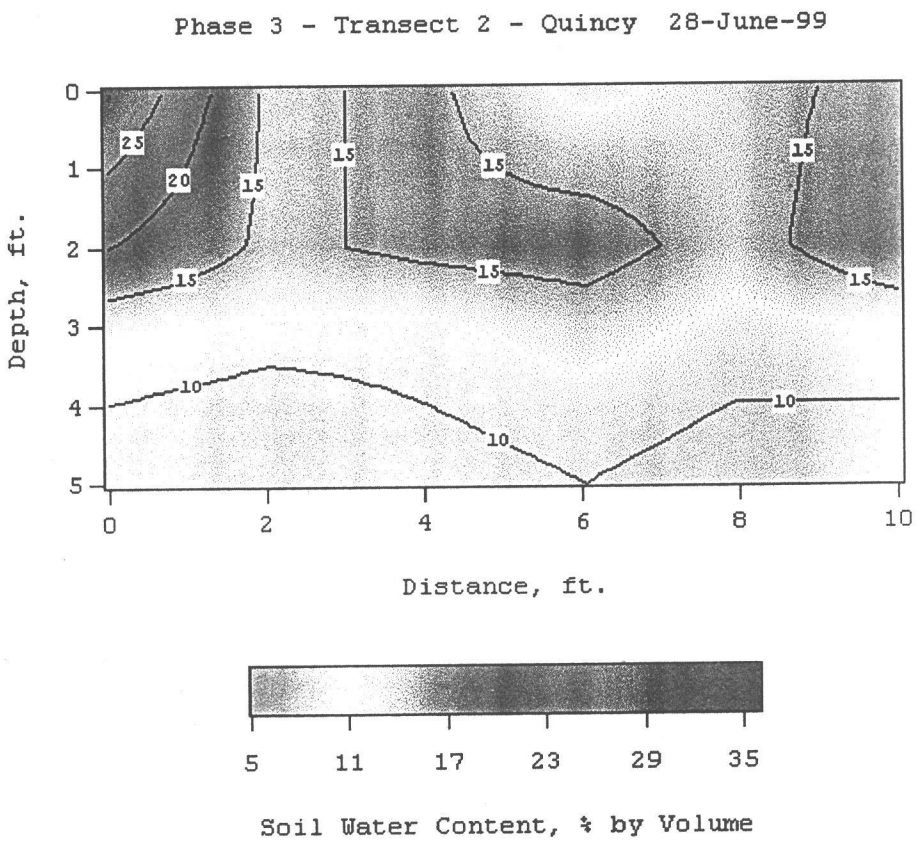
			Applied Water	T1 Weekly ET (cm)		
Date	**Depth (cm)**	**Depth Change (cm)**	**(irr+rain)**	**(Change + App)**	**Rain**	**Irrig.**
3/29/99	27.99		0.00			
4/5/99	28.36	-0.36	0.74	0.38	0.13	0.61
4/12/99	28.29	0.06	0.51	0.57	0.13	0.38
4/19/99	27.68	0.62	0.38	1.00	0.00	0.38
4/26/99	26.92	0.75	0.46	1.21	0.00	0.46
5/3/99	26.38	0.55	0.94	1.49	0.25	0.69
5/10/99	25.83	0.54	1.42	1.97	0.51	0.91
5/17/99	23.09	2.75	1.40	4.14	0.25	1.14
5/24/99	24.14	-1.05	1.57	0.52	0.13	1.45
5/31/99	23.30	0.83	2.13	2.97	0.00	2.13
6/7/99	23.28	0.02	2.67	2.69	0.00	2.67
6/14/99	22.39	0.89	3.20	4.09	0.00	3.20
6/21/99	22.24	0.15	3.96	4.11	0.00	3.96
6/28/99	21.67	0.57	4.72	5.29	0.76	3.96
7/5/99	22.16	-0.48	3.96	3.48	0.00	3.96
7/12/99	21.85	0.31	4.80	5.11	0.00	4.80
7/19/99	21.60	0.25	5.05	5.31	0.25	4.80
7/26/99	21.54	0.06	4.80	4.86	0.00	4.80
8/2/99	20.65	0.89	5.33	6.22	0.00	5.33
8/9/99	21.74	-1.09	6.40	5.31	0.00	6.40
8/16/99	21.93	-0.19	5.33	5.14	0.00	5.33
8/23/99	21.27	0.67	5.33	6.00	0.00	5.33
8/30/99	21.27	-0.01	5.05	5.05	0.25	4.80
9/6/99	21.04	0.23	3.05	3.28	0.00	3.05
9/13/99	20.41	0.63	3.20	3.83	0.00	3.20
9/20/99	20.09	0.32	2.67	2.99	0.00	2.67
9/27/99	19.64	0.45	2.13	2.58	0.00	2.13
10/4/99	19.87	-0.24	2.13	1.90	0.00	2.13
10/11/99	19.51	0.37	2.26	2.63	0.13	2.13

3.2.2 Significant Drainage

It is assumed that the applied water and the change in soil moisture content matches the evapotranspiration and that no drainage is occurring. Figure 3.1 is a plot of the interpolated soil moisture content at each of the reading levels for each of the neutron probe access tubes. Transform software (Fortner Research LLC, Sterling, VA) was used to graphically display these data. No drainage is occurring in the data used because the soil moisture data at the 1.52 m level does not reflect a change due to the applied irrigation for the data used. (Figure 3.1) The 1.52 m level was closely examined for the six years of moisture content data and the soil moisture data were used if it was determined that drainage not occurring. (Chapter 3.2.2)

During periods of intense rainfall, the evapotranspiration calculation can yield a negative number. These data are erroneous and were removed from the database. The data from the week following a rainfall event shows a soil moisture change that does not represent the evapotranspiration. This week is a correction week and these data were also removed from the database. Table 3.4 shows the percentage of days that were used for each age group. The days not used represent days when weather data were missing or when significant drainage occurred.

Figure 3.1 Plot of interpolated soil moisture content



3.2.3 Hybrid Poplar Evapotranspiration Data on a Daily Basis

The Penman-Monteith equation can be used on an hourly or a daily basis. This study uses the Penman-Monteith equation on a daily basis. Weekly ET values are determined using a water balance approach (Chapter 3.2.1). The weekly hybrid poplar evapotranspiration was weighted with the AgriMet daily reference evapotranspiration data to yield a daily estimated hybrid poplar evapotranspiration value.

The reference evapotranspiration data were grouped so that there were three days of daily reference evapotranspiration data previous to the weekly hybrid poplar soil moisture reading, the hybrid poplar soil moisture reading day and three days after the soil moisture reading. These seven days constitute an irrigation week. The daily reference evapotranspiration values for the irrigation week were used to sum a weekly reference evapotranspiration value. The daily reference evapotranspiration values were divided by the weekly reference evapotranspiration value to yield a weight percent. The weight percent of the reference evapotranspiration was multiplied by the weekly hybrid poplar value. The calculation yields a daily weighted hybrid poplar evapotranspiration. The daily estimated poplar ET was used in the Penman-Monteith equation. Table 3.6 shows the ranges of ET for the different age groups of hybrid poplar trees.

Table 3.6 Weighted Daily ET Values (mm/d)

Age Class (yr)	Minimum	Maximum	Seasonal Average
1	0.64	6.57	2.71
2	0.39	11.13	4.05
3	0.54	12.65	5.16
4	1.04	10.77	5.28
5	0.75	14.65	5.55
6	1.14	11.40	5.40

The range of values shown in table 3.6 are consistent with estimates generated by Potlatch and HST (Eaton, personal communication; Cuenca, personal communication). The data above show an increase in the daily average for each age class of tree. The change in daily average is substantial up until age three when the full canopy develops. After age three, the daily average continues to increase slightly as the girth and height of the tree continue to increase. The apparent reduction in ET for 6-year-olds may be attributed to having only 1 year of data.

3.3 Calculation of r_s using the Penman-Monteith equation

The r_s parameter of the Penman-Monteith equation is very difficult to estimate due to the combined influence of plant, soil and climatic factors (Stockle, 1996). In this study, the Penman-Monteith equation was set up in a spreadsheet program and arranged to directly solve for the surface resistance, r_s. Table 3.7 is a

Table 3.7 Calculation of r_s for Three Year Old Hybrid Poplar Trees

Date	Temp	Solar	RH	Wind	λ	ET	ET	Δ	R_s	G	ρ	Cp
	^{o}C	Langley	%	m/s	MJ/Kg	mm/day	$MJm^{-2}day^{-1}$	$kPa/^{o}C$	$MJm^{-2}day^{-1}$	$MJm^{-2}day^{-1}$	Kg/m^3	$MJ/Kg\ ^{o}C$
4/15/96	12.12	368.41	71.0600	4.5464	2.4724	2.1859	5.4044	0.0931	15.4216	0.0000	1.2109	0.0010
4/16/96	9.90	445.39	62.4200	3.6747	2.4776	2.6543	6.5764	0.0818	18.6440	0.0000	1.2202	0.0010
4/17/96	9.96	537.26	63.3000	6.1558	2.4775	4.3632	10.8098	0.0821	22.4897	0.0000	1.2200	0.0010
4/18/96	7.59	225.74	74.7100	3.1293	2.4831	2.4240	6.0190	0.0713	9.4495	0.0000	1.2300	0.0010
4/19/96	9.31	579.47	63.7300	5.4852	2.4790	4.3632	10.8165	0.0790	24.2566	0.0000	1.2227	0.0010
4/20/96	8.64	259.83	69.9000	2.1637	2.4806	2.4240	6.0130	0.0759	10.8765	0.0000	1.2255	0.0010
4/21/96	9.64	187.82	90.1900	1.7122	2.4782	1.2120	3.0036	0.0806	7.8621	0.0000	1.2213	0.0010
	e_a	e_s	γ	r_s	P	T_{kv}	h3 (m)	Uz 3	r_a 3	R_{nl}		
	kPa	kPa	$kPa/^{o}C$	s/m	kPa	K	m	m/s	s/m	$MJm^{-2}day^{-1}$		
4/15/96	1.0044	1.41339	0.065901	126.512	99.0992	285.281	12.2	3.299	6.085850204	3.18062203		
4/16/96	0.7614	1.21976	0.06589	116.182	99.0822	283.063	12.2	2.6665	7.529573792	4.51492904		
4/17/96	0.775	1.22431	0.06589	65.8815	99.0826	283.118	12.2	4.4668	4.494778255	5.85497411		
4/18/96	0.7796	1.0435	0.065878	66.6517	99.0641	280.757	12.2	2.2707	8.841870939	1.01305922		
4/19/96	0.7472	1.17241	0.065887	62.7569	99.0776	282.474	12.2	3.9802	5.044262149	6.38269003		
4/20/96	0.7834	1.12077	0.065883	86.8462	99.0724	281.807	12.2	1.57	12.78782987	1.48065672		
4/21/96	1.0814	1.19901	0.065888	76.9155	99.0802	282.808	12.2	1.2424	16.16007743	0.36799741		
	R_{so}	R_a	δ	d_r	W_s	φ	J	Date	R_n	R_s/R_{so}	N	
	$MJm^{-2}day^{-1}$		rad	rad			DOY		$MJm^{-2}day^{-1}$		hr	Ref ET
4/15/96	24.771	32.8674	0.165279	0.99231	1.74305	0.79901	105	4/15/96	12.24102057	0.62257413	13.317	3.556007
4/16/96	24.958	33.1159	0.171689	0.99176	1.74994	0.79901	106	4/16/96	14.12909636	0.74701499	13.37	4.318009
4/17/96	25.143	33.3618	0.178048	0.99121	1.75679	0.79901	107	4/17/96	16.63472949	0.89445688	13.422	4.572009
4/18/96	25.327	33.6053	0.184355	0.99066	1.76361	0.79901	108	4/18/96	8.436417177	0.37310075	13.474	2.540005
4/19/96	25.508	33.8461	0.190607	0.99012	1.77039	0.79901	109	4/19/96	17.87392417	0.95092819	13.526	4.572009
4/20/96	25.688	34.0842	0.196803	0.98958	1.77714	0.79901	110	4/20/96	9.395827075	0.42341034	13.577	2.540005
4/21/96	25.865	34.3195	0.20294	0.98904	1.78386	0.79901	111	4/21/96	7.494147791	0.3039663	13.629	1.270003

copy of the spreadsheet used to determine r_s for 3-year-old hybrid poplar trees. The equations used to determine the surface resistance are provided in Chapter 2.2.

The input variables of mean temperature (°C), solar radiation (langley), mean relative humidity (%), wind speed (m/s) and the evapotranspiration (mm/d) as calculated from a water balance are used. It is also necessary to know the day of year, the elevation of the experiment site, the latitude of the experiment site, the height of poplar trees for different years and the hybrid poplar's growing season.

The aerodynamic resistance was computed according to equation 17. The aerodynamic resistance required tree height and wind speed as measured input parameters. The tree heights used were 3.66 m for 1-year olds, 8.54 m for 2-year olds, 12.20 m for 3-year olds, 15.85 m for 4-year olds, 19.51 m for 5-years olds and 22.56 m for 6-year olds (Jake Eaton, personal communication). Relationships published in the ASCE No. 70 manual are used to solve equation 14.

The slope of the saturation vapor curve with temperature uses constants published in the FAO Irrigation and Drainage Paper 56. The measured input parameter is the mean temperature (equation 18).

The computation of net radiation is shown by equation 19. The incoming shortwave solar radiation and the outgoing net long wave radiation are required. Incoming shortwave radiation is measured at the AgriMet station. The calculation of equation 20 uses the Stefan-Boltzman constant, the mean absolute temperature and the measured shortwave radiation. Equation 20 requires the calculation of the actual vapor pressure, equation 34, and equation 21, the clear sky radiation.

Equation 21 requires the measured weather station elevation and the calculation of the extraterrestrial radiation. Equation 22 uses the measured latitude, the solar constant and requires the computation of the inverse relative distance from the earth to the sun, the sunset hour angle, the latitude and the solar declination. The inverse relative distance from the earth to the sun is calculated according to equation 23. Equation 23 requires the measured day of year, as the sole input parameter. Equation 24 requires the computation of the sunset hour angle and the solar declination. The sunset hour angle is the measured latitude converted to decimal degrees according to equation 25. The solar declination requires the measured day of year to calculate equation 26. The extraterrestrial radiation can now be solved for. The extraterrestrial radiation allows for the calculation of equation 21. Equation 21 allows for the calculation of equation 20. Equation 20 allows for the calculation of equation 19.

In accordance with assumptions outlined in Allen et. al, 1996, the soil heat flux is relatively small in comparison to net radiation for closed canopy situations and may be ignored.

The atmospheric density was calculated according to equation 27. Equation 27 requires the application of the appropriate specific gas constant, the calculation of the virtual temperature, and the calculation of the atmospheric pressure at the weather station elevation. The calculation of the virtual temperature is presented as equation 29. Equation 29 requires the computation of the absolute temperature, the actual vapor pressure and atmospheric pressure. The absolute temperature is

calculated by equation 30. The actual vapor pressure is computed by equation 34. Equation 34 requires the measurement of the mean relative humidity and the saturation vapor pressure function. The saturation vapor pressure function is solved for according to equation 33 and requires the measurement of the mean daily temperature. The atmospheric pressure is computed by equation 31. Equation 31 requires the atmospheric pressure at sea level, the elevation at the reference level, the specific gas constant, the gravitational acceleration and the constant lapse rate of moist air. Equation 31 requires the measurement of the weather station elevation and the mean daily temperature. With the atmospheric pressure value, equation 27 can now be solved.

The specific heat of moist air at a constant pressure is a constant.

The saturation vapor pressure is calculated by equation 32. Equation 32 requires the saturation vapor pressure function at the mean temperature.

The psychrometric constant is calculated according to equation 36. Equation 36 requires the specific heat of moist air, the atmospheric pressure, the ratio molecular weight of water vapor to dry air and the calculation of the latent heat of vaporization. The latent heat of vaporization is calculated according to equation 35. Equation 35 requires the measurement of the mean daily temperature. With all of the variables solved for, the surface resistance can now be calculated.

4. Analysis

The calculation of r_s for 6 years of tree growth has been grouped by tree age. The trees have been analyzed for the time period April 15 – October 1. It is generally assumed that the trees are fully leaved from April 15 – October 1 (Eaton, personal communication). At age three there exists a full canopy of leaves (Eaton, personal communication). The author will concentrate this analysis and the subsequent discussion on 3-year old hybrid poplar trees. However all years of growth have been analyzed in exactly the same way. (See Appendix) It has been the author's intention, in fulfillment of the objectives outlined in the purpose, to develop a useful, accurate curve fit to the calculated surface resistance data. A curve representing the surface resistance as a function of one or more of the meteorological variables is the primary focus of this analysis. A statistical analysis of these curves will determine the most applicable curve.

The data retained in this analysis were for ideal conditions. Table 4.1 details the ranges of the surface resistance values.

Table 4.1 Surface Resistance Values (s/m)

Age Class (yr)	Minimum	Maximum	Average
1	48.96	997.83	306.40
2	1.49	632.03	167.39
3	6.99	734.31	131.94
4	0.80	489.71	130.09
5	6.63	512.37	120.00
6	2.32	490.99	97.62

The ranges found in Table 4.1 are consistent with previous studies (Dingman, 1994; Stewart, 1988). The maximum and minimum surface resistance values are special case scenarios for extreme weather conditions. The seasonal average surface resistance shows that from 1-year-old to 6-year-old hybrid poplars the average surface resistance decreases with each year. The largest decrease is from the 1-year-olds to the 2-year-olds. From inspection of the Potlatch site, it is known that 1-year-olds are mere saplings with an extremely limited canopy. The average surface resistance values drop as the canopy continues to close in. This trend implies that larger trees have less resistance to transpire and thus consume more water.

Figures 4.1, 4.2 and 4.3 are graphs of temperature, relative humidity and solar radiation versus surface resistance. These graphs show that the data do not follow any clear pattern. It is assumed that the Potlatch Poplar Farm irrigates with an optimum amount of water and thus water is not limiting tree growth. Figures 4.1, 4.2 and 4.3 show the unfiltered data. The data are centrally weighted by including data that are within 30% above and below the median. This filtering

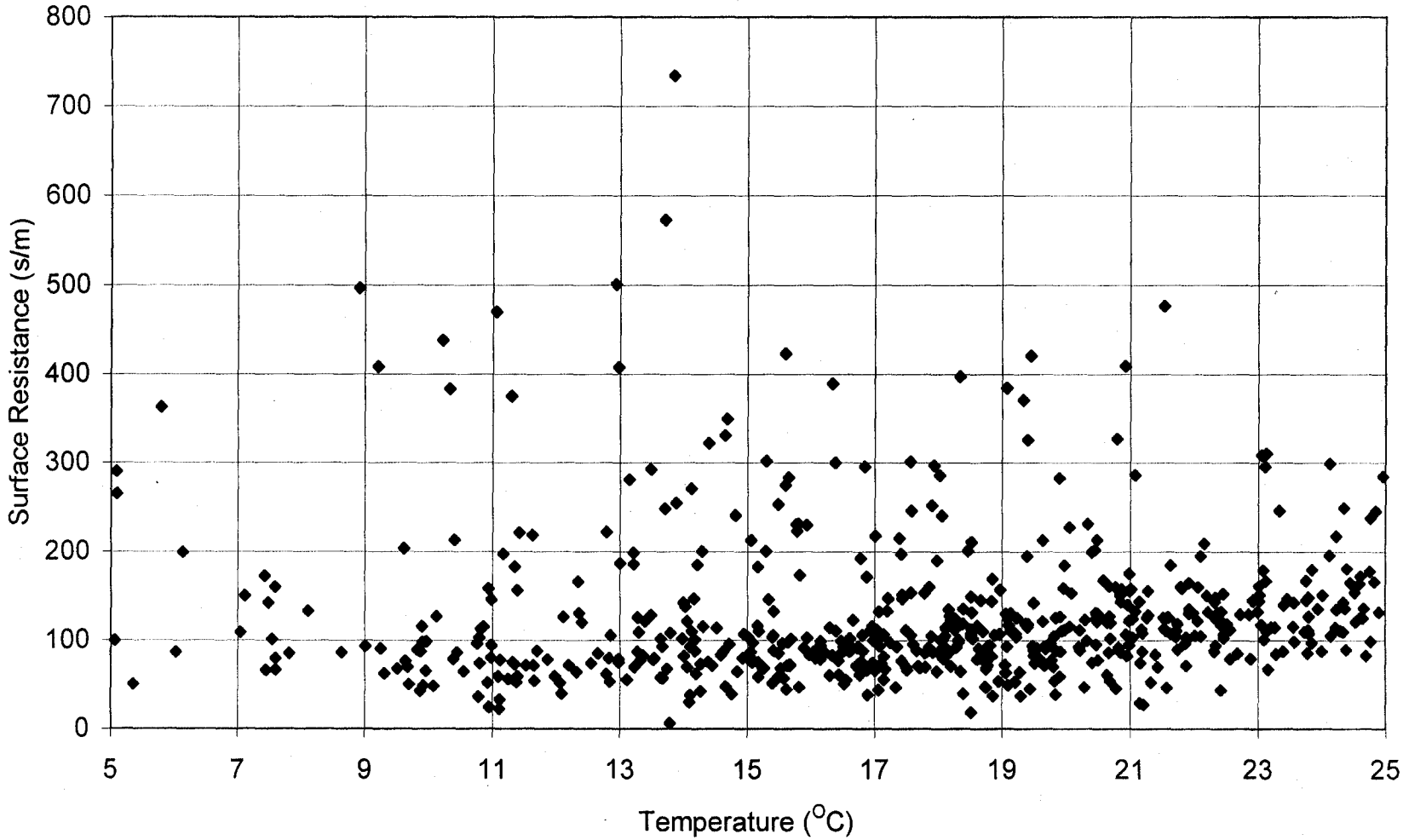


Figure 4.1 Temperature versus Surface Resistance data for three year old hybrid poplar trees.

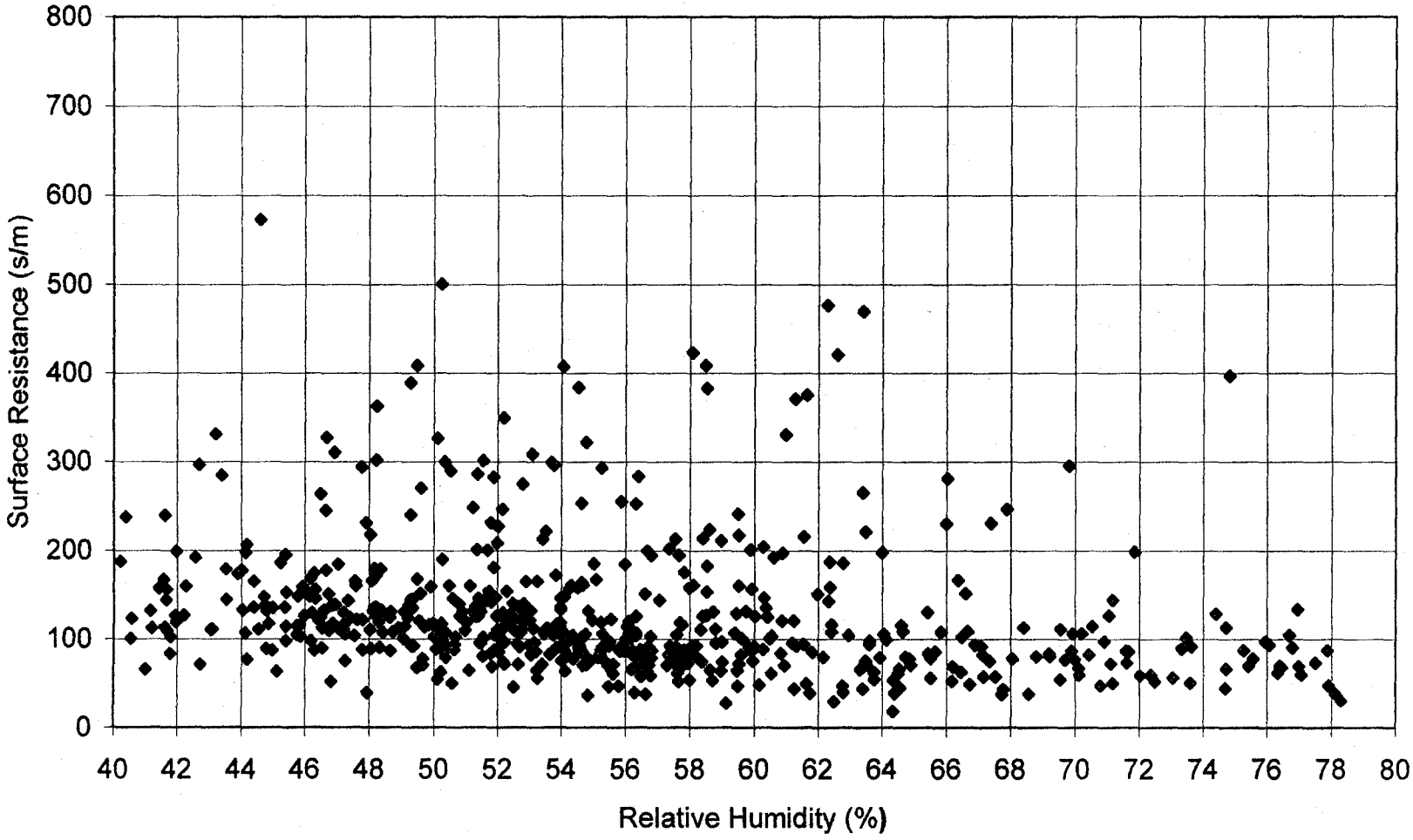


Figure 4.2 Relative Humidity versus Surface Resistance data for three year old hybrid poplar trees.

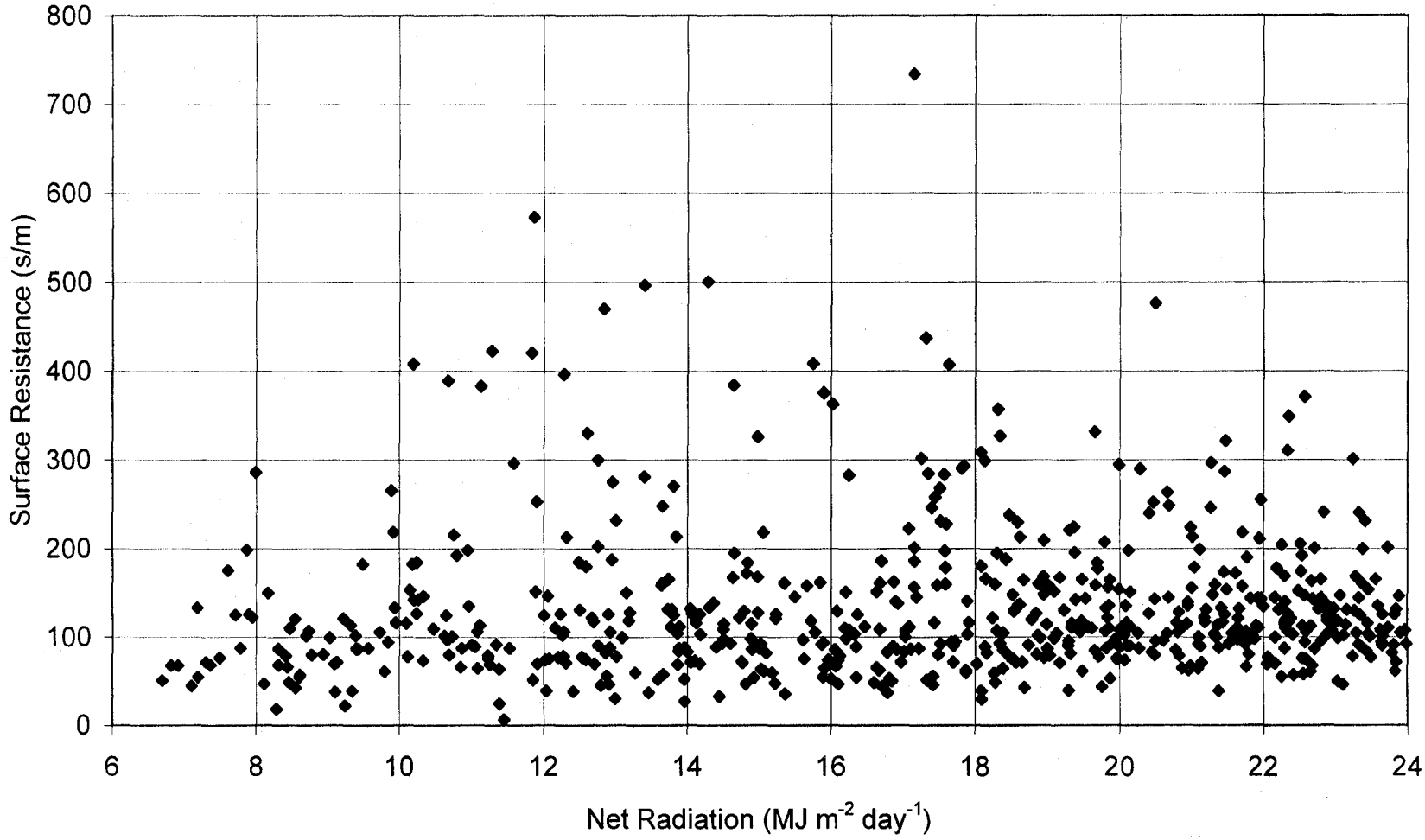


Figure 4.3 Net Radiation versus Surface Resistance data for three year old hybrid poplar trees.

method was implemented to focus the data analysis on an optimum range of meteorological values. The use of optimized values was an attempt to reduce the scatter. The temperature range is 12.72 to 23.62 ^{o}C. The relative humidity range is 38.06 to 70.66%. The solar radiation range is 391.73 to 727.51 langleys. The method used to determine which of these meteorological factors drive the surface resistance under the centrally weighted conditions was to filter the data in the Microsoft Excel spreadsheet. Two of the meteorological variables were filtered in the spreadsheet, Table 3.7, for these centrally weighted conditions, while the third variable was left unfiltered. The unfiltered variable and the surface resistance were plotted. Figures 4.4, 4.5 and 4.6 show the curves of solar radiation, relative humidity and temperature for 3-year-old hybrid poplar trees under filtered conditions. Table 4.2 shows the percentage of days used when filtered under these criteria. Days when no meteorological data are available or there is significant drainage, see Table 3.6, are filtered out of the data in Table 4.2.

Table 4.2 Percentage of Days Used for Filtered Data.

Age	Days Used	Total Days	%	Total Filtered
One Year Old	454	852	53	398
Two Year Old	431	852	51	421
Three Year Old	336	679	49	343
Four Year Old	261	512	51	251
Five Year Old	176	342	51	166
Six Year Old	97	172	56	75

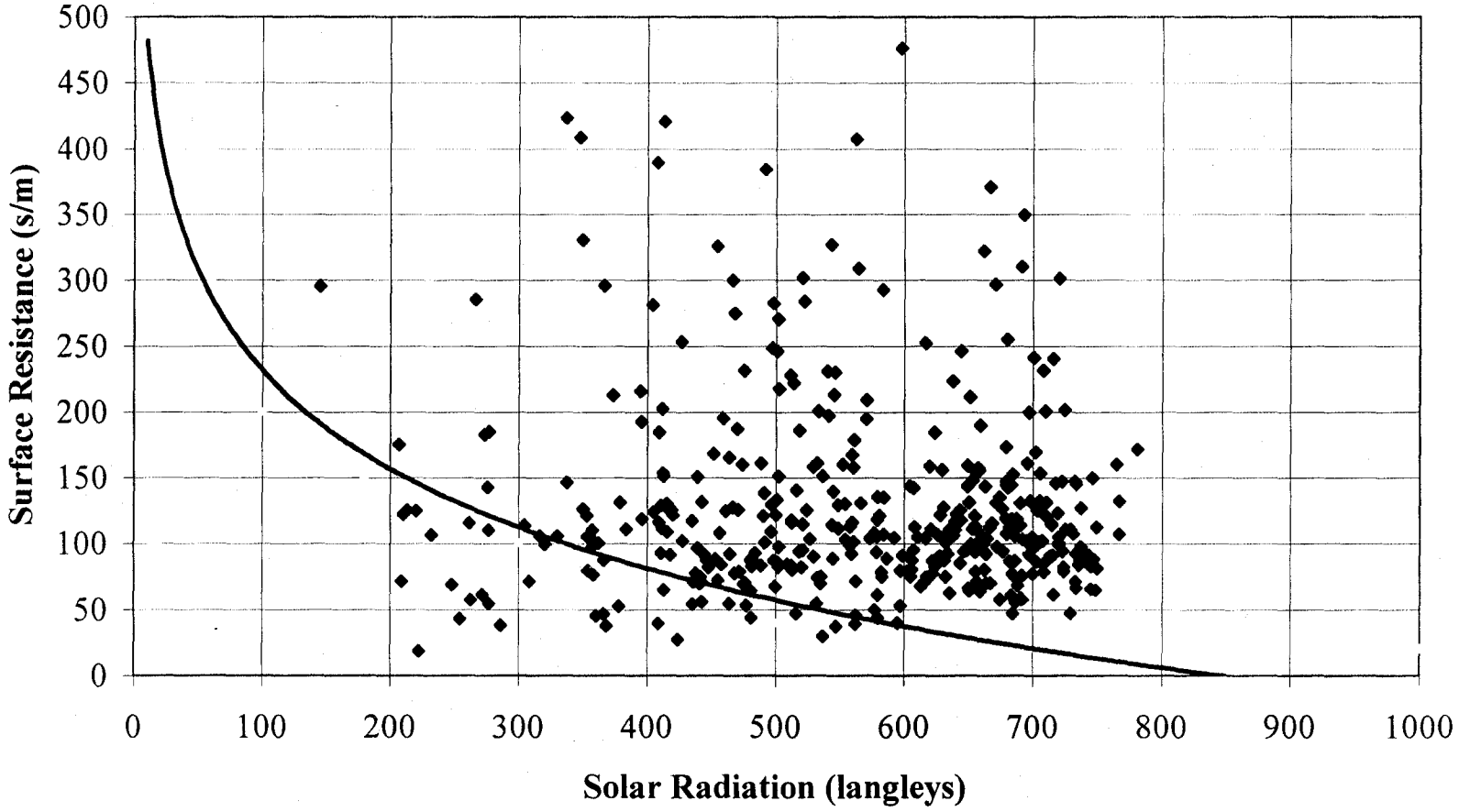


Figure 4.4 Curve of r_s and R_s for 3-year old hybrid poplar trees when the temperature is in the range 12.7 to 23.6 °C and RH is in the range 38.1 to 70.7%.

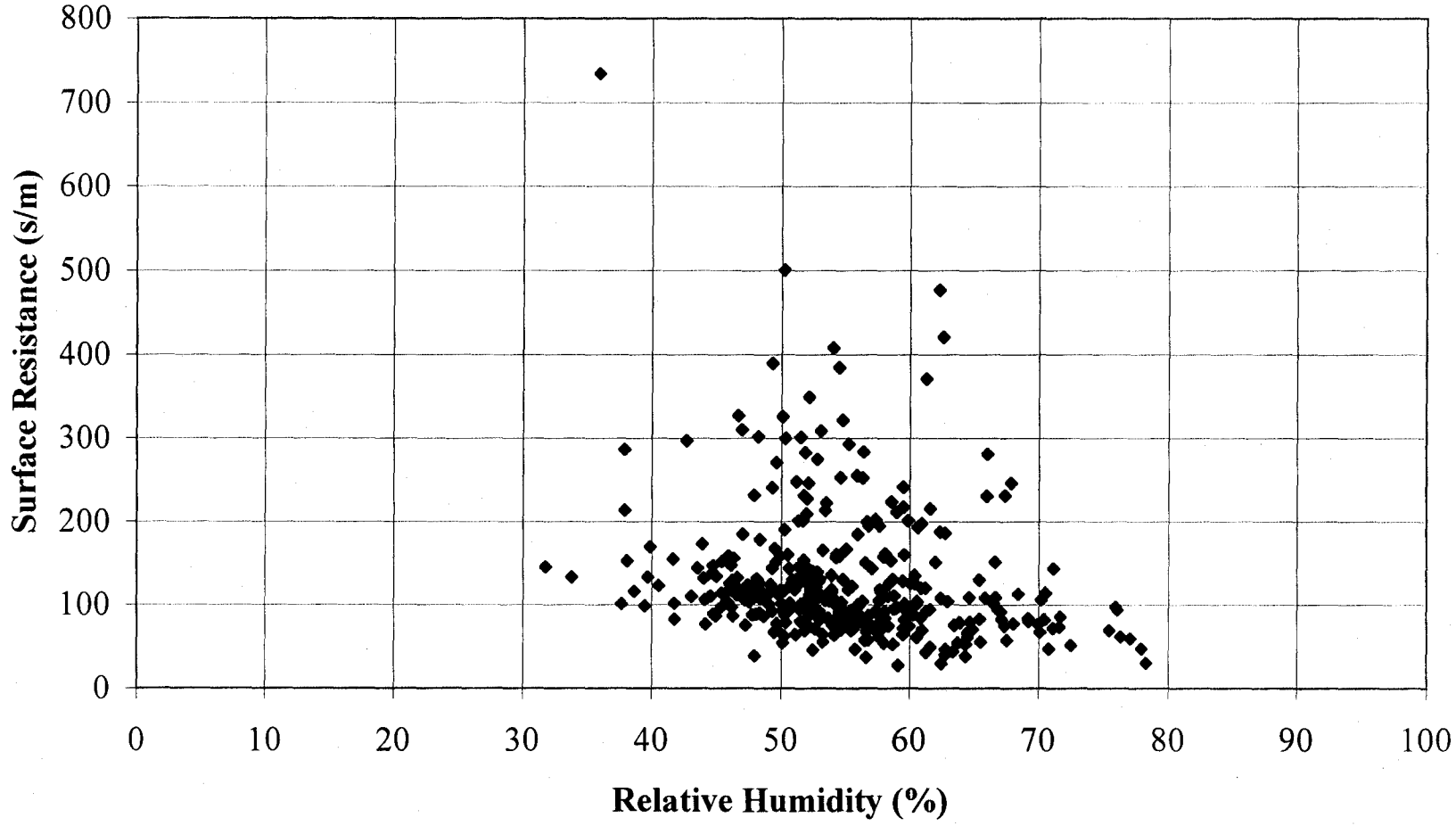


Figure 4.5 Curve of r_s and RH for 3-year old hybrid poplar trees when the temperature is in the range 12.7 to 23.6 °C and R_s is in the range 391.7 to 727.5 langleys.

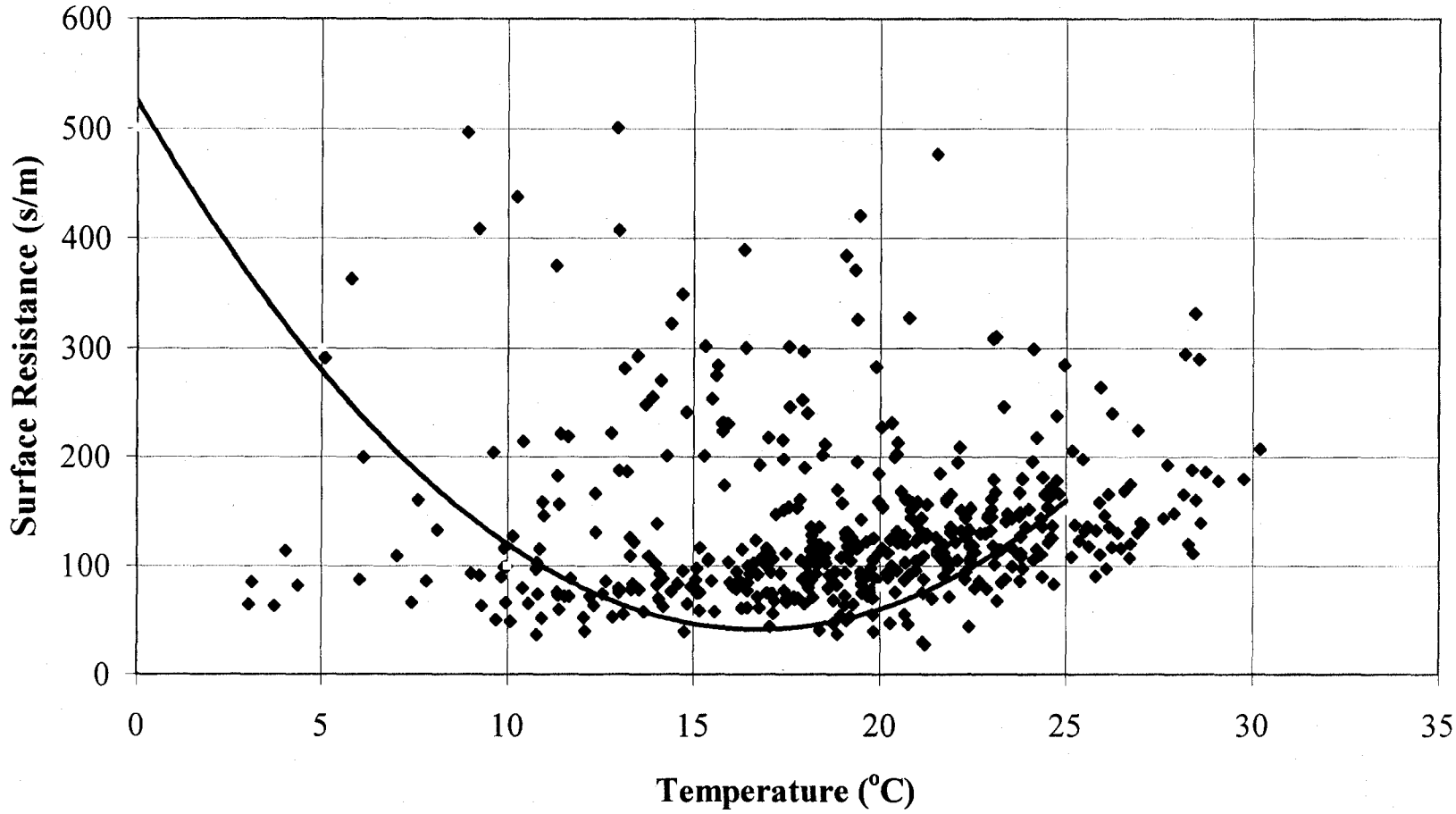


Figure 4.6 Curve of r_s and T for 3-year old hybrid poplar trees when R_s is in the range 391.7 to 727.5 langleys and RH is in the range 38.1 to 70.7%.

The total number of days used under filtered weather conditions ranges from 97days to 454 days. This is not a large data set for an area that prides itself on long, optimum growing seasons. When the data are optimized around 50% of the days are used.

Stewart's criteria are curves developed by Stewart, 1988, that relate surface conductance of a pine forest at Thetford, England to four environmental variables: solar radiation, specific humidity deficit, temperature and soil moisture deficit. The inverse of Stewart's conductance functions is surface resistance. Stewart's functions are plotted on the temperature, solar radiation and vapor pressure deficit graphs. (Figure 4.5, 4.6 and 4.7) Stewart's study used a complex mathematical model to develop the curves. In this study, exponential, logarithmic and polynomial curves were plotted through the data, but no curve fit was found. Stewart's study is further discussed and compared with the findings of this study in Chapter 5.1.

In an attempt to find a better correlation than shown in Figures 4.5, 4.6 and 4.7, graphs between surface resistance and other parameters were developed. The surface resistance data were graphed with the filtered hybrid poplar evapotranspiration data, the unfiltered hybrid poplar evapotranspiration data, and the wind speed. (Figures 4.8, 4.9, 4.10) Figure 4.11 is the curve reference evapotranspiration and hybrid poplar evapotranspiration versus DOY.

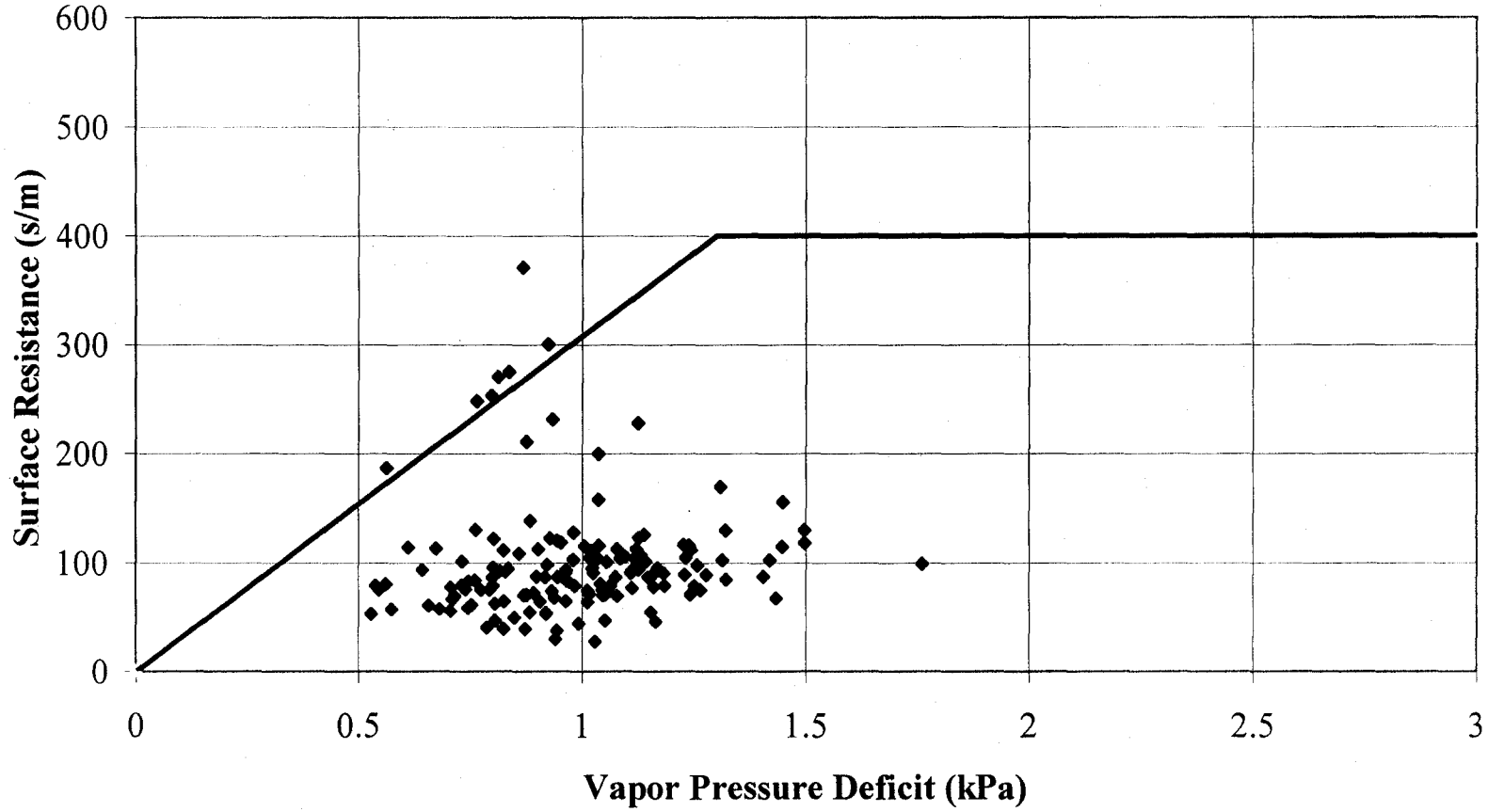


Figure 4.7 Curve of r_s and vapor pressure deficit for 3-year old hybrid poplar trees when T is in the range 12.7-23.6 °C, RH is in the range 38.1 to 70.7% and R_s is in the range 391.7 to 727.5 langleys.

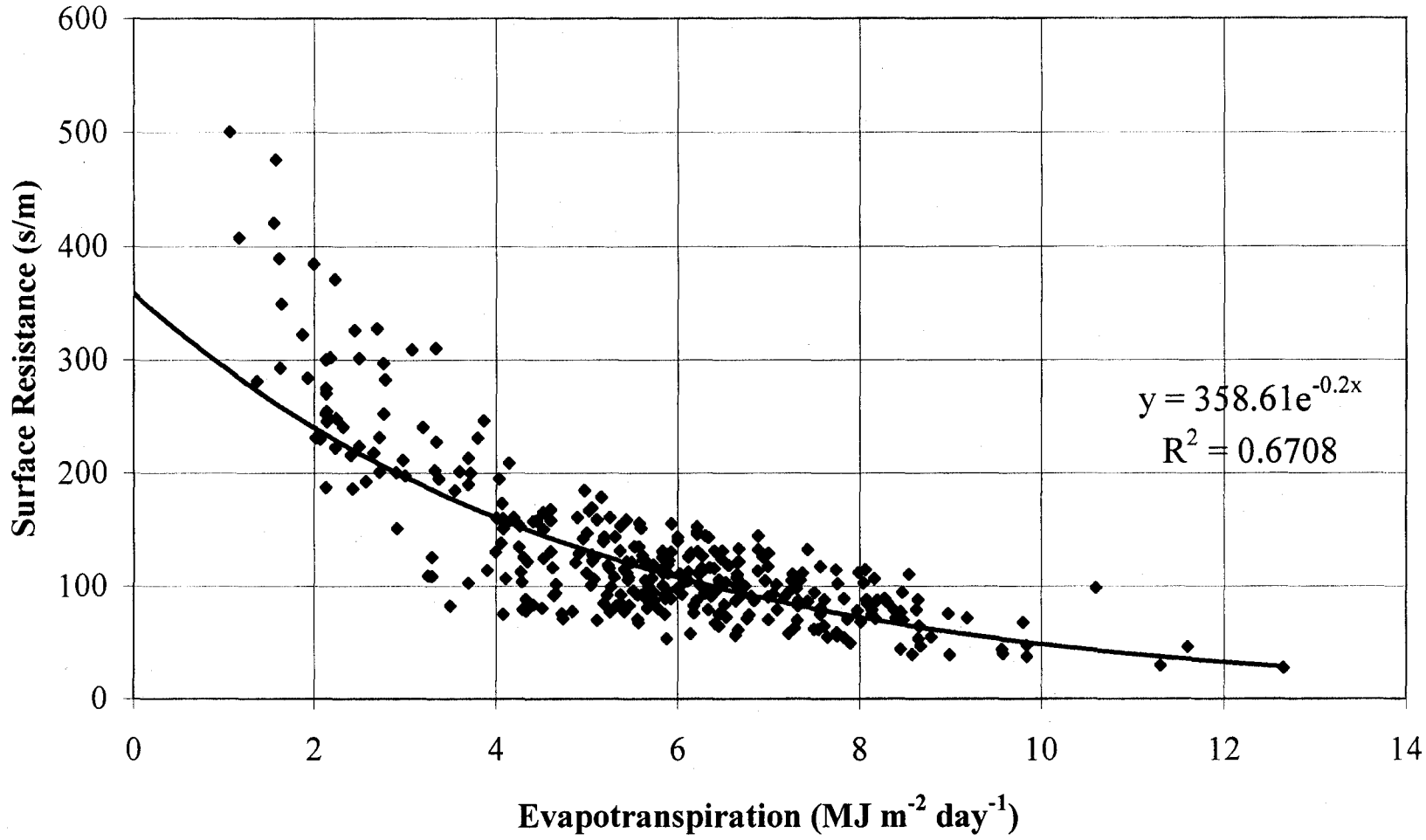


Figure 4.8 Curve of r_s and evapotranspiration for 3-year old hybrid poplar trees when the data are centrally weighted.

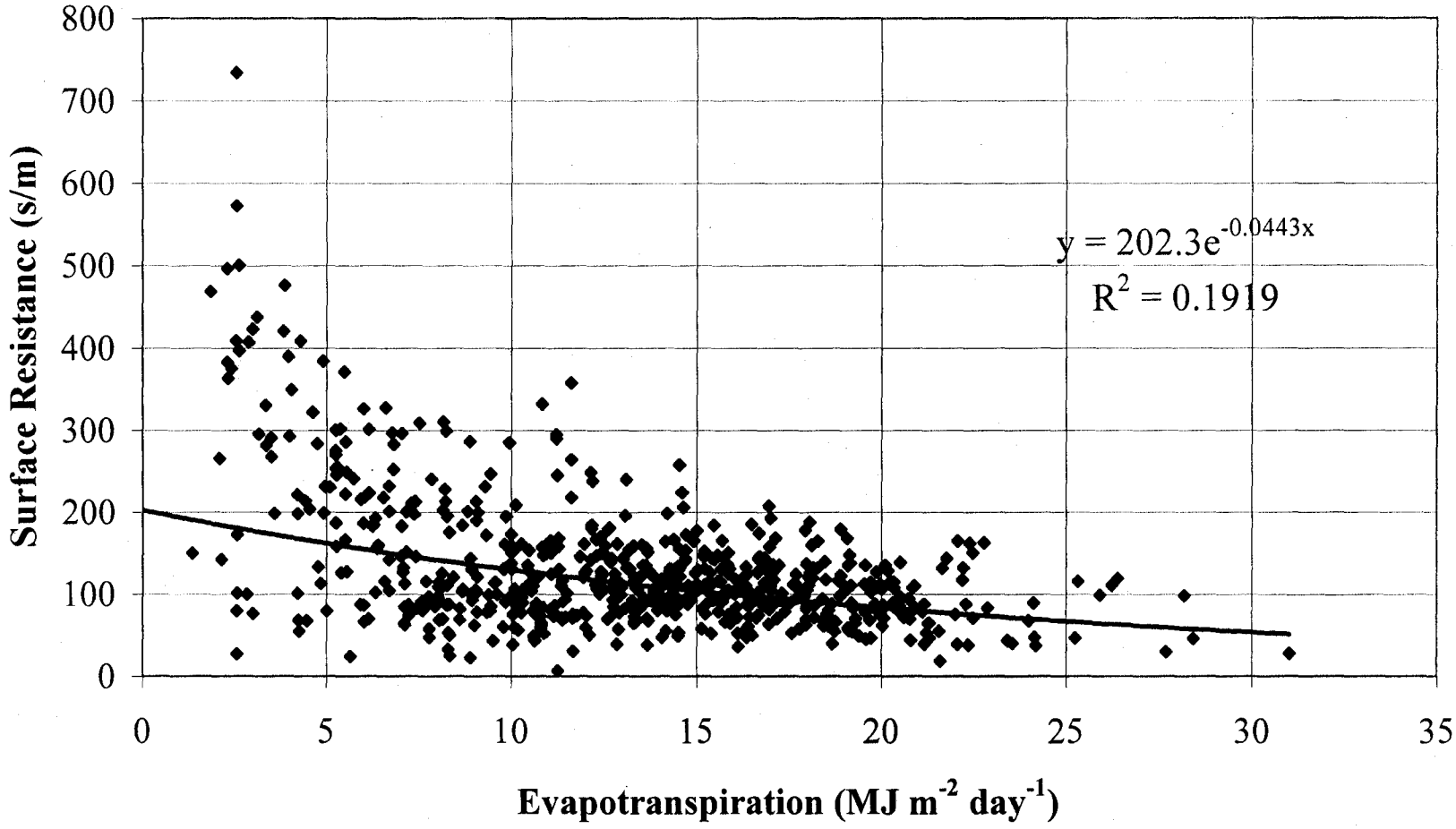


Figure 4.9 Curve of r_s and evapotranspiration for 3-year old hybrid poplar trees when the data are unfiltered.

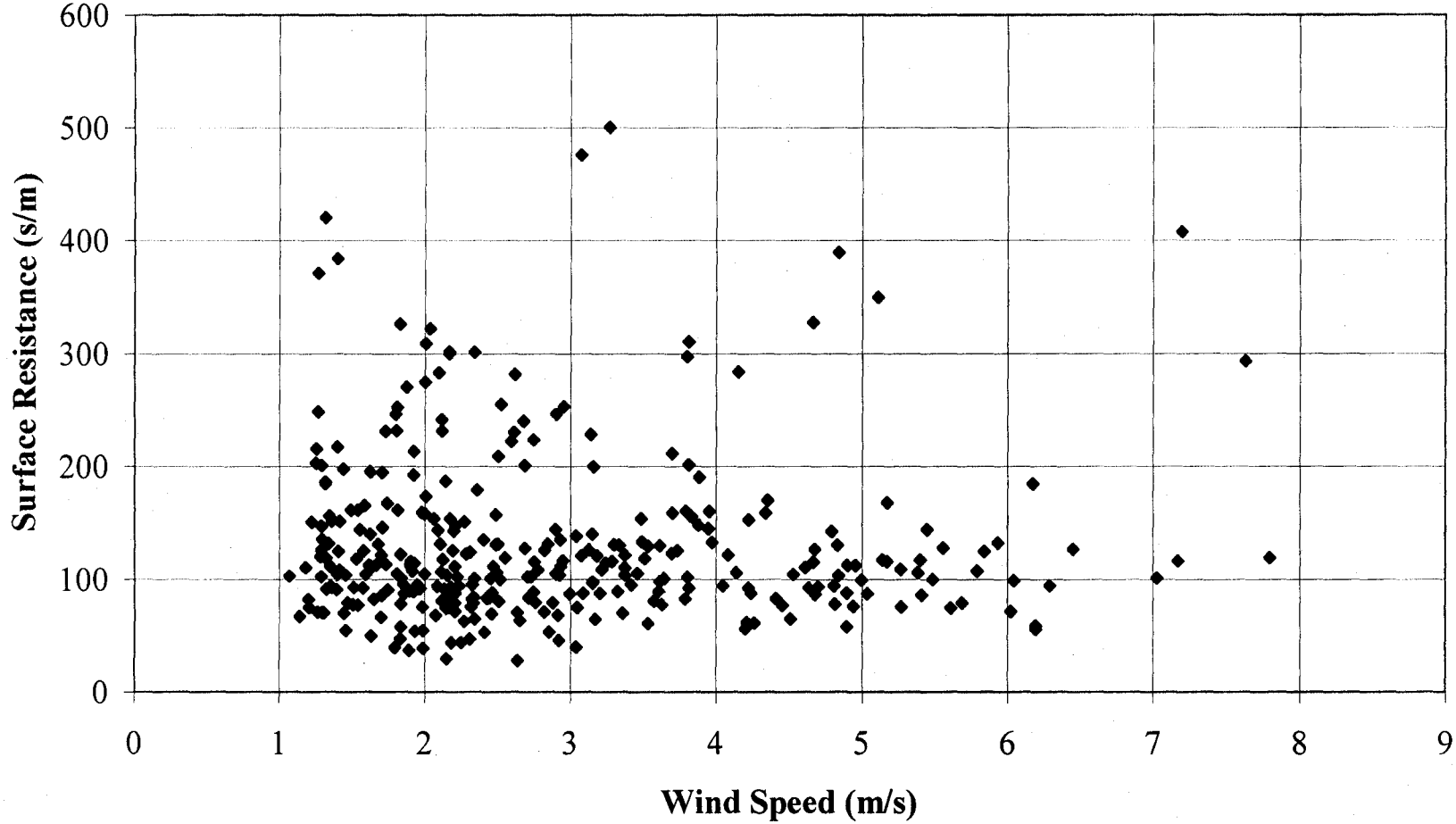


Figure 4.10 Curve of r_s and wind speed for 3-year old hybrid poplar trees when T is in the range 12.7 to 23.6 °C, RH is in the range 38.1 to 70.1% and R_s is in the range 391.7 to 727.5 langleys.

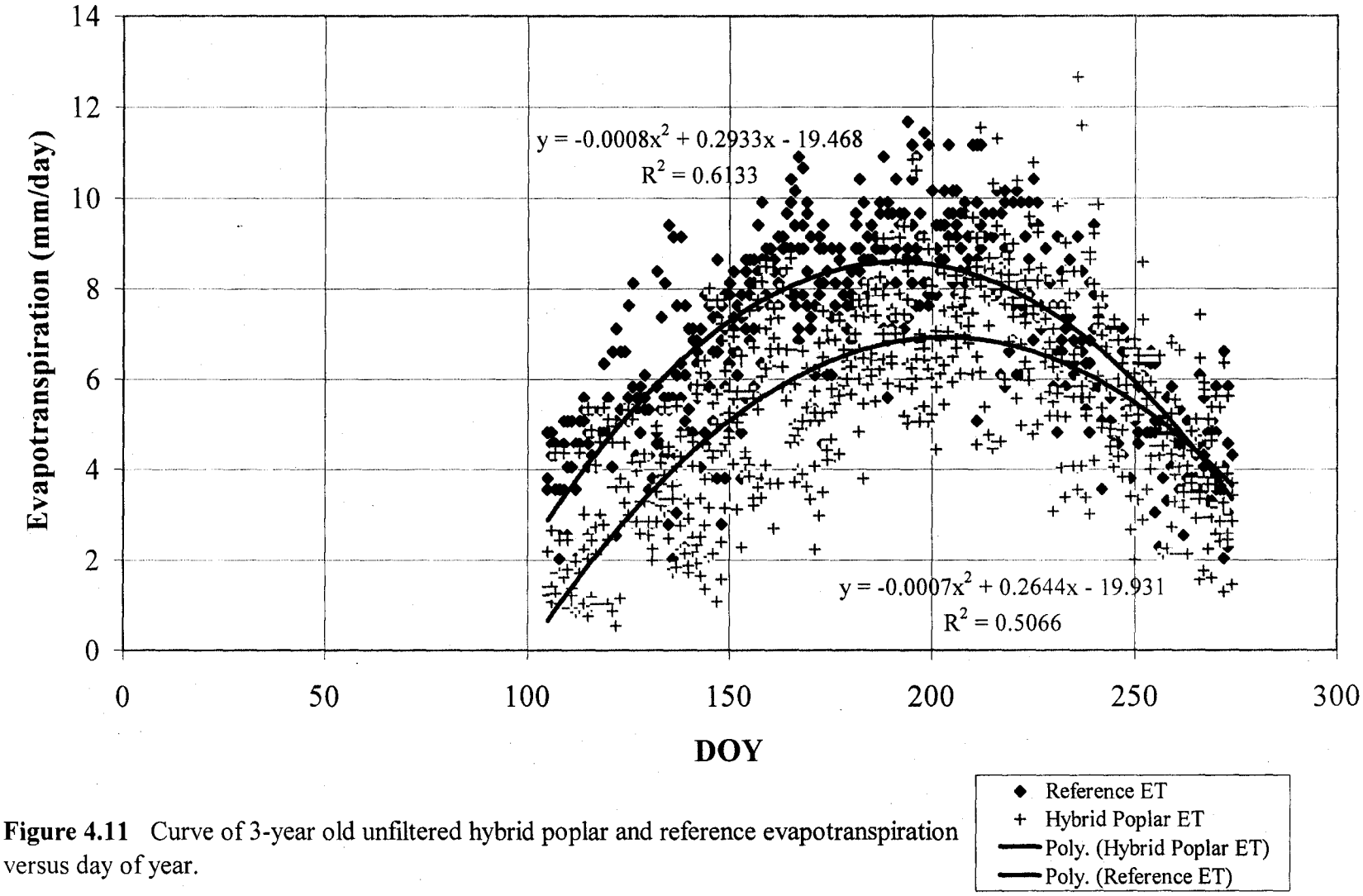


Figure 4.11 Curve of 3-year old unfiltered hybrid poplar and reference evapotranspiration versus day of year.

5. Results and Discussion

5.1 Results

The graphs of the solar radiation, the relative humidity and the temperature versus r_s show large unexplainable ranges (Figure 4.4, 4.5, 4.6). The r_s value is 349.4 s/m at a solar radiation of 693 langley. (Figure 4.5) The r_s value is 92 s/m at a solar radiation of 697 langley. (Figure 4.5) This range makes it extremely difficult to find a curve that will represent these data. The relative humidity data show a large range of surface resistance values for a small change in relative humidity values. The r_s value is 217 s/m at a relative humidity of 59%. (Figure 4.6) The r_s value is 82 s/m at a relative humidity of 59%. (Figure 4.6) The temperature data show a large range of surface resistance values for a small change in temperature values. The r_s value is 71 s/m at a temperature reading of 11 °C. The r_s value is 407 s/m at a temperature of 12 °C.

No explanation was determined for this scatter and it was not possible to make a curve to fit these data that resembled the widely accepted Stewart's functions or any other curve (Dingman, 1994). The graph one would expect is a resistance curve that peaks when the temperature is too hot or too cold, Figure 4.6. The expected graph of resistance versus relative humidity is for an increase in resistance with increasing relative humidity until the air is saturated and no transpiration can occur, Figure 4.5. For solar radiation, the expected response is a

decrease in resistance as the solar radiation increases. Stewart's functions (Figure 4.4) show these relationships, but the data do not provide a definitive surface conductance function. The surface conductance has no units and is labeled as relative conductance and is a percent.

r_s was also been graphed against the vapor pressure deficit, reference ET, wind speed, hybrid poplar filtered ET and hybrid poplar unfiltered ET. The vapor pressure deficit curve is expected to follow Stewart's criteria. The vapor pressure deficit curve appears to trend in a consistent manner, however a linear curve fit yields an r^2 value of just 0.055 (Figure 4.7). Wind speed was graphed versus surface resistance in an attempt to see if the increase in airflow over the leaves, which usually means increased evaporation, would have a clear trend in surface resistance values. The wind speed data, Figure 4.10, show no discernable pattern.

Statistically the graph of the filtered daily evapotranspiration and r_s, Figure 4.8, provides a good exponential curve fit. The r^2 values for the six years of tree growth are between 0.62 and 0.69. (See Appendix) The graph of the unfiltered daily evapotranspiration and r_s, Figure 4.9, has an r^2 value of 0.1919 when fitted with an exponential curve.

The graph of reference ET and unfiltered hybrid poplar ET against the day of year, Figure 4.11, yields a second order polynomial with an r^2 value of 0.51 for the poplar data. The r^2 value of the reference data when fit with a second order polynomial curve is approximately 0.61. The r^2 values were produced in the spreadsheet. Both of the curves follow a similar trend with poplar

evapotranspiration values reaching peak values around DOY 200. The graph shows that the trend of evapotranspiration values for a given DOY is similar to the graph for a well-established, homogenous alfalfa crop where the best available techniques are being applied.

5.2 Discussion

The graphical display of the r_s data for hybrid poplar trees from this experiment reveal that there is no way to predict this variable based on the meteorological data of solar radiation, relative humidity and temperature (Figures 4.5, 4.6, 4.7). Other studies have been successful in developing trends when examining the surface resistance as compared to meteorological data. Allen, et al. (1989) found that as leaf area increases, bulk stomatal resistance decreases. Monteith (1965), Hatfield (1985), and Choudhury (1983) have reported that instantaneous values of r_s vary inversely with net radiation (Allen, et al., 1989). Hatfield et al. (1987) has found a relationship between values of r_s to leaf temperature. For well-watered plants, the stomates remain closed until temperatures are high enough to require the evaporative cooling of the leaves (Hatfield, 1987). The data found here are not in agreement with the conclusions of Allen, Monteith, Hatfield and Choudhury.

A comparison to the curves developed by Stewart for pine forests is the most appropriate for this study. Figures 4.4, 4.6 and 4.7 have an adaptation of Stewart's curves graphed on them. Reading further into Stewart's study, it is seen that his ability to predict the surface resistance had a large amount of uncertainty. Stewart's study showed that only changes in parameters describing the dependence of the surface conductance on specific humidity deficit and soil moisture deficit had a significant effect on the estimates of transpiration (Stewart, 1988). Stewart found that when he used his model to predict the surface conductance and transpiration, significant errors and biases in the estimates were found (Stewart, 1988). He concluded that either the surface conductance depends on an additional variable that was not included in the model or that the dependence of surface conductance on the included variables changed from year to year (Stewart, 1988). Stewart's study and the study presented here have found that there is not a clear functional relationship between surface conductance and temperature, relative humidity, solar radiation or vapor pressure deficit alone. Although Stewart developed visually pleasing curves, his conclusion is basically in agreement with the findings of this study. The graph of r_S and calculated hybrid poplar evapotranspiration (Figure 4.8) makes us question how well the Penman-Monteith Equation works fort this species. The r^2 values indicate several values of ET for a given r_S. In agreement with Stewart, other factors are affecting ET that are not included in the Penman-Monteith equation. The other source of error may be an error in ET carried over from the water balance calculation.

5.3 Sources of Error

The equipment used to measure the Penman-Monteith inputs all contain instrument error. The data measured using scientific instruments include soil moisture, rain, temperature, wind speed, solar radiation and relative humidity.

This study does not use surface measurements and the error associated with soil moisture readings cannot be quantified.

The soil moisture data are computed from neutron probe counts by a single calibrated equation. The soil over the entire farm is non-homogeneous. There is some spatial variability in these soils even though they are characterized as similar soils. The equation is intended to be a best fit for all of the soils in the area, however it is an unquantifiable source of error.

The AgriMet Weather Station data from HERO are the best available meteorological data for this study. The weather station is located over five miles away from some of the trees on the farm. The local variability in wind speed, temperature, solar radiation and relative humidity results in unquantifiable errors. The hybrid poplar trees also seem to create a local influence on the weather. There is no documentation on how much the closed canopy nature of older hybrid poplars can affect the meteorological values used in this study.

There is local variation in the rainfall over each phase. The rainfall is measured with one catch-can for the entire phase and are the best available data. It

is likely that this study uses rainfall values that do not reflect the actual rainfall at a given tree. The amount of error is unquantifiable.

The Penman-Monteith method on a daily basis is insensitive to synchronization between humidity and wind (Hess, 1996). Two days may have the same mean relative humidity and mean wind speed, however the timing and the magnitude of the peaks may be very different (Hess, 1996). Using mean data in the approach presented here ignores diurnal variations. Under conditions of high saturation deficit and low wind speeds, the error may be equal to one irrigation cycle (Hess, 1996). It is recommended from a study by Hess that where high value, drought-sensitive crops are being grown, the improved resolution of evapotranspiration may justify the application of automatic weather stations that take hourly readings.

The calculation of r_s contains several sources of error. The most significant source of error may be the use of weekly evapotranspiration values in an effort to find a daily r_s value. r_s varies greatly over a 24-hour period. It may take substantial data to average out errors and develop a valid daily r_s value.

The irrigation rate is assumed to be optimum and not limiting growth. This assumption is difficult to quantify, but it is entirely conceivable that, on occasion, the trees did not receive the optimum irrigation rate.

The irrigation application rate is reported in hours of irrigation. As described in Chapter 3.1.1 it is necessary that application rate, the volume of the irrigated soil and the irrigation hours be known. On occasion, the irrigation lines

leak or become blocked. At these times, the irrigation application rate is not accurate. It is impossible for the author to account for these rare circumstances.

The trees are all hybrid poplars, however there are different hybrids within each age group. Although the hybrids are similar, some of these trees may develop a complete canopy sooner than others and some of the trees have broader leaves. These physiological differences may yield a different r_s value. One tree height was used for each age group of trees. The trees are not at one height for the entire growing season. Several heights used throughout the growing season would yield more correct aerodynamic resistance and r_s values.

The weekly evapotranspiration data are converted to daily by weighting the values with the reference evapotranspiration data. The reference data were taken at the AgriMet Weather Station. The weekly hybrid evapotranspiration data that is weighted to daily evapotranspiration data with the AgriMet data, may be calibrated by a weight that doesn't represent the conditions at the Potlatch Poplar Farm.

6. Recommendations

This study was unable to predict r_s values for hybrid poplar trees based on meteorological data. The sources of error can only account for some unquantifiable portion of the shotgun blast presentation of the data. These data have been measured to comply with Oregon Water Resource Department regulations and thus soil moisture readings are taken on a weekly basis. It is the author's opinion that daily or hourly soil moisture readings, and thus a daily or hourly measured hybrid poplar evapotranspiration, would be of great benefit to subsequent analyses.

The meteorological data would better represent hybrid the poplar tree farm if the data were taken on site. A weather tower that would measure all of the necessary parameters would insure less localized variation in the data. An automatic weather station would make it possible to calculate evapotranspiration over small time steps

One of the concerns with using the Penman-Monteith is the acceptance of the big leaf concept (Alves, et al., 1998; Kjelfaard, et al., 1994). The entire canopy of the crop is treated as one big leaf. There is one location where all of the net radiation is absorbed and from where water vapor and heat escape from the canopy (Alves, et al., 1998). In the resistance terms the crop height is assumed to be uniform. It has been shown that air inside a canopy can be more humid than the air at the reference height (Alves, et al. 1998). There will be no evapotranspiration if there is no gradient of vapor between the leaf and the air.

More consideration must be given towards accounting for the resistance of individual leaves.

A method for predicting surface resistance values for hybrid poplar trees from common meteorological data is necessary to advance efficient irrigation management. New studies into this area should use methods to measure the surface resistance directly such as a leaf porometer. It would be interesting to see if the values attained in a procedure where surface resistance was directly measured corresponded with the Penman-Monteith back-calculated values. It is conceivable that the accumulation of unquantifiable errors has caused the scatter seen within this study. It is more conceivable in the author's opinion that there is something affecting the surface resistance that is not being accounted for in the Penman-Monteith equation. As the Penman-Monteith equation continues to gain widespread popularity, so too should studies like this one. It is not enough to develop K_c values and crop curves for estimating hybrid poplar evapotranspiration. A method to directly calculate hybrid poplar evapotranspiration should be developed.

The methods presented here were unsuccessful in relating evapotranspiration to surface resistance. Continued collection of data at the Potlatch Poplar Farm will most likely reveal continued scatter of surface resistance data. The use of an instrument to directly measure the surface resistance, such as the Stomatal Aperture Porometer type AP4 – Dynamax, Inc., is recommended in further studies.

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APPENDIX

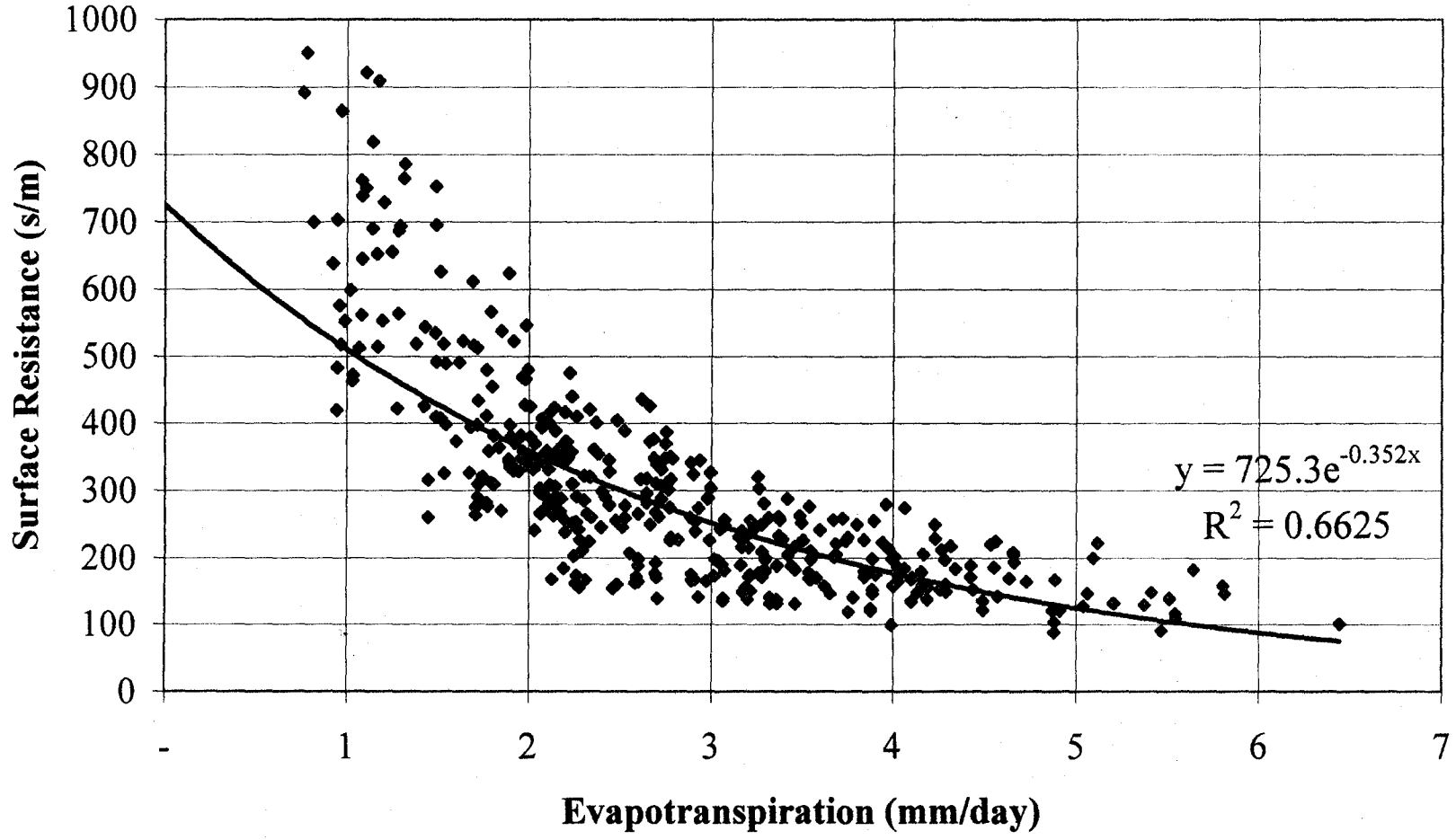

Figure A.1 Curve of r_s and evapotranspiration for 1 year old hybrid poplar trees when T is in the range 12.7-23.6 °C, RH is in the range 38.1-70.1% and R_s ranges from 391.7-727.5 langleys.

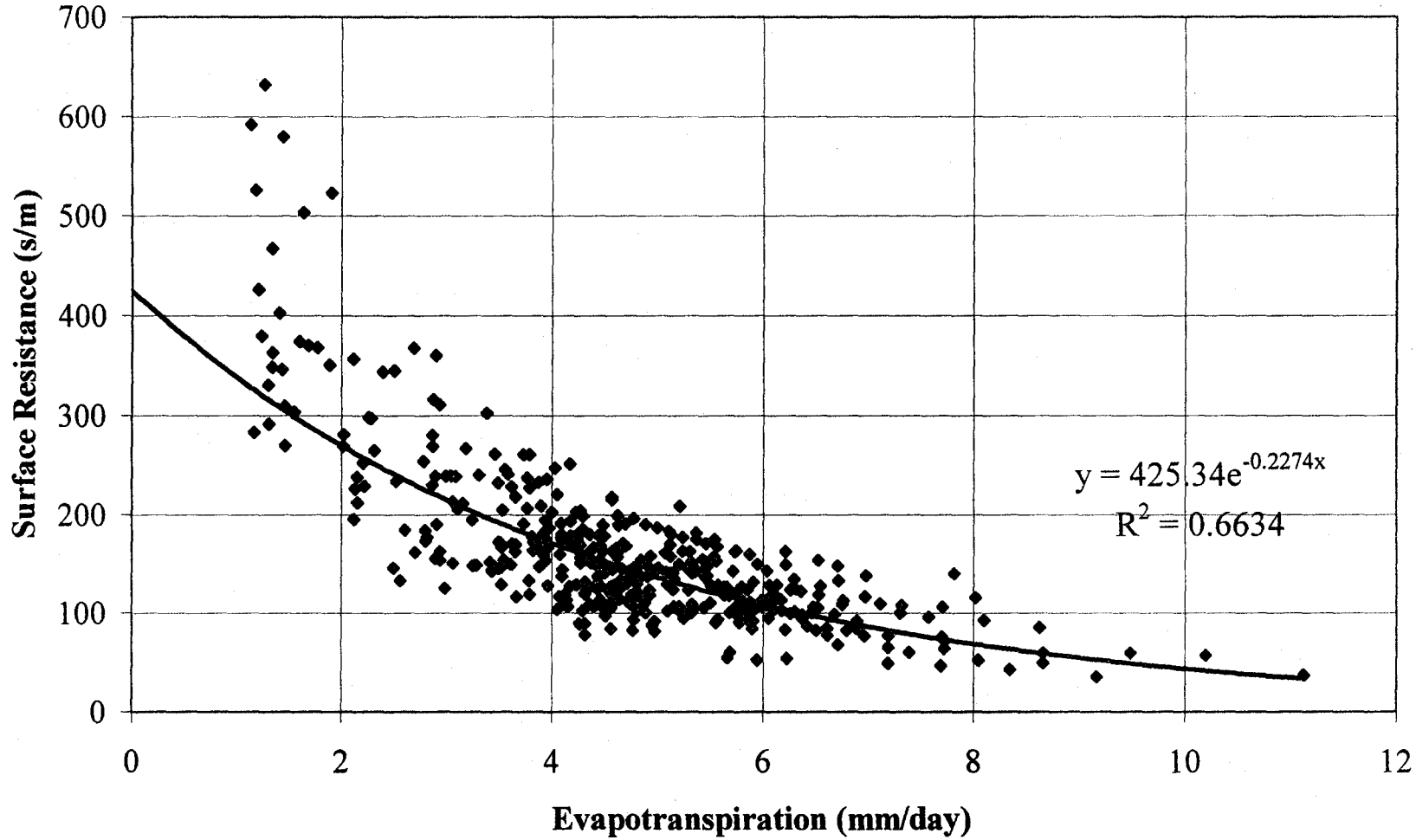

Figure A.2 Curve of r_s and evapotranspiration for 2 year old hybrid poplar trees when T is in the range 12.7-23.6 °C, RH is in the range 38.1-70.1% and R_s ranges from 391.7-727.5 langleys.

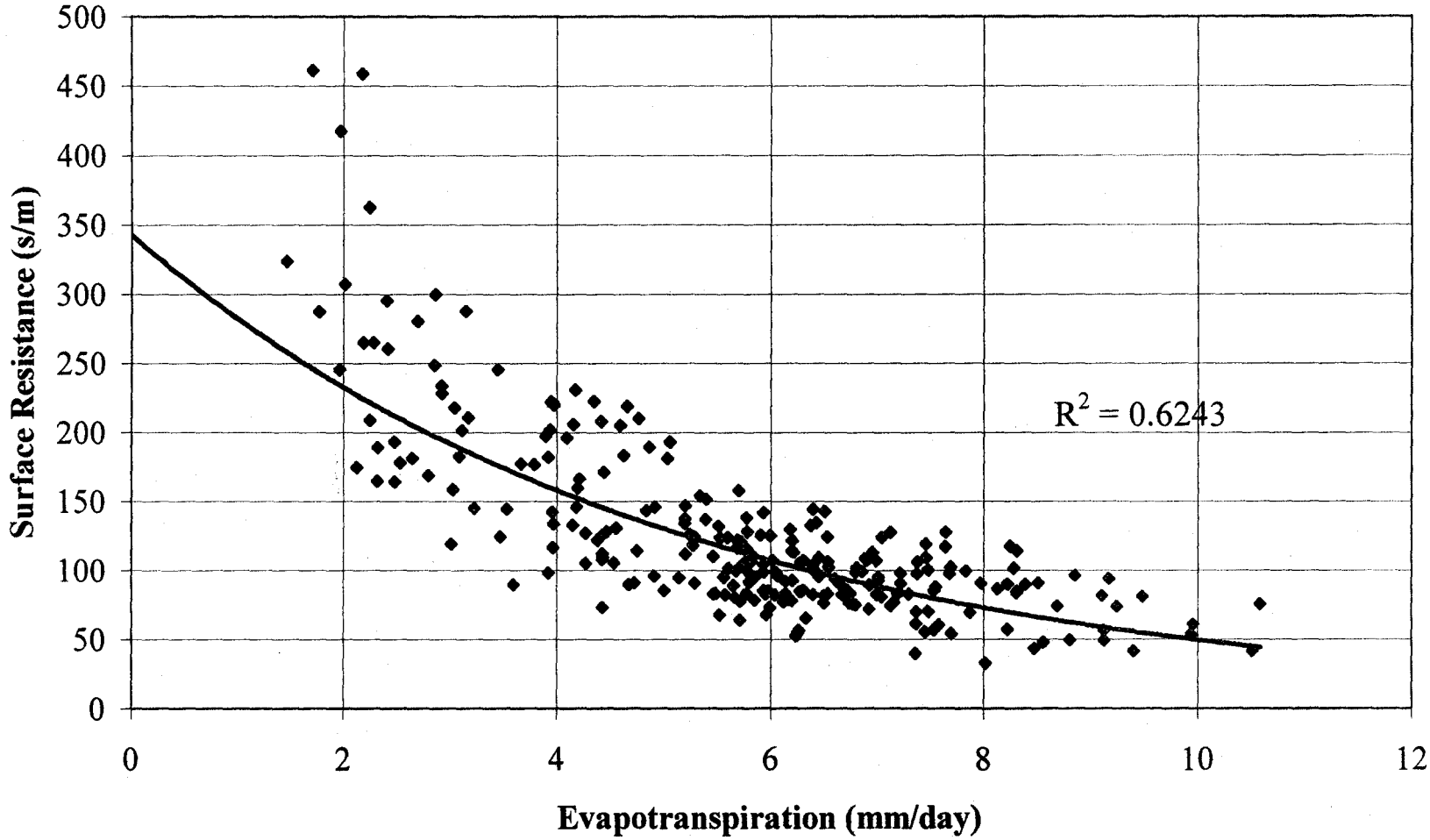

Figure A.3 Curve of r_s and evapotranspiration for 4 year old hybrid poplar trees when T is in the range 12.7-23.6 °C, RH is in the range 38.1-70.1% and R_s ranges from 391.7-727.5 langleys.

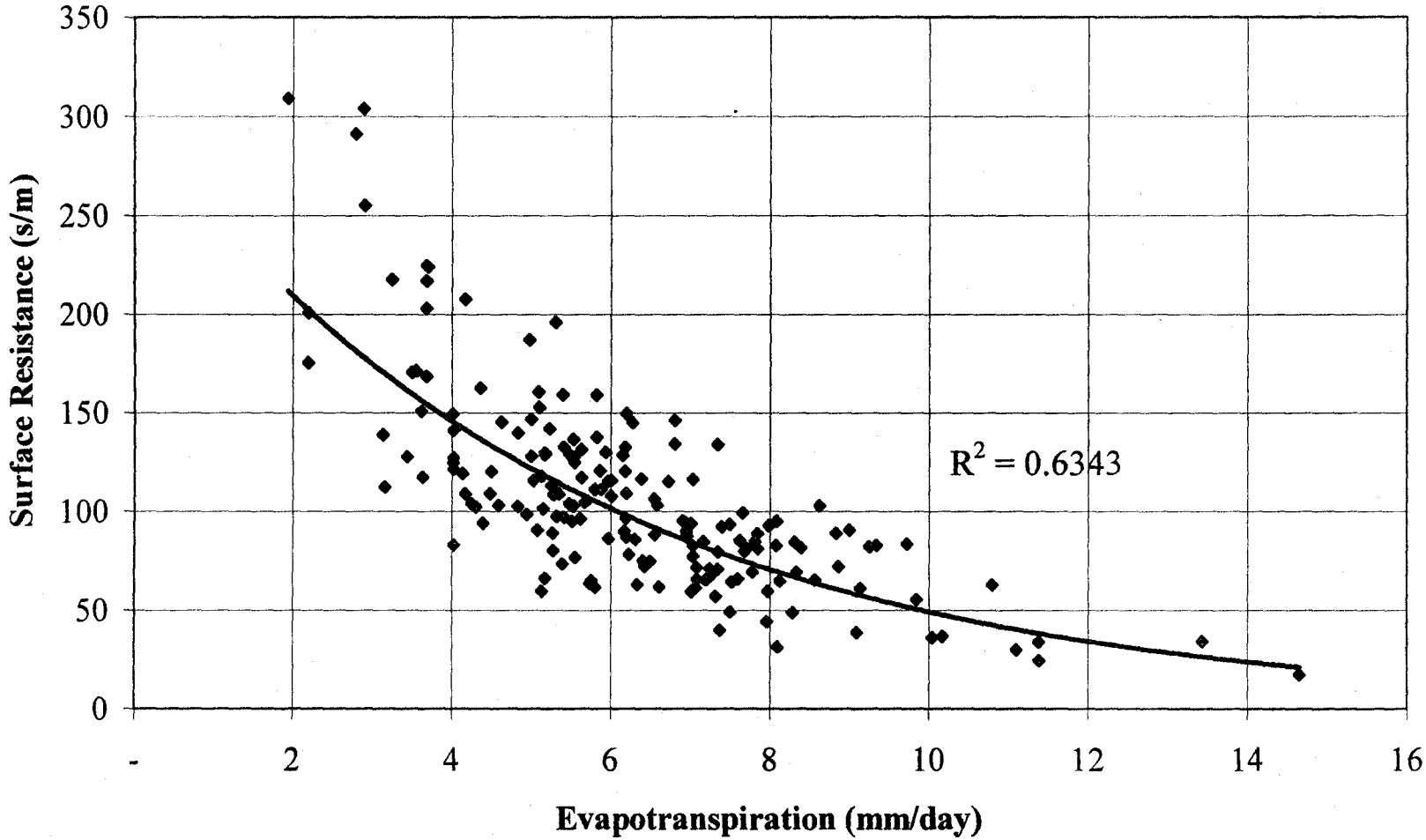

Figure A.4 Curve of r_s and evapotranspiration for 5 year old hybrid poplar trees when T is in the range 12.7-23.6 °C, RH is in the range 38.1-70.1% and R_s ranges from 391.7-727.5 langleys.

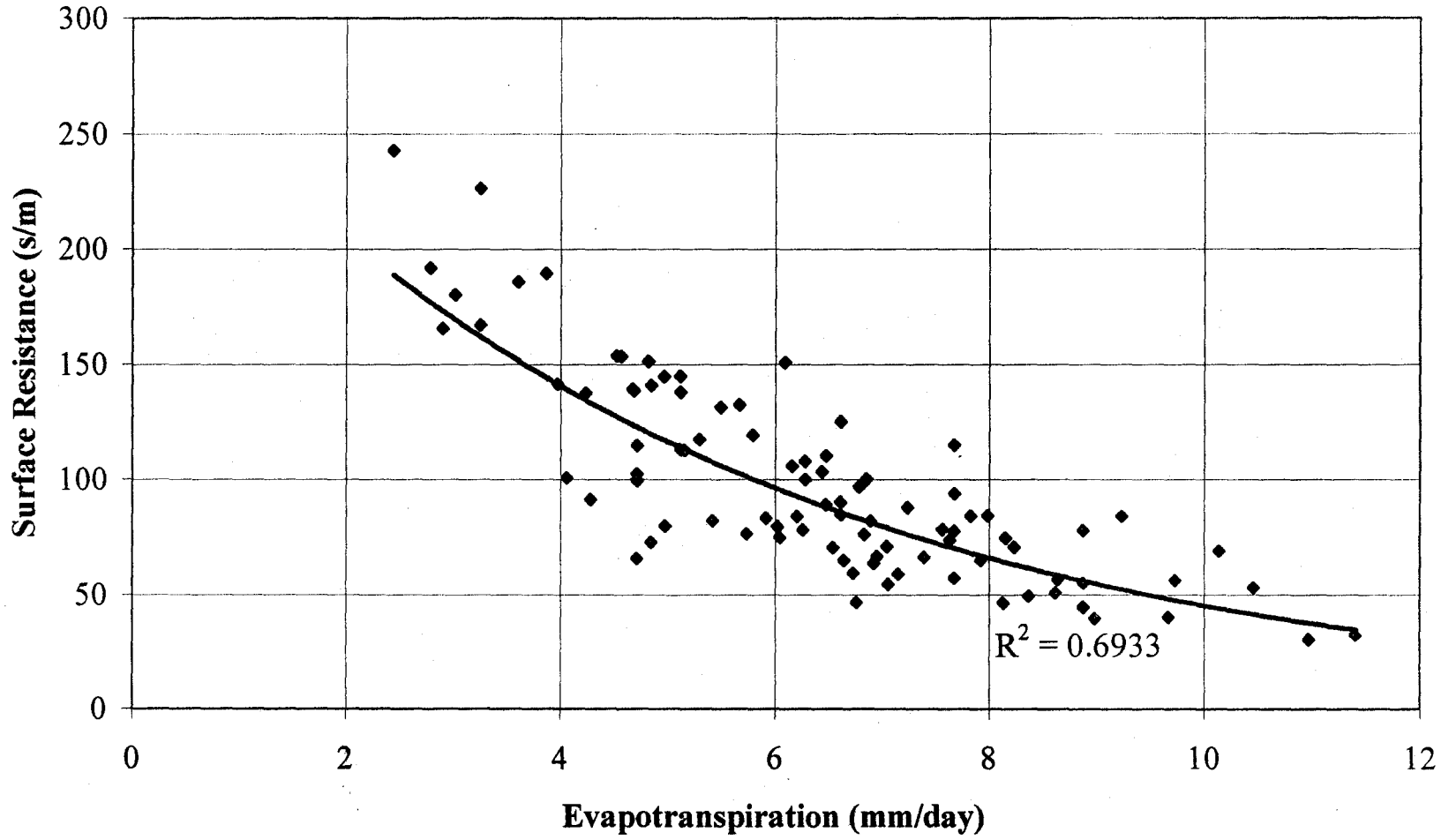

Figure A.5 Curve of r_s and evapotranspiration for 6 year old hybrid poplar trees when T is in the range 12.7-23.6 °C, RH is in the range 38.1-70.6% and R_s ranges from 391.7-727.5 langleys.