WATER BALANCE AND IRRIGATION SCHEDULING IN THE FOREST NURSERY, KOKSILAH, BRITISH COLUMBIA: A CASE STUDY

by

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ABSTRACT

This paper studies evapotranspiration and irrigation needs in Douglas fir seeding beds at the British Columbia Forest Nursery, Koksilah, British Columbia.

Research data were collected over the summer of 1970 and 1971. Potential evapotranspiration was measured through the use of a two-bin drainage lysimeter. Climatic elements measured were temperature, relative humidity, hours of sunshine, precipitation and windspeed.

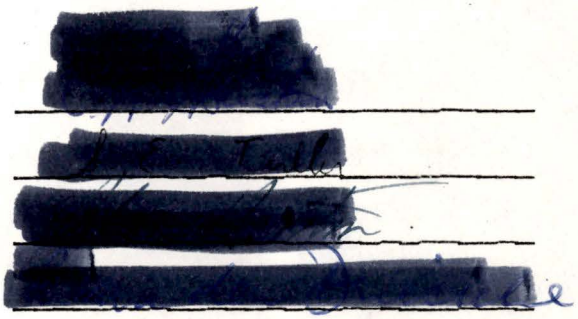
The applicability of existing methods for the prediction of potential evapotranspiration was tested through a correlation analysis. Results indicated that no formula gave reliable predictions at Koksilah.

The measured climatic elements were tested for their individual relationships to potential evapotranspiration. Using a ten day running average, hours of sunshine explained the lowest percentage (66%) while maximum relative humidity explained the highest percentage (97%) of variation in measured potential evapotranspiration.

The individual climatic elements were tested in various combinations through a multiple regression analysis. The combination of maximum temperature, minimum temperature, and average windspeed explained 39 percent of the variation in potential evapotranspiration readings. This method re-

quired much less detailed data and less calculation than existing formulae. The results achieved using this combination were more reliable than those obtained using the existing formulae.

From the newly developed formula, a nomograph and table were developed by which the actual evapotranspiration (i.e. irrigation needs) can rapidly be determined.

Signatures: 

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CHAPTER I

I. INTRODUCTION

> Tree growth is reduced by water deficits indirectly through interference with physiological processes such as photosynthesis, nitrogen metabolism, salt absorption, and translocation, and directly by the effects of reduced cell turgor on cell enlargement and other processes more directly involved in growth . . .
>
> Theodore T. Kozlowski
> (1962, p. 172)

Man has continually faced the problem of inadequate water to meet the needs of optimum agricultural production. The issues related to this problem have been studied by engineers, physicists, plant physiologists, soil scientists, and climatologists. Much of the work done by climatologists has been more recent and more theoretical than work conducted by other professions studying the problem.

Studies of the climate and its relationship to agricultural production and plant growth can aid man in his selection of sites for specific crop production. By studying such climatic factors as evapotranspiration (i.e. the combined loss of water from a given area by evaporation from the soil and transpiration from plants), solar radiation, temperature, humidity, and wind, along with water balance in the soil, man can develop a plan to realize maximum economic return from a given crop in a particular area.

Robertson and Holmes (1959) stated that maximum crop production from an area is achieved when soil moisture is kept just below field capacity (i.e. amount of water remaining in the soil subsequent to saturation and after free drainage has practically ceased). The study of climatological data for determining optimum levels of soil moisture (i.e. the level of soil moisture at which plants will make most rapid and sustained growth) is gaining prominence in agrometeorology. The study of climatic factors not only aids in determining soil moisture but also benefits the assessment of the effect of fertilizers, crop rotation, and crop variety on the growth of crops.

Evapotranspiration is one of the most important climatic factors affecting water availability and crop growth. Taylor (1962) stated that plant growth bears no direct relation to general evapotranspiration but rather evapotranspiration is one of several climatological factors which together with other environmental considerations comprise the physical environment of plants. The development of evapotranspiration studies and crop-growth-moisture relationships, based on soil moisture estimates calculated from climatological factors, is a comparatively new aspect of agrometeorology.

Chang (1968) suggested that maximum crop production may be obtained by applying water to match the rate of potential evapotranspiration (i.e. the amount of water that,

if available, would be lost through evapotranspiration).

Since Thornthwaite's studies into potential evapotranspiration in 1948, researchers have attempted to develop statistical methods of determining potential evapotranspiration through its relationship with other climatic parameters such as solar radiation, temperature, relative humidity, and wind. These statistical methods vary in degrees of complexity and in the climatic parameters used. Researchers in this aspect of agrometeorology have included Blaney and Criddle (1950), Hamon (1971), Makkink (1957), Turc (1954), Penman (1956), Stephens and Stewart (1963), Van Bavel (1966), and Haude (1958). Subsequent to these developments (in the field of potential evapotranspiration prediction) researchers have modified various of the formulae to develop site specific relationships. Aside from the adaptation of existing methods to new problems, more detailed studies must be conducted to determine individual crop-moisture requirements where an understanding of actual evapotranspiration is needed. By applying water to the crop-soil system at a rate equal to actual evapotranspiration, it is possible to maintain the soil moisture at an optimum level.

The problem of irrigation scheduling with respect to soil moisture balance was brought to the attention of the author and the University of Victoria, Department of Geography, by Dr. R. J. van den Driessche of the B.C. Forest Service, Research Division. Crop yields at forest nurseries

have periodically been reduced due to drought conditions. These detrimental effects have, in the past, been alleviated by sprinkler irrigation, regulated on a poor to non-existent meteorological basis. Improper scheduling of the irrigation has resulted in poor growth and some seedling losses (H. Mueller, personal communication).

The Koksilah nursery complex was chosen as a study site. This nursery suffers from numerous dry periods and offered a study area that was new (as a forest nursery), relatively unobstructed (topographically) and easily accessible. It was felt that information gathered in this study area would be useful and would contribute to knowledge in the fields of evapotranspiration and water balance.

II. KOKSILAH NURSERY: PERSPECTIVE AND PROBLEM

The Koksilah nursery is one of the two nursery areas falling under the Duncan Forest Nursery administration. The Koksilah nursery originated with the purchase of 53.17 acres of alluvial flats in 1963. In 1966, an additional 10 acres were leased from the neighbouring Cowichan Indian Reserve, increasing total acreage to 63.17 acres.

The nursery lies on a flood plain bounded on the south by the Koksilah River and on the north by the Cowichan River. To the west are situated the hills of central Vancouver Island, which protect the area from some of the precipitation associated with weather systems that

pass over the area from the west (i.e. it is a rain shadow area). To the east the land slopes gradually to Cowichan Bay, some three miles (approximately 5 km.) away.

Species grown at the Koksilah nursery are Douglas fir (dominant), Sitka spruce and Western red cedar.

Summer months are generally warm and dry. This climatic condition leads to problems of water deficit and the need for an effective irrigation system.

This study focuses on evaporative moisture loss in the Douglas fir seedling beds at the Koksilah nursery. The prime purpose is to aid the nursery in scheduling irrigation with a view to keeping the seedling beds at their optimum moisture level during hot, dry periods. A method of predicting irrigation needs will promote the best use of the water resources and the maximization of tree growth.

The study first examines some of the history of the calculation of evapotranspiration. Subsequently, various widely used methods are examined with a view of (potentially) adopting one or more of these procedures for use at the Koksilah nursery.

The second phase of the study examines the relation of individual climatic elements to potential evapotranspiration. Individual climatic elements are grouped and then compared to potential evapotranspiration in order to determine if a combination may be developed that satisfactorily predicts potential evapotranspiration trends.

Advective effects are reviewed and applied to the experimental results in order to correct the 'oasis' effect (i.e. the vertical transfer of energy from the air to the surface and the "clothesline" effect (i.e. the horizontal transfer of energy over a plot with no guard area).

The concept of soil moisture budgets and the relation of potential evapotranspiration to actual evapotranspiration will be briefly reviewed. A soil moisture budget approach is then applied to the results in order to correct for differential drying of the soil with depth.

The final phase of this study provides a detailed description of the use of the experimental results. This description is provided as an aid to Nurserymen. It details (through examples) procedures to be followed in the determination of actual water needs.

In the determination of the final results and throughout the study certain basic conditions prevail. If these conditions are to result in a satisfactory solution they must i) include a quick and accurate estimate of irrigation needs, ii) be practical for use in the Nursery situation, and iii) be straightforward for use by any nursery personnel.

CHAPTER II

I. EVAPORATION THEORY

A. Evaporation and Evapotranspiration

In order to understand the processes involved in this study it is necessary to define various terms.

Evaporation is defined as the change of state of water from a liquid to a vapour (Trewartha, 1968). Hounam (1971) further states that evaporation includes the transfer of water vapour from a surface on the earth to the atmosphere.

Evapotranspiration is defined as the total amount of water vapour transpired by vegetation and evaporated from the surface of the earth, over a given area, in a given time period. The term potential evapotranspiration is used to designate the amount of water vapour transpired by vegetation and evaporated from the surface of the earth when the soil is never short of water. Actual evapotranspiration is defined as the amount of water vapour transpired by plants and evaporated from the surface of the earth no matter what the soil moisture.

Potential evapotranspiration is reached in nature over open water surfaces and over land surfaces where water availability is not a limiting factor (i.e. saturated surfaces). Actual evapotranspiration occurs at the potential

rate over saturated surfaces until drying of the surface takes place. At this point, the actual rate will fall below the potential rate. Evapotranspiration from a drying surface (i.e. a non-saturated surface) decreases rapidly as the surface dries and varies with the replacement rate from water reserves deeper in the soil. This movement of water toward the surface is greatly dependent on the type of crop, its rooting depth, and the soil type. Within any specific study area the type of crop may be uniform or it may vary. Whether the plant is a succulent or not, whether the crop completely covers the ground, or whether the crop is deciduous or evergreen are just a few possible variations in crop characteristics that might affect soil moisture movement.

Rooting depth varies according to the type of crop and the age of the crop. Crop types vary in their root structure from deep rooting species (eg. alfalfa) to shallow rooting species (eg. lawn grasses). Over the growing season rooting depth will increase thereby increasing the range of available soil moisture.

The third factor affecting water availability is the soil type. Water availability in different soil types is a function of the moisture storage capacity of the soil. For example, the storage capacity of soil types on the Canadian Prairies varies from one inch per foot of soil (2.54 cm.) in a sandy loam to two and two-tenths (2.2) inches

per foot of soil (5.59 cm) in a clay soil (Robertson & Holmes, 1959). In this example, the amount of water available to plants is much greater in the clay soil than in the sandy loam soil.

The amount of water available for evapotranspiration is also affected by climatic factors of which the most important is precipitation. Precipitation influences water availability through the addition of moisture to the surface. If no artificial means of adding water (i.e. irrigation) is available, precipitation is the major supplier of water to the study area. Within limited regions other potential sources of moisture may include surface streams, underground water, and artificial sources such as irrigation.

As well as soil moisture content, evapotranspiration is affected by other climatic factors such as solar radiation, net radiation, wind, vapour pressure, and surface temperature. The following sections will illustrate how these and other climatic factors interact to influence water availability and evapotranspiration trends at the Koksilah nursery.

B. Climatic Parameters Influencing Evapotranspiration

Radiation

Physical processes taking place on the surface of the earth require energy to work and they release energy when work is carried out. Ninety-nine point nine percent (99.9%) of the energy required for these processes originates from the sun (Sellers, 1965).

In order to understand the concept of evapotranspiration it is necessary to understand what part energy plays in the process. Energy received from the sun enters the earth-atmosphere environment as shortwave radiation (wave-length between 0.15 microns and 4.00 microns). As this shortwave radiation is absorbed, the absorber heats up due to an increase in internal energy. These absorbers then radiate energy in the longwave portion of the spectrum (4 microns to 100 microns) by virtue of their cooler temperatures (i.e. cooler than the sun). The balance between shortwave and longwave radiation is termed net radiation (Mukkamel and Bruce, 1960; Graham and King, 1961). Net radiation at the surface of the earth is represented by the equation:

$$\pm R = (+Q+q)\ (1-r) + LW\downarrow - LW\uparrow = \pm H \pm G \pm LE \qquad (1)$$

where:

R = Net radiation at the surface of the earth.

Q = Incoming direct beam solar radiation.

q = Incoming diffuse beam solar radiation.

r = Fraction of (+Q+q) reflected by the surface.

LW↓ = Longwave radiation from the atmosphere.

LW↑ = Longwave radiation emitted by the earth's surface.

H = Sensible heat flux.

G = Ground heat flux.

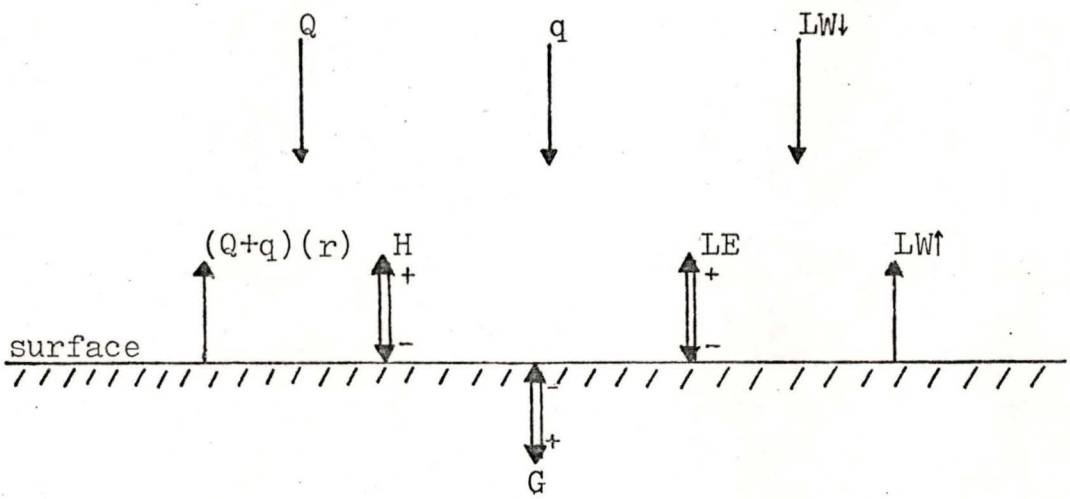
L = Latent heat of condensation and vapourization (590 cal g^{-1} @ $20^{\circ}C$).

LE = Latent heat flux.

Figure 1 presents a graphical representation of the energy balance at the surface of the earth as outlined by equation (1).

Figure 1

ENERGY BALANCE AT THE SURFACE OF THE EARTH



In equation (1), ±Q represents the shortwave solar radiation that reaches the earth's surface directly from the sun. The shortwave radiation, reaching the earth's surface after having been diffused by interference from clouds and constituents of the atmosphere, is represented by ±q. The fraction of this direct and diffuse shortwave radiation that is reflected from the surface is represented by r. Some of this is lost back to space while some is absorbed and/or reflected by clouds and atmospheric constituents. (-)LW↑ represents the amount of longwave radiation that objects on the earth's surface radiate to the atmosphere. As with r, some of this longwave radiation is lost to the

earth-atmosphere system while a portion of it is absorbed by clouds and other atmospheric constituents. (+)$\underline{LW}\downarrow$ is the longwave energy that is received at the surface of the earth from the atmosphere. The total net radiation ($\pm\underline{R}$) is the sum of the above terms and represents the total amount of radiant energy available at the earth's surface.

The distribution of this available energy ($\underline{R}$) on the surface of the earth is termed the energy budget. The primary job of the available energy ($\underline{R}$) is to heat the earth's surface. The heating of the earth's surface determines the direction of flux and the distribution of energy between heating the atmosphere immediately adjacent to the earth's surface, evaporation, energy conducted into the sub-surface, and for such processes as snow melt and photosynthesis.

The portion of energy used for such processes as snow melt and photosynthesis is small when compared to the total amount of energy available at the earth's surface. Of the total net radiation available over a one year period, an average of less than three percent (3%) is used for photosynthesis and snow melt (Hounam , 1971). Because this amount is so small when compared to the total energy involved, it is common to neglect this portion when referring to the energy budget at the earth's surface.

The remaining ninety-seven percent (97%) of the available net radiation is ultimately utilized in three

processes: i) heating of the earth's sub-surface as represented by G in equation (1); ii) direct heating of the atmosphere via conduction and convection as represented by H in equation (1); and iii) evapotranspiration at the surface of the earth as represented by LE in equation (1).

Ground heat flux (G) is the flow of energy into and out of the earth's sub-surface. It is a function of the thermal conductivity and specific heat of the soil, and the soil temperature profile (Geiger, 1965). The thermal conductivity of the soil is the amount of heat that can pass through a unit area of soil having a given vertical temperature gradient ($1^{o}C/cm$) in a given time span (1 second), if no heat is lost in any direction. This value may easily be calculated for any soil constituent. One method of measuring the thermal conductivity, irrespective of soil type and moisture content is through the use of heat flow probes as designed by de Vries and Peck (1957), Buettner (1955), and Blackwell (1954), among others. These probes consist of a thermocouple about the size of a hypodermic needle, that is inserted directly into the soil. These probes are calibrated to read directly the thermal conductivity of the medium, continuously and in situ.

The soil temperature profile may be measured by inserting temperature reading devices (similar to the probes mentioned above) directly into the soil at varying depths. Surface temperatures may be measured through the

use of an infrared thermometer. Temperatures near the surface of the soil, however, require more precise instantaneous readings due to large and rapid temperature fluctuations. Sinclair (1922) found that a temperature difference of 21.1°C existed between 0.4 and 2.0 cm. below the soil surface at midday at Tucson, Arizona. In addition to the use of small size thermocouples, temperature sensitive plates may be used to measure directly ground heat flux ($\underline{G}$). Large errors often occur, however, if the thermal conductivity of the plates varies greatly from that of the surrounding medium (Sellers, 1965). These plates are rugged (compared with the sensitive hypodermic needle type sensor) but they do interfere with the natural flow of heat and moisture in the soil.

Ground heat flux ($\pm\underline{G}$) is a cyclical process. During the day time, the net incoming radiation ($+\underline{Q}+\underline{q}+\underline{LW}\downarrow$) at the surface is at a maximum and usually exceeds net outgoing radiation ($-\underline{LW}\uparrow$ and $1-\underline{r}[\underline{Q}+\underline{q}]$). This overbalance of incoming radiation permits the transference of heat into the subsurface ($+\underline{G}$). In the early afternoon incoming radiation starts to decrease. When the outgoing radiation ($1-\underline{r}[\underline{Q}+\underline{q}]$ and $-\underline{LW}\uparrow$) exceeds the incoming radiation ($+\underline{Q}+\underline{q}+\underline{LW}\downarrow$) the surface starts to lose heat energy. As the surface loses its energy it cools and a negative temperature gradient is established (i.e. surface cooler than subsurface). At this stage heat energy is transferred from the subsurface to the surface creating a negative heat flux in the soil ($-\underline{G}$).

This is the reason why the soil heat flux may fluctuate from positive to negative. This cycle of energy transfer may also be observed on a seasonal basis, as well as a daily basis. The seasonal variation in such heat flux is a result of the seasonal variation of solar energy input, based on the angle of the sun's rays incident on the earth's surface. Monteith (1950) showed that soil heat flux balance varied from ten percent (10%) down to less than two percent (<2%) of the total net radiation, on a daily and seasonal basis, respectively. Tanner and Pelton (1960) concluded that the soil heat flux may be neglected for studies covering a growing season but should be considered for intensive twenty-four hour (24 hour) or shorter studies.

When the soil heat flux is neglected the energy budget equation reduces to:

$$\pm R = \pm H \pm LE \qquad (2)$$

The sensible heat flux ($\underline{H}$) represents a direct exchange of energy between the earth's surface and the atmosphere.

Heat energy is conducted into the atmosphere when the surface is warmer than the air immediately adjacent to it. This condition generally occurs during the daytime when the ground is being heated ($+\underline{H}$). When the ground is colder than the air adjacent to it, heat is conducted to the surface from the atmosphere ($-\underline{H}$).

A parcel of air adjacent to the ground is heated by the surface through molecular interaction (i.e. conduction).

When this parcel of air is heated it becomes less dense than the air above it. Due to this difference in densities the less dense (warmer) parcel rises through the atmosphere until it reaches a level of equal density. As the parcel of less dense air rises it expands and cools. Upon rising, this parcel of air is replaced on the ground by a parcel of cooler, more dense air. Through this process heat energy is taken away from the earth's surface. This cycle of heating, rising, cooling, and falling is called convection (i.e. the mass motions within a fluid resulting in transport and mixing of the properties of that fluid).

Factors controlling the magnitude of this heat flux include vertical gradients of temperature near the surface, the specific heat of the air, density of the air, and eddy transfer coefficients (which also depend on wind). The measurement of these factors is complicated and expensive.

The final parameter in equation (2) is $\pm LE$. The L in the term LE refers to the latent heat of vapourization and condensation. The latent heat of vapourization is the amount of energy required to evaporate moisture. The latent heat of condensation is the energy given off when vapour condenses. The latent heat of water is 590 cal g^{-1} at $20^{o}C$.

The E term in LE refers to evapotranspiration. To determine E certain parameters must be known, including

the vertical gradient of specific humidity or the vapour pressure near the surface, the density of moist air, and the eddy transfer coefficient of moist air (Hounam, 1971).

The determination of $\underline{E}$ is difficult (as is the value of $\underline{\pm H}$), as very precise readings are required on the surface of the earth and on the surface of plants (Hounam, 1971). Due to the constant changing of the values to be measured, instantaneous readings must be obtained (i.e. mean daily readings are misleading) (Chang, 1968).

In an effort to assess the distribution of net radiation between $\underline{\pm H}$ and $\underline{\pm LE}$, Bowen (1926) proposed a method of dividing net radiation. The Bowen relationship is:

$$\beta = \frac{H}{LE} = \frac{C_p}{L} \left(\frac{\Delta T}{\Delta q} \right) \qquad (3)$$

where:

β = the Bowen ratio.

C_p = specific heat of air at constant pressure.

L = latent heat of vapourization (590 cal g^{-1}).

ΔT = vertical temperature gradient near the surface.

Δq = vertical gradient of specific humidity near the surface.

Calculation of the Bowen ratio through the measurement of these values offers an indication of how net

radiation is divided amongst sensible heat flux and evapotranspiration. Generally, the Bowen ratio is negative when heat is being transferred from the atmosphere to the surface and positive when the situation is reversed.

In order to determine the quantity of moisture evaporated (i.e. $\underline{E}$ of $\underline{LE}$) it is possible to solve the energy budget equation (2) by substituting the Bowen ratio.

$$E = \frac{R-G}{L} \frac{1}{1+B} \qquad (4)$$

In this substitution, an assumption is made. The variation of $\underline{H}$ and $\underline{E}$ fluxes to any height are similar (Hounam, 1971). This assumption is reasonable provided observation heights are kept to a minimum (this minimizes buoyancy and advection effects)(McIlroy, 1968).

As long as the Bowen ratio is small the error in estimating $\underline{E}$ is small (Aslyng, 1960; Koberg, 1958; Frankenberger, 1960). Tanner (1960) has shown that the use of the Bowen ratio does not work when its value is less then -0.5. The Bowen ratio method of calculating $\underline{E}$ has been extensively used by Harbeck (1958) and Tanner (1963), among others.

The Bowen ratio method is still one of the most effective ways of solving the energy budget equation. However, due to high capital and maintenance costs involved in gathering data its use has been limited (Hounam, 1971).

The use of energy budget methods in the determination of evapotranspiration will be discussed further, in a later

section of this paper.

Temperature

The energy budget approach of determining evapotranspiration (as noted in the previous section) is complex and expensive. Due to these factors, many researchers in agrometeorology have attempted to utilize other more easily obtained climatic parameters such as temperature. They have at the same time attempted to show the relation of temperature to solar radiation at the earth's surface.

As outlined in the previous section (Radiation), the primary effect of available energy at the surface of the earth is to heat that surface. This heating of the earth's surface then determines the magnitude and distribution of the available energy between heating the atmosphere directly adjacent to the earth's surface, evaporation and heating the subsurface. The heating of the layer of air directly adjacent to the earth's surface is carried out through molecular conduction. The processes involved in the convective heating of the layers above the earth's surface are explained in more detail in the previous section. Mather (1974) summarized by saying that temperature at the earth's surface, determined by the net radiation and its transformation into sensible and latent heat fluxes at the earth-air interface, is directly related to the temperature of the air near the surface. It is upon this direct relationship that many researchers have based the

substitution of temperature parameters for radiation, in the calculation of evapotranspiration.

Three temperature parameters are commonly used in climatological studies of evaporation: i) average monthly temperature, ii) mean monthly maximum temperature, and iii) mean monthly minimum temperature.

Thornthwaite (1948) derived a formula for the calculation of potential evapotranspiration through the use of average temperature readings. When using average temperature readings, some of the problems encountered are, firstly, average air temperature is not always a good indicator of energy available for evapotranspiration. Van Wijk and de Vries (1954) indicated that, in the Netherlands, during November and March, the average temperatures were 5.4°C and 5.0°C and the average solar radiation was 67 langleys per day and 195 langleys per day, respectively. The potential evapotranspiration during these two months, as calculated from the energy balance, was nearly four times as high in March as it was in November.

Secondly, because air temperature lags behind radiation, the Thornthwaite method of estimating potential evapotranspiration shows a time lag with respect to measured evapotranspiration. Van Bavel (1956) noticed a lag between measured evapotranspiration and average temperature of up to four weeks.

Thirdly, the Thornthwaite formula does not consider the effect of warm and cold air advection on the temperature. In areas of warm air advection, the air temperature might be greatly increased while solar radiation and evapotranspiration are not. In areas of cold air advection, estimated potential evapotranspiration might fall well below measured potential evapotranspiration. Pruitt (1960) found that in California, where warm air advection was high, potential evapotranspiration calculated by the Thornthwaite method was higher than measured potential evapotranspiration by a factor of 1.72.

These are a few of the drawbacks in Thornthwaite's use of average temperature for the determination of potential evapotranspiration. As an alternative to the use of average temperatures, Mather (1974) suggested the use of maximum daily temperatures. Generally, daytime net radiation is higher (+$\underline{R}$) than nighttime net radiation (-$\underline{R}$). Usually, this leads to higher daytime temperatures than nighttime temperatures. Pruitt (1962) points out that recorded potential evapotranspiration is higher during the daytime than the nighttime. It might be concluded, therefore, that a direct relationship does occur between the magnitude of daytime temperature and the magnitude of daytime potential evapotranspiration. The actual relationship between these two parameters will vary, however, depending upon other climatic factors such as humidity and wind, and depending upon crop and soil

moisture characteristics.

The use of these temperature parameters might be a practical alternative to the use of the expensive and complex energy budget approach. The relation of maximum, minimum, and average temperature to evapotranspiration should, however, be evaluated on an individual basis in order to prove applicability to any particular study site.

Vapour Pressure and Humidity

The concepts of vapour pressure and other humidity parameters are often confused. Vapour pressure is defined as that part of the atmospheric pressure which is due to water vapour (Trewartha, 1968). Specific humidity is defined as the weight of water vapour per unit weight of air (Trewartha, 1968). Specific humidity and vapour pressure are nearly proportional and are often interchanged. When air contains all the water vapour it can hold at a given temperature and pressure, it is said to be saturated or it is said to have reached its dew-point temperature and saturation vapour pressure. Relative humidity differs from the above parameters of humidity as it represents the amount of water vapour actually present in the air compared with the maximum that could be contained under conditions of saturation, at a given temperature and pressure (Trewartha, 1968).

In the process of evaporation vast amounts of latent heat energy are required (i.e. 590 cal g^{-1}). Conversely, vast amounts of latent heat are given off when water vapour condenses. Natural evaporation can only occur when the vapour pressure of the ambient air is less than the vapour pressure at the evaporating surface and can continue only while there is an external source of energy.

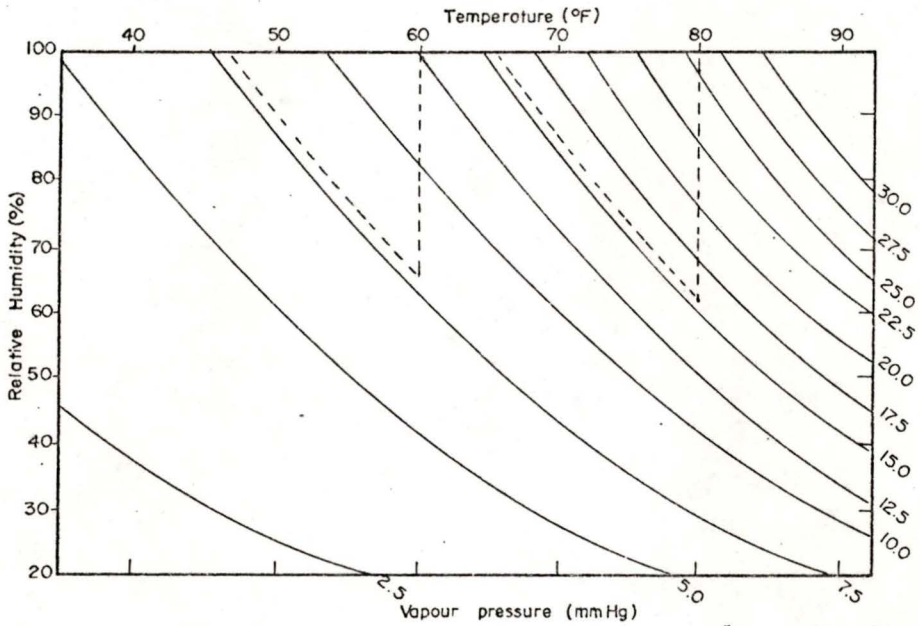
Evaporation is proportional to the vapour pressure gradient between the evaporating surface and the air (Webb, 1960; Marciano and Harbeck, 1954; Linsley, Kohler, and Paulhus, 1958). Evaporation is not, as some investigators believe, proportional to the vapour pressure deficit or saturation deficit (i.e. the amount of water vapour required to bring a non-saturated parcel of air to saturation at a given temperature and pressure)(Mather, 1959). This was clearly pointed out by Thornthwaite (1940) and Leighly (1937).

The relationship between vapour pressure, temperature, and relative humidity is often misused. Mather (1959) constructed a diagram to illustrate the relationship and cited an example of the misuse.

> Consider, for instance, an example of the rate of evaporation from two moist surfaces having exactly the same temperature into two air samples both having a relative humidity of sixty percent (60%) and with temperatures of 60°F and 80°F, respectively. While it might at first appear that the rate of evaporation would be greater into the air at 80°F, such is not the case. Figure 2 depicts the rough relation between air temperature, relative humidity and vapour pressure of the air.

Figure 2

RELATION BETWEEN TEMPERATURE AND MOISTURE CONTENT OF THE AIR



after Mather, 1959

The air at 80°F and 60 percent relative humidity has a vapour pressure of just less than 16 mm. Hg. This is the same vapour pressure which would exist at a water surface temperature of about 64.5°F. If the surface water temperature were below 64.5°F, the vapour pressure at the surface would be below the vapour pressure of the air and condensation onto the surface would be occurring instead of evaporation.

The air at 60°F and 60 percent relative humidity has a vapour pressure of about 8 mm. Hg., which is equal to the vapour pressure at a water surface at a temperature of about 45.5°F. Thus, if the water surface in our example had a temperature between 45.5°F and 64.5°F there would be evaporation into the air sample at 60°F and condensation from the air sample at 80°F. Only if the temperature of the moist surface is above 64.5°F will evaporation into both samples occur. Then the rate would be greater into the air at 60°F than into the air at 80°F because the evaporation is proportional to the vapour pressure gradient.

Although the concepts of vapour pressure gradients and relative humidity may be easily understood, the interrelationships between evaporation, air temperature, vapour pressure, and relative humidity are complex and easily confused. If these factors are utilized in any calculation of evapotranspiration, care must be taken that they are used in the appropriate context and with a full working knowledge of their relationships.

Wind

Wind influences evapotranspiration by bringing fresh parcels of air into contact with an evaporating surface. This process helps to stimulate evapotranspiration through the maintenance of vapour pressure and temperature gradients between the evaporating surface and the air, and through

the process of turbulent transfer. The turbulence of wind near the surface plays a part in the partitioning of energy into latent heat flux (LE) and sensible heat flux (H) and in the removing of heat and water vapour from the air layer adjacent to the evaporating surface. Under conditions of non-turbulence, the transfer of heat and water vapour along the temperature and vapour pressure gradients, is slow. Under turbulent conditions this transfer is rapid. The actual relationship between temperature and vapour pressure gradients and the degree of turbulence, is more complex than outlined above. The upward flow of water vapour from the surface is equal to the product of the gradient of vapour pressure and the rate of mixing. The rate of mixing does not depend upon the wind speed at a particular height but upon the rate of change of wind speed with height. For instance, if two air masses possess different wind speeds, a turbulent transfer will result in the contact zone (i.e. zone of friction) between the two air masses. The greater the friction between the two air masses the greater the rate of mixing. The rate of mixing is also dependent upon the degree of surface roughness. Over a rough surface, heat and water vapour are readily transferred, even though the wind speed may be fairly low. Tanner and Pelton (1960) state that if all other factors are held equal, an increase in surface roughness will lead to an increase in vapour pressure gradients and a subsequent increase in evapotranspiration.

As well as the ways in which evapotranspiration is affected by wind, it is important to compare the relative importance of wind with respect to other climatic factors which also affect evapotranspiration. Skidmore, Jacobs, and Powers (1969) conducted a study in Kansas to determine the relative contribution of radiation and wind to evapotranspiration. It was determined that on consecutive "non-windy" and "windy" days (i.e. windspeeds equal to 0.88 and 2.26 m sec^{-1} respectively), the wind contributed 33 percent and 113 percent more to evapotranspiration than did radiation.

The relative contribution of wind to evapotranspiration will vary according to a number of interrelated factors. Some of these factors include vapour pressure gradients, temperature gradients, variations of wind speed with height, and surface roughness. Any use of wind in the determination of evapotranspiration must, therefore, be evaluated on an individual study basis.

Summary

The relation of certain climatic parameters to evapotranspiration has been shown to be a complex one. No one climatic parameter can adequately predict evapotranspiration over all possible varieties of climatic and physical circumstances. As a consequence, researchers in the field of evapotranspiration have endeavoured to derive relationships that utilize a variety of climatic, crop and

soil factors. They hoped that these methods would increase the success of any one solution in predicting evapotranspiration trends and/or water requirements. These derived relationships, however, prove adequate for the conditions under which they were developed but are not necessarily valid in other environments. In the following section various techniques for determining evapotranspiration and water requirements will be reviewed as a basis for experimental procedures utilized later in this study.

II. MODELS AND FORMULAE

Studies into earth-atmosphere-water relationships generally utilize one of three different procedures in the determination of evapotranspiration: a) physical modeling, b) direct measurement, and c) statistical or empirical relationships.

A. Physical Models

Physical models work on the principle of equating evapotranspiration with energy or vapour transfers. Two basic methods of physical modeling exist: i) vapour transfer methods, and ii) energy budget methods.

Some vapour transfer methods are based on the Dalton approach and are empirical. The Dalton approach is based upon the concept that water vapour is carried upward from an evaporating surface by turbulent transfer and convection.

The general form of the Dalton equation is:

$$E = f(u)(e_s - e_z) \qquad (5)$$

where:

E = evaporation from a water surface.

f(u)= wind function.

e_s= saturation vapour pressure at the temperature of the water surface.

e_z= vapour pressure of the air at height z.

The value of the wind function depends upon the heights of the wind speed and vapour pressure measurements and, although these two heights need not be the same, the same experimental layout must be used for a particular value of the wind function.

If the rate of vertical mixing is approximated from the wind speed and the vapour pressure gradient is measured, then the rate and amount of evapotranspiration may be determined.

The relation of vertical mixing to wind speed plus the non-similarity of momentum and vapour transfer coefficients is the major problem in vapour transfer methods of calculating evapotranspiration. The rate of vertical mixing due to wind is not dependent on wind speeds at just one height but upon the rate of change of wind speed with height.

Air flowing along the ground encounters frictional resistance and slows down. This frictional resistance is transferred to successively higher layers of air at a decreasing rate. The air at higher layers is, therefore, moving faster than the air below due to a lack of frictional resistance. This differential in speeds sets up a sheer zone between layers, resulting in a vertical displacement of small parcels of air. If a fast moving parcel of air moves into a slower parcel of air it will have a tendency to increase the speed of the slower parcel. Similarly, a slow moving parcel will tend to slow down a faster moving body of air. The greater the difference in velocity between layers of air, the greater the sheer and the stronger the turbulence.

These measurements of turbulence are difficult to assess due to the need for monitoring vertical wind speeds. If only horizontal measurements of wind speed are available then vertical transfer coefficients must be approximated through the use of velocity gradients.

Due to the complexities of vapour pressure gradient determination and the difficulties of accurately determining vertical mixing, the calculation of evapotranspiration by the vapour transfer method is not an easy or practical method to use.

The energy budget method requires vertical profiles of temperature and humidity as well as measurements of net radiation and soil heat flux in order to determine the division of ($\underline{R}$ - $\underline{G}$) between $\underline{H}$ and $\underline{LE}$. There are no simple

instruments for measuring the vapour pressure of an evaporating surface which is not at one hundred percent (100%) relative humidity. The use of the energy budget method requires instantaneous readings as mean daily values are misleading (Chang, 1968). A further complicating factor is the need for complex, expensive equipment.

Many other factors exist which make the use of the energy budget approach for calculating evapotranspiration complex. Some of these problems were outlined previously in the section entitled "Radiation."

B. Direct Measurement

Direct measurement, although not a model, is widely used to determine evapotranspiration. The most commonly used method of direct measurement is soil sampling. Soil samples are collected (two or more at different times) in sealed containers and brought to the laboratory where they are weighed, dried, and weighed again. The resultant difference in weight is the soil moisture content, usually expressed as a percentage of soil weight. This method provides a means of determining changes in soil moisture. In order to determine evapotranspiration from these results precipitation, irrigation water, percolation, and runoff must all be known. From the water balance equation, evapotranspiration may then be calculated by:

$$\text{Evapotranspiration} = \text{Rainfall} + \text{Irrigation} - \text{Percolation} - \text{Runoff} \pm \text{Changes in Soil Moisture.} \quad (6)$$

A second method of direct measurement is lysimetry. Lysimeters are tanks in the ground used to determine evapotranspiration. They are the most dependable method of determining evapotranspiration as long as four basic requirements are met. First, the lysimeter must be large enough to reduce the boundary effects of the sides and bottom on soil character and soil moisture conditions, and in order to reduce root restriction to a minimum. Secondly, soil conditions within the lysimeter should be comparable to the area as a whole. Thirdly, the crop planted in the lysimeter should be the same as that surrounding it. Lastly, the lysimeter should have a "guard ring" area around it maintained under exactly the same conditions as the lysimeter itself.

Two basic types of lysimeters are used. Weighing lysimeters are used to measure actual evapotranspiration by measuring drainage out of the soil block and the change of weight of that block of soil. The change in weight is a measure of the amount of water that is evaporated and/or transpired when moisture added via precipitation and the loss of moisture by drainage, are known. The weighing lysimeter is capable of measuring evapotranspiration over a period as short as ten minutes.

Drainage lysimeters are used to measure potential evapotranspiration based on the assumption that potential evapotranspiration is equal to the amount of moisture added to the system, minus drainage, when the soil is kept in a

saturated state. Water is added to the top of the lysimeter and after a given period of time the amount of drainage through the soil is recorded. The difference between the amount added and the drainage is recorded as the amount of water that has been evaporated and/or transpired.

Lysimeters have been extensively used (Kohnke and Dreibelbis, 1940) for both long and short duration studies. Weighing lysimeters are for the most part prohibitively expensive and their use has, therefore, been limited. Drainage lysimeters, however, are much less expensive but do suffer from the effects of drainage time lag. When water is added to the surface of a lysimeter, soil characteristics determine the rate at which it will percolate. Percolation is normally a slow process. Therefore, subsurface runoff may not appear for some time after water has been applied to the surface. This "lag" effect thereby limits the use of drainage lysimeters to long term studies. One method of negating the lag effect is through the use of running averages. Running averages are generally calculated over an extended period of time in an effort to minimize minor fluctuations that might occur in percolation rates. Table 1 illustrates some typical evapotranspiration readings and three day running averages.

TABLE 1

EVAPOTRANSPIRATION READINGS AND
RUNNING AVERAGES (EXAMPLE ONLY)

	Day						
	1	2	3	4	5	6	7
Evapotranspiration	10	11	8	5	10	12	13
3 Day Running Average		9.66	8.0	7.66	9.0	11.66	

The three day running average for day 2 is 9.66, which is the average of evapotranspiration for the first, second, and third day. To obtain the three day running average for the third day, subtract the value for day 1 from the previous total, add the value for day 4 and divide by three. The process continues for the duration of available data. Running averages may be taken on any length of period desired. The longer the time period, the greater the effect of smoothing of the results will be. The use of this method to smooth out results from a drainage lysimeter obviates the need for data over an extended period of time.

Lysimeter results have proven useful as a means of calibrating other methods of direct measurement. Some of these other direct measurement methods include the Piche evaporimeter, the Livingston atmometer, the Bellani plate, and the evaporation pan. All of these methods are only valid for measuring evaporation from the specific instrument used.

Pan evaporimeters have been widely used to determine

evapotranspiration relationships in a variety of situations. Some of the situations using evaporation pans include complete grass cover at Aspendale, Australia (McIlroy and Angus, 1964), rice crops in Australia (Butler and Prescott, 1955), sugar cane in Hawaii (Chang, 1961), cotton in Israel (Stanhill, 1962), the A.E.S. network in Canada, the N. O. A. A. network, and that for most meteorological services around the world. The relation of pan evaporation to evapotranspiration, for a particular crop, varies with the frequency of moisture application (i.e. precipitation and/or irrigation), soil characteristics, and the completeness of vegetation cover.

These methods of direct measurement have been widely used to check the validity of derived statistical techniques. These statistical techniques include a variety of methods of calculating evapotranspiration and/or evaporation from climatic data. The following section reviews a few of these techniques, their derivation and their applicability to certain given situations.

C. Statistical Techniques

Statistical techniques for the calculation of evapotranspiration and water needs from climatic data, are numerous and have been used at different locations with varying degrees of success. These methods range from complex calculations based on the physics of evaporation and transpiration to methods based on simple empirical relationships between evaporation and temperature.

Statistical relationships between climatic variables and evapotranspiration are often used rather than direct measurement techniques due to the difficulty of obtaining accurate direct readings. These relationships are often used, however, in conditions very different from those for which they were developed. It is, therefore, important to test such methods before initiating them under a new set of conditions. This test frequently utilizes direct measurement techniques.

Statistical estimates have been successfully used in climatological classifications, water balance computations, drought investigations, studies of irrigation management, and crop-water requirement studies (Baier, 1965).

Reviews of attempts to quantify the evapotranspiration formulae indicate failure on the part of a lot of researchers (Dermine and Klink, 1966; Pfau, 1964; Shaw, 1964). Reasons for some of these failures include i) plant-weather relationships were too complex to be expressed by a simple equation, ii) mean values did not reflect variations of parameters over time, iii) the meteorological factors selected did not appropriately measure the physical environment, and iv) the interaction between meteorological variables was not adequately studied (Baier, 1967).

In this paper, only certain widely used empirical formulae will be reviewed. These represent a range of complexities from simple temperature-evaporation relationships

to complex aerodynamic-energy budget approaches.

The best known empirical relationship between temperature and potential evaporation was developed in 1948 by Thornthwaite (Appendix I). Developed from a series of studies conducted in North and Central America, this relationship uses mean monthly air temperature and length of daylight.

Results using the Thornthwaite method have been varied. Pelton and Korven (1969) showed that on a 3.7 acre area of alfalfa on the Canadian Prairies, the Thornthwaite method accounted for only twenty-seven percent (27%) of the variation in daily actual evapotranspiration. Over a seven day period, however, they showed that the Thornthwaite method accounted for seventy-nine percent (79%) of the variation in actual evapotranspiration. Stanhill (1961) compared results of the Thornthwaite method with actual evapotranspiration in southern Israel. On a weekly basis Thornthwaite's method accounted for seventy-three percent (73%) of the variation in actual evapotranspiration while on a monthly basis it accounted for ninety-four percent (94%) of the variation. In Florida, Stephens and Stewart (1963) compared the results of various formulae to measured pan evaporation and lysimeter results, on a monthly basis. The Thornthwaite method accounted for seventy-eight percent (78%) of the variation in the pan evaporation and eighty-six percent (86%) of the variation in evaporation measured by the lysimeter.

All of the above results indicate that the Thornthwaite method offers a good means of calculating potential evapotranspiration on a monthly basis in areas where the temperature and radiation are strongly correlated. This conclusion has been substantiated by Mather (1954), Decker (1962), and Fitzgerald and Rickard (1960).

Blaney and Morin (1942) developed a formula for calculating potential evapotranspiration based on mean monthly temperature, relative humidity and daylight hours. Crop coefficients were also used in the formula and were based on actual measurements of crop consumptive water use in tanks and soil moisture studies. Blaney and Criddle (1950) modified the formula by dropping the relative humidity term (Appendix I).

Pelton and Korven (1969) showed that on the Canadian Prairies, the Blaney and Criddle method underestimated actual evapotranspiration by thirty-one percent (31%) on a daily basis and by thirty-four percent (34%) on a weekly basis. Stanhill (1961) showed that in southern Israel, the Blaney and Criddle method accounted for seventy percent (70%) of the actual evapotranspiration on a weekly basis and ninety percent (90%) on a monthly basis. Stephens and Stewart (1963) showed that in Florida, the Blaney and Criddle method accounted for eighty-three percent (83%) of the variation in pan evaporation and ninety-one percent (91%) of the variation in lysimeter readings. Bordne and

McGuinness (1973) point out that as long as care is taken to ensure correct crop coefficients, the Blaney and Criddle method gives good results, but is recommended for use only on a weekly or monthly basis.

The Makkink (1957) formula differs greatly from the previous formulae in that it is based on solar radiation measurements, weighted according to air temperature (i.e. the higher the temperature, the greater the proportion of solar radiation used to provide energy for evaporation). The Makkink formula (Appendix I) was developed in the Netherlands from lysimeter measurements made with a grass crop grown under conditions of unlimited water supply. One of a few people to use this formula was Stanhill (1961). He found that in southern Israel, the Makkink formula accounted for seventy-five percent (75%) and ninety-five percent (95%) of the variation in actual evapotranspiration on a weekly and monthly basis, respectively. It was shown, however, that the Makkink method underestimated the magnitude of actual evapotranspiration by a factor of 1.49 times.

The four formulae described above calculate potential evapotranspiration (i.e. when water is non-limiting) but this seldom occurs under field conditions.

Turc (1954) derived a series of formulae to calculate actual evapotranspiration over short periods of time. Factors involved in the Turc method include precipitation, a soil factor, soil moisture deficit and the evaporative power of

the air. Turc's method is so complex that its use has been limited. Ahmad (1962) utilized a modified version of the Turc procedure and found good results when calculating water needs in the Quetta Valley of West Pakistan.

A portion of the Turc method is the calculation of the evaporative power of the air (Appendix I). This formula utilizing mean temperature and incoming solar radiation, gives a good indication of the ability of the climatic environment to force evaporation, through the use of two easily measured climatic parameters.

None of the aforementioned methods of calculating potential evapotranspiration or the evaporative power of the air take into account the influence of the wind. Penman (1956) derived a formula that combined the aerodynamic and energy budget approaches to evapotranspiration (Appendix I). Penman's method requires the measurement of several climatic variables including duration of bright sunshine, mean air temperature, mean vapour pressure, and mean wind speed. The Penman method has been widely used to estimate water needs over a variety of crops in a number of climatic conditions. Stephens and Stewart (1963) showed that estimates of potential evapotranspiration on a monthly basis, by Penman's method, accounted for seventy-two percent (72%) of the variation in evaporation pan readings and eighty-nine percent (89%) of the variation in lysimeter readings, in Florida.

Chang (1968) stated that, in a study of potential evapotranspiration from a lysimeter, Penman's approach showed deviations of twenty-five percent (25%) on a daily basis but only a one percent (1%) deviation over a twenty-five day period. Pelton and Korven (1969) showed that, on the Canadian Prairies, estimates of potential evapotranspiration by the Penman method had a correlation of 0.65 with lysimeter readings. Stanhill (1961) found that Penman formula estimates of potential evapotranspiration correlated well with actual evapotranspiration on a weekly and monthly basis (i.e. correlation coefficients of 0.76 and 0.96, respectively).

The Penman approach does suffer, however, from certain limitations. Jackson (1960) and Hounam (1958) found that in hot, dry climates the Penman method underestimated actual evapotranspiration by thirty-five percent (35%) to fifty percent (50%). Pruitt (1960) found that over a grassy field in California, the Penman method gave a good estimation of actual evapotranspiration at low wind speed (5 m.p.h.) but was less accurate at a higher wind speed (17 m.p.h.). At the lower wind speed the Penman method overestimated actual evapotranspiration by six percent (6%) while it overestimated by fifty percent (50%) at the higher wind speed.

The Penman estimate is likely to be low for vegetation rougher than short grass, unless the wind function is modified for surface roughness (Tanner and Pelton, 1960). They

concluded that the Penman approach is suitable for estimating potential evapotranspiration for periods as short as one day. Provided that appropriate soil and crop factors are used, the Penman method holds out considerable promise for the successful estimation of actual evapotranspiration (Ward, 1971).

In conclusion, it may seem that a variety of methods for estimating evapotranspiration are available to the researcher in agrometeorology. The complexity and usefulness of each method is different and to a large extent is a product of the environment in which it was developed.

This review has concentrated on a few of the many types of methods that have been utilized to predict water needs and evapotranspiration. Every method, however, must be evaluated for each new situation in which it is used.

In the following section, the statistical methods of Thornthwaite, Blaney and Criddle, Blaney and Morin, Penman, Turc, and Makkink will be tested against potential evapotranspiration as measured by a drainage lysimeter at the Koksilah nursery.

CHAPTER III

I. STUDY SITE AND METHODOLOGY

The Koksilah nursery lies south of the City of Duncan on Vancouver Island, British Columbia (Figure 3). It is located on alluvial flats between the Koksilah and Cowichan Rivers (Figure 4).

The Koksilah nursery consists of five large fields of nursery beds, and one seed orchard, surrounding a central compound and storage area (Figure 5).

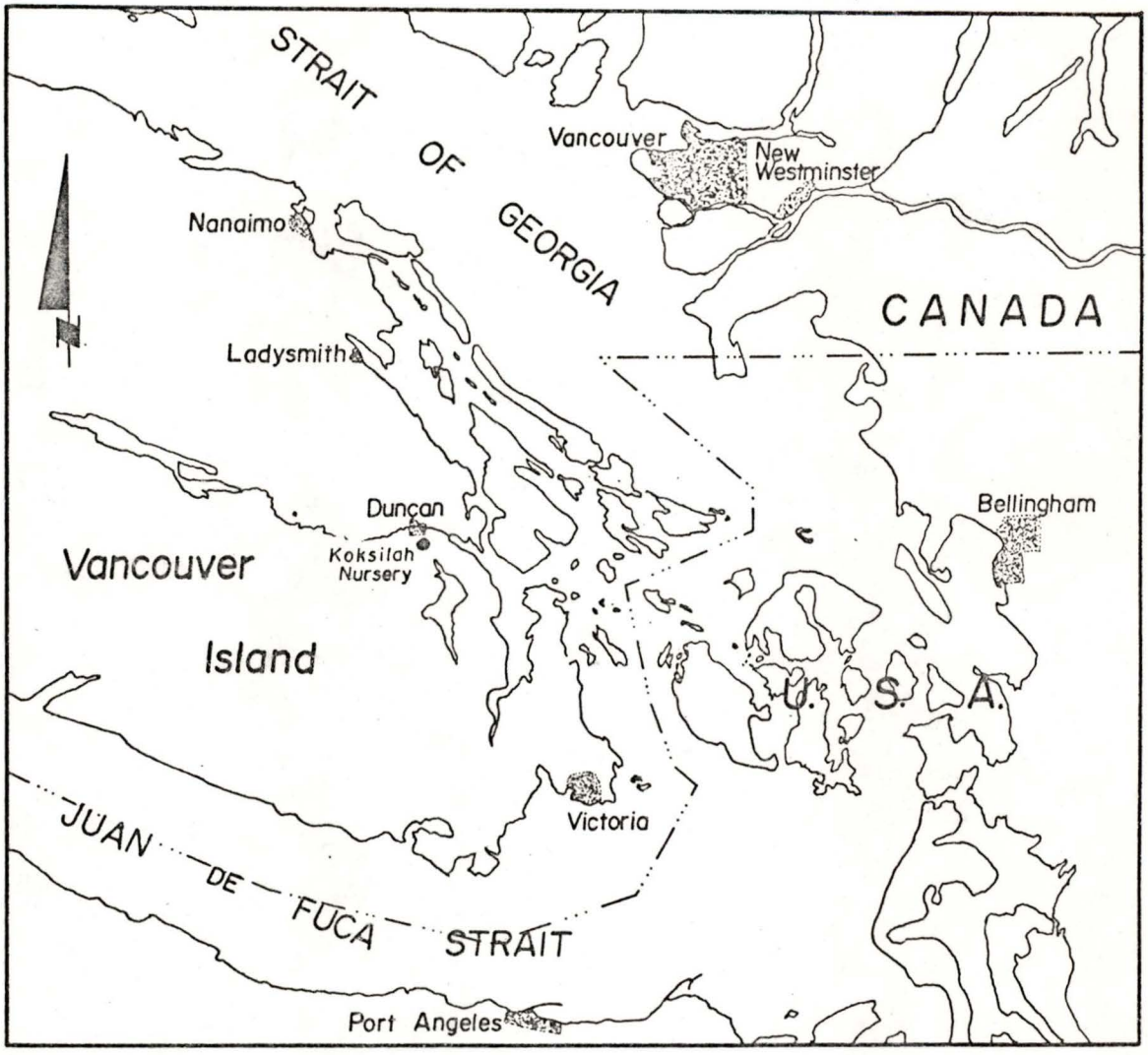
The first seeds were sown at the nursery in 1964. One thousand one hundred and fifty-nine (1,159) seed beds were sown, each being fifty-nine feet (15.24 metres) long by 3.6 feet (1.12 metres) wide, encompassing seven rows of seedlings.

The main species grown at the nursery is Douglas fir, with minor quantities of Sitka spruce and Western red cedar also being grown. Consequently, the investigation was carried out with a crop of Douglas fir seedlings. These seedlings are grown at the nursery for two years, at which time they are removed for transplanting into the forest.

MAP

Figure 3

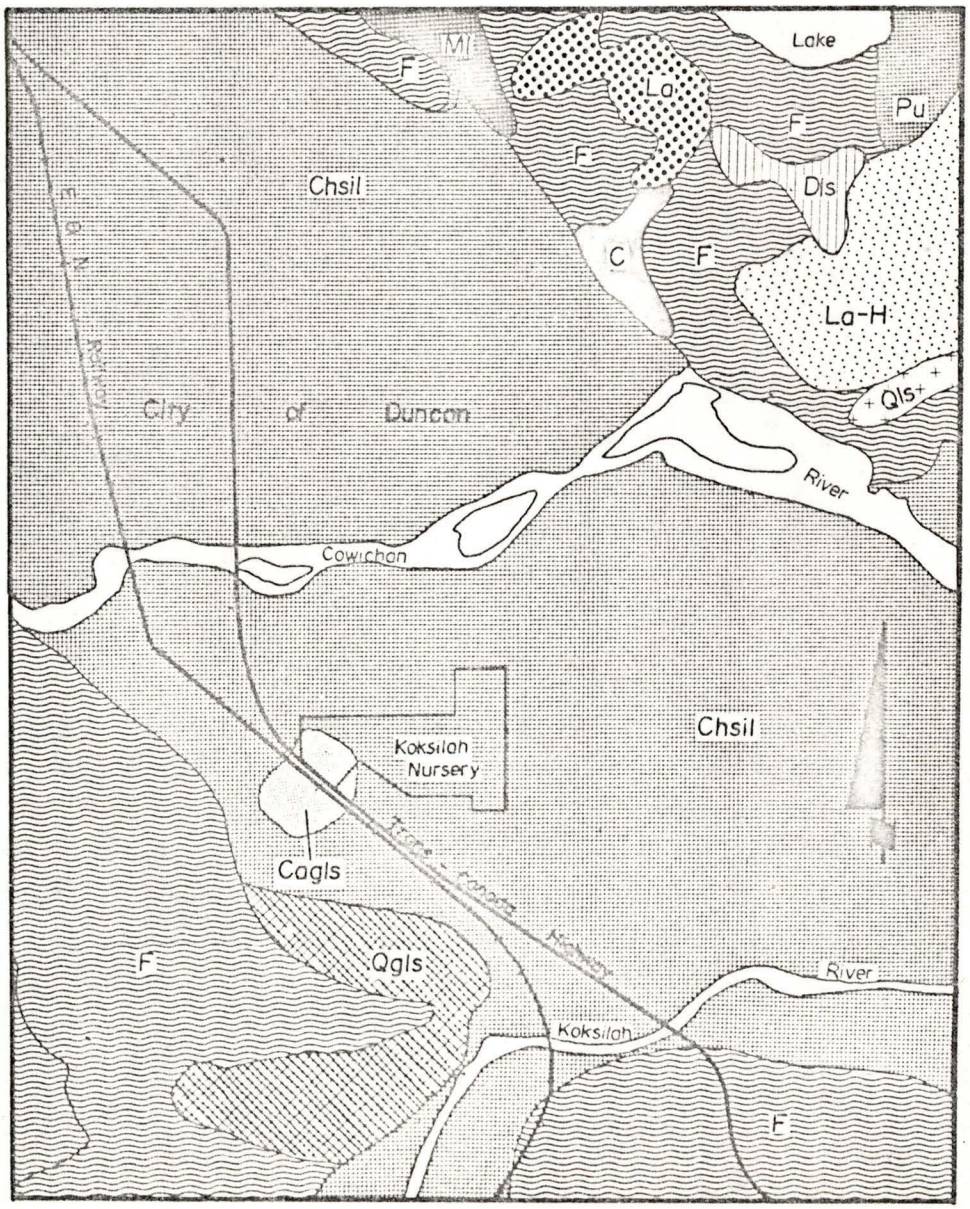
scale : 1 inch = 12 miles



SOIL MAP -(not to scale)

Legend

Cagls	Cassidy – gravelly loamy sand
Chsil	Chemainus – silty loam
C	Cowichan – clay loam
Dis	Dashwood – loamy sand
F	Fairbridge – silty loam
La	Lazo – loam
La-H	Lazo-Haslam – loam
Ml	Merville – loam
Pu	Puntledge – fine sandy loam
+Qls-	Qualicum – loamy sand
Qgls	Qualicum – gravelly loamy sand



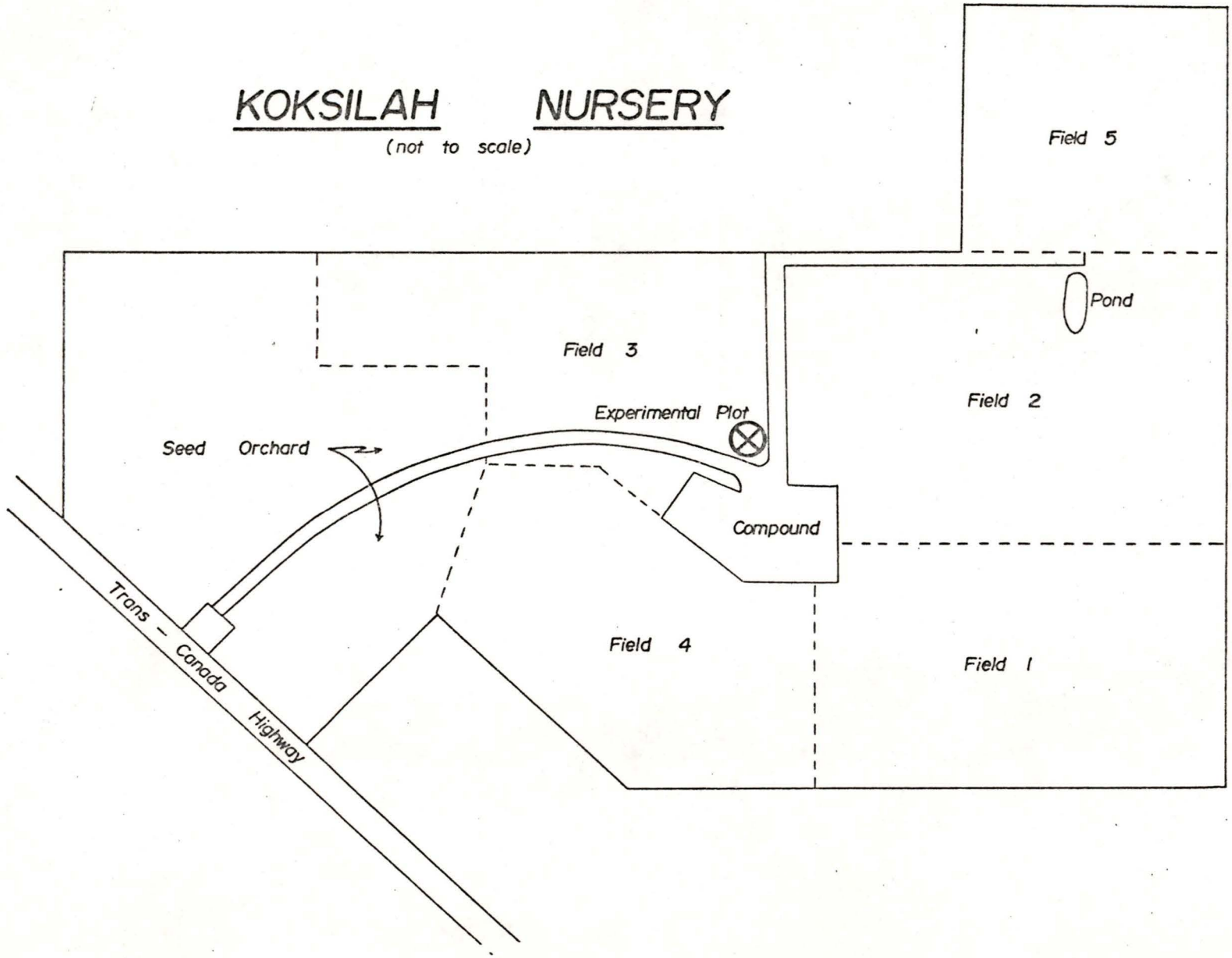

KOKSILAH NURSERY
(not to scale)
Field 5
Pond
Field 3
Field 2
Experimental Plot
Seed Orchard
Compound
Trans - Canada Highway
Field 4
Field 1

Figure 5

The Koksilah nursery, being located on alluvial flats, has no hard pan layer, thus good drainage is present. Two major soil types exist at the Koksilah nursery (Figure 4): a Cassidy gravelly alluvial soil and a Chemainus silty loam soil (Day, Farstad and Laird, 1959).

A two bin drainage lysimeter was used in the study. Soils from each lysimeter bin were analyzed according to the following procedure. Three soil samples were collected from each bin. Each sample was weighed, dried for 24 hours at 85°C, and weighed again, in order to determine the soil moisture content. Samples were subjected to a sieving process to determine their particle size composition by weight. The particle sizes were categorized using the Wentworth Scale for sediment analysis (Appendix II, Table 2) and these results were then analyzed according to methods outlined by Nikol'skii (1959)(Appendix II, Tables 3, 4, 5). Lysimeter bin one contained a slightly stony, heavy loam similar to a Chemainus silty loam. Lysimeter bin two contained a stony heavy loam similar to a Cassidy gravelly alluvium. These results indicate that lysimeter soil conditions reflected the major soil conditions found in the Koksilah nursery as a whole. Detailed soil analysis results are presented in Appendix II, Table 1 .

A location for the experimental plot was chosen at the geometric centre of the nursery (Figure 5). The site was selected because it offered easy access to a water supply (i.e. near the compound). This central location also minimized influences and effects created by the external environment.

Climatic parameters measured at the experimental site were potential evapotranspiration, temperature, wind speed and direction, relative humidity, and precipitation. The instruments were situated as illustrated in Figure 6. A two bin drainage lysimeter was located in the centre of the experimental plot (after Garnier, 1952). Each bin was connected to a central collection point which housed collection pans for daily runoff measurements (Figure 7). The lysimeter bins were each thirty inches (0.76 m.) long, eighteen inches (0.46 m.) wide, and eighteen inches (0.46 m.) deep. A thin layer of gravel was placed at the bottom of each soil bin to allow the unhindered movement of percolation water toward the bottom outlet (Ward, 1963). The soil removed from each site was replaced in the respective soil bin. The top rims of the soil bins were located just above ground level (to eliminate surface runoff). A crop of Douglas fir was planted in each soil bin in a similar fashion to the nursery beds, at large.

Figure 6

EXPERIMENTAL PLOT

scale : 1 inch = 3 feet (approx.)

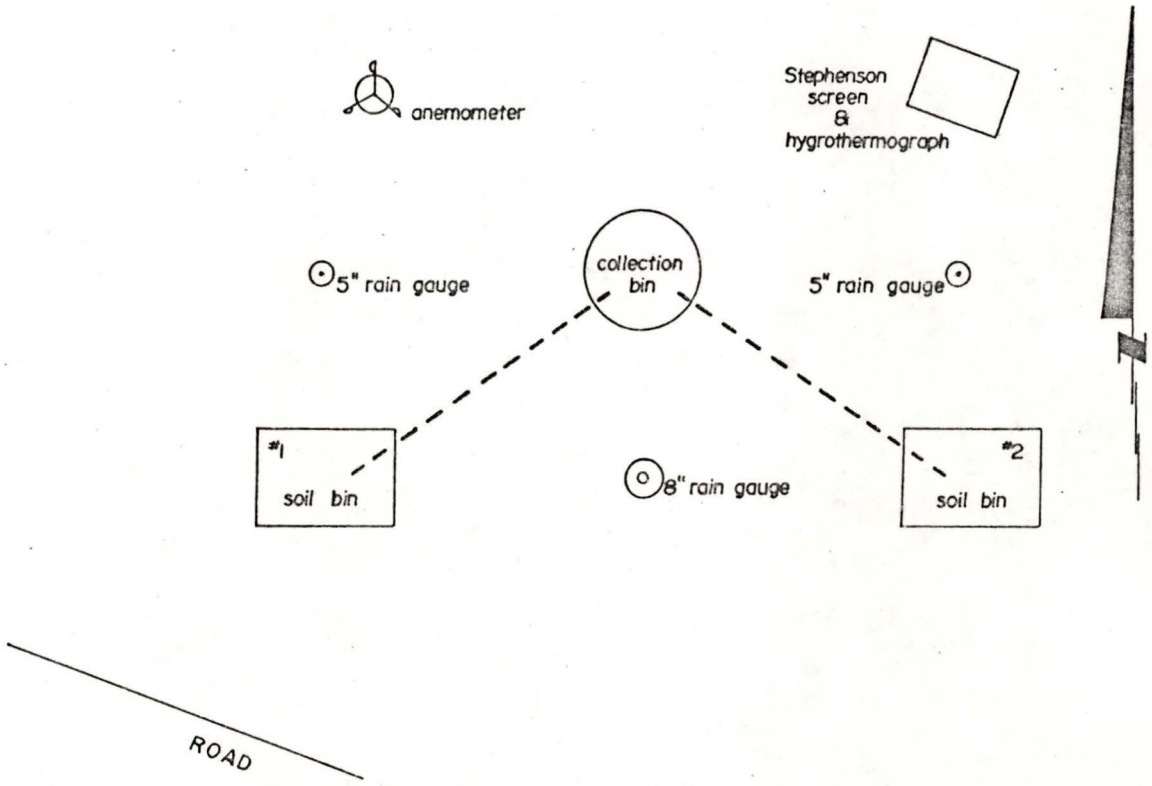


Figure 7

DRAINAGE LYSIMETER PROFILE

(not to scale)

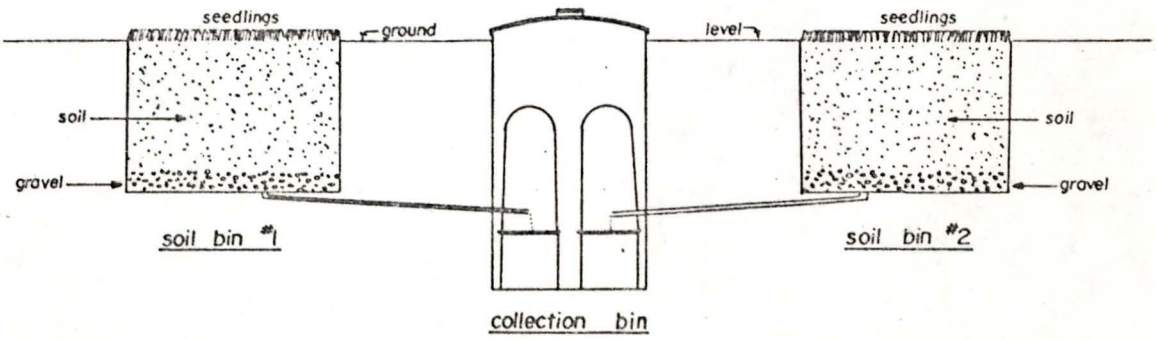


Figure 8

Experimental Plot at the Koksilah Nursery

Figure 9

Lysimeter Bin #1 after Morning Irrigation

Figure 10

Lysimeter Bin #2 after Morning Irrigation

Meteorological instruments were placed around the lysimeter to measure climatic conditions affecting the area. These instruments included a recording anemometer, a hygrothermograph, one eight inch rain gauge and two five inch rain gauges.

The recording anemometer was a model 1071, Mechanical Weather Station manufactured by Meteorology Research Inc. It was located north of lysimeter soil bin one (Figure 6), approximately eighty inches (2.03 m.) above the ground. This instrument recorded wind run and wind direction over the experimental plot. Wind run data were abstracted from the monthly chart and converted to average daily wind speed in miles per hour.

A hygrothermograph, Kahlsico model no. 200944 (produced by Kahl Scientific Instrument Corporation), recorded temperature and relative humidity. This instrument was located in a Stephenson screen directly north of lysimeter soil bin two. The Stephenson screen was located forty-two inches (1.07 m.) above the ground. Temperature and humidity data were recorded on a weekly chart. Data abstracted from these charts included daily maximum and daily minimum temperature, and relative humidity. Daily mean temperature was calculated from the daily maximum and daily minimum temperatures.

The three rain gauges were situated as indicated in Figure 6. The distribution of these gauges ensured a good

indication of rainfall at the experimental site. Rainfall was measured daily. The data from the three rain gauges were averaged to give the daily rainfall at the experimental site.

These meteorological data were compiled and compared to measured potential evapotranspiration readings from the drainage lysimeter. Lysimeter results were recorded every day according to a rigorous schedule. At 8:00 a.m. every morning two and one half gallons (9.47 l.) of water were added to each lysimeter bin. This water was applied with an ordinary garden sprinkling can in order to closely simulate precipitation. Prior to the morning sprinkling, the amount of water collected in the runoff bins was measured. The runoff indicated the amount of water that had percolated through during the previous twenty-four hours. This runoff water was then reapplied to the lysimeter bins as a portion of the two and one-half gallons added every day. In this fashion, nutrient leaching was kept to a minimum. By subtracting the amount of runoff from the amount added each day (plus precipitation), the potential evapotranspiration was determined:

$$PE = \text{Precipitation} + \text{Water Added} - \text{Percolation}. \quad (7)$$

Prior to each days sprinkling the soil bins underwent slight preparation. The soil between the trees was broken and shallow holes were punched in the surface, to aid percolation to lower depths. Weeding was undertaken on

a regular basis, in order to simulate closely actual nursery conditions.

In addition to data collected on site, sunshine records were procurred from the Canada Department of Transport Meteorological Recording Station at Cowichan Bay, 3.5 miles (5.65 km.) to the southeast.

Meteorological sampling was conducted over two summers (approximately May-September) at the Koksilah nursery. Observations were conducted by Forest Service personnel during the week days while weekend observations were conducted by the author.

The following sections of this paper will analyze data collected during the summers of 1970 and 1971 in an effort to determine: i) if any of the existing methods of calculating potential evapotranspiration work well in this situation; ii) which climatic parameters best account for fluctuations in potential evapotranspiration; and iii) if a means of readily assessing irrigation needs from meteorological variables can be developed for use at Koksilah nursery.

II. STATISTICAL ANALYSIS

Data collected during the summers of 1970 and 1971, were subjected to a variety of statistical analyses. These analyses are described in three sections.

Prior to the first analytical section, the basis for the use of running averages will be outlined. Running averages are used in analyzing results in this study in order to smooth out lag effects in the lysimeter (see previous section on Direct Measurement for an explanation of running average).

In the first section, formulae commonly used to predict potential evaporation and/or evapotranspiration were tested with the data which had been collected. These formulae were reviewed in a previous section of this paper and are listed in Appendix I. Calculated potential evapotranspiration is correlated with actual measured potential evapotranspiration in an effort to determine the usefulness of these formulae at the Koksilah nursery.

The second section of the analysis involves the comparison of numerous meteorological variables and measured potential evapotranspiration. This analysis utilizes the correlation technique. The purpose of this section is to determine if any strong linear relationships exist between meteorological variables and potential evapotranspiration, as measured at the study site.

The final analytical section involves the grouping of certain meteorological variables into combinations and the submitting of these combinations to a multiple linear regression analysis. The purpose of this exercise is to determine if a formula could be developed for the Koksilah

nursery that would quickly, simply and accurately determine potential evapotranspiration.

A. Basis for the Use of Running Averages

A drainage lysimeter has the problem of drainage "lag." It is known that approximately ninety percent (90%) of the water excess in a drainage lysimeter percolates through within twenty-four hours (Green, 1959). Green (1959) assumes that after seventy-two (72) hours the amount of water left to percolate is negligible. Percolation rates are not constant, however. On days with high moisture inputs on a relatively dry soil, percolation will not occur as fast as with high moisture inputs on a wet soil. This is due to the need for the moisture to spread its effect down through the soil until the soil is moist (Ward, 1963). Chang (1965) concludes, therefore, that due to lag effects drainage lysimeter results should not be used for periods less than three (3) days.

Green (1959) illustrates one method of overcoming these fluctuations in percolation rates and these lag effects in drainage lysimeter results. This is through the use of running averages (see previous section on Direct Measurement). The running average smoothes out minor fluctuations (i.e. lag effect and percolation rates) in lysimetric results so that general trends may be more easily noticed. In this study, data are analysed on a daily basis (no use

of running averages), three day running averages, five day running averages, and ten day running averages. These time spans are used as they offered a broad range of time intervals.

The following analyses utilize these time intervals in order to assess which one is most useful in overcoming unrepresentative fluctuations in lysimetric data collected at the Koksilah nursery.

B. Relevance of Existing Formulae

Through the use of correlation analysis, six of the most common formulae used for calculating potential evapotranspiration are tested against potential evapotranspiration readings from a drainage lysimeter. Formulae tested are Thornthwaite (1948), Makkink (1957), Turc (1954), Penman (1956), Blaney and Morin (1942), and Blaney and Criddle (1950).

The purpose of this analysis is to establish if any of the above mentioned formulae are applicable to the Koksilah Nursery.

The Thornthwaite (1948) method is tested by grouping climatological data into monthly means. Using this procedure, it is possible to compute three (monthly) results per annum (i.e. June through August, 1970, and May, July and August, 1971). A correlation analysis is not utilized on this data due to the limited number of readings that were available.

TABLE 2

COMPARISON OF MEASURED POTENTIAL EVAPOTRANSPIRATION AND POTENTIAL EVAPOTRANSPIRATION AS CALCULATED BY THE THORNTHWAITE (1948) FORMULA

		Potential Evapotranspiration			
		Measured		Calculated	
Year	Month	Inches	Cms.	Inches	Cms.
1970	May*	--	--	--	--
	June	16.04	40.74	9.02	22.91
	July	15.88	40.34	8.93	22.68
	August	15.80	40.13	6.98	17.73
1971	May	12.60	32.00	7.94	20.17
	June*	--	--	--	--
	July	12.80	32.51	9.84	24.99
	August	12.65	32.13	9.66	24.54

*No Data Due to Equipment Failure

Comparisons of calculated potential evapotranspiration and measured potential evapotranspiration are shown in Table 2. Data in this table illustrate that the Thornthwaite formula underestimated potential evapotranspiration by up to fifty percent (50%).

It may be concluded from the above data (Table 2) that the Thornthwaite method of calculating potential evapotranspiration does not work well at the Koksilah nursery.

There are various reasons for the underestimation of potential evapotranspiration by the Thornthwaite method. It may be due to the fact that the Thornthwaite formula was developed from data collected in the southern United States and in Central America, an area climatically different from the Koksilah nursery. The Koksilah nursery is a coastal location as opposed to the continental location in which the Thornthwaite method was derived. Because of this, temperature, the basis of the Thornthwaite formula, might not be as good an indicator of potential evapotranspiration trends at Koksilah, as it was in the continental location where the Thornthwaite method was developed.

Temperatures reach a higher maximum over a land surface than over a water surface, and they reach it more quickly. Conversely a land surface cools more rapidly and cools to a lower temperature than does a water surface (Trewartha, 1968). Continental climates, therefore, have large daily and seasonal fluctuations in extremes with

trends in maximum and minimum temperatures correlating closely with trends in maximum and minimum solar radiation. Marine climates have smaller extremes with a greater lag between maximum and minimum solar radiation and maximum and minimum temperature (i.e. temperature lags behind solar radiation). Trewartha (1968) states that, in middle and higher latitudes, there are large differences between marine and continental temperatures, due primarily to the fact that the earth does not store up as large an amount of heat as does the ocean.

It is suggested, therefore, that due to these differences in location between the study site and the site of origin of the formula used, the role of temperature in potential evapotranspiration at these respective locations may also vary (i.e. temperature may bear less relation to potential evapotranspiration at Koksilah than it does in the southern United States).

At Koksilah, potential evapotranspiration may be more affected by wind than by temperature. Due to the nearness of the study site to a large body of water, winds might be of significance. During the day, the land will heat up more rapidly and to a higher temperature than the water. This differential in heating may set up a potential for onshore winds. At night the reverse holds true, and offshore breezes may occur. In a continental climate, however, without the differential effects between the ocean and land, the

potential for these breezes would be small.

Numerous studies have utilized the Thornthwaite formula and the results have been varied. McGuinness and Bordne (1972) showed that potential evapotranspiration as calculated by Thornthwaite's method was lower than potential evapotranspiration as recorded by a lysimeter (26.63 inches per year and 40.14 inches per year, respectively). This result was derived in the continental climate of Ohio and is similar to the results of this study in the maritime climate of Koksilah. Makkink (1957) found that the Thornthwaite method produced results very similar to lysimeter recorded potential evapotranspiration. Climatically the Netherlands and Koksilah are comparable, yet test results are markedly different, once again illustrating the unreliability of the Thornthwaite method.

Smith (1964) found that the Thornthwaite method overestimated potential evapotranspiration in the marine climate of northern England.

The Thornthwaite formula has also been shown to be unreliable when based upon short term temperature data (Pelton, King, and Tanner, 1960). Pelton, King and Tanner (1960) reasoned that the Thornthwaite method failed over short periods because short term temperature is not a suitable index of incoming solar radiation. Stern and Fitzpatrick (1965) drew similar conclusions while working in the monsoonal climate of northwestern Australia.

All of these studies show that results based upon the Thornthwaite formula fluctuate randomly. It may be concluded that the Thornthwaite method must be tested for each new study location and that it is not generally applicable.

Correlation analyses were conducted on the relationship between potential evapotranspiration, as calculated by the remaining five formulae, and measured potential evapotranspiration. The analyses were conducted with individual daily values, as well as three, five, and ten day running averages. The results of these analyses are shown in Tables 3 and 4.

In order to interpret the results it is necessary to define the values represented. The correlation coefficient (r) refers to the degree of relationship between two variables (Chou, 1969). The correlation coefficient used in this study is the product-moment correlation coefficient which measures how well the data fit a straight line (Kalton, 1966). A correlation coefficient of zero indicates no direct relationship between variables. A correlation coefficient of +1.0 indicates a direct or perfect positive relationship (line slopes up to the right) while a coefficient of -1.0 indicates an inverse or perfect negative relationship (line slopes down to the right).

TABLE 3

COMPARISON BETWEEN CALCULATED POTENTIAL EVAPOTRANSPIRATION AND MEASURED POTENTIAL EVAPOTRANSPIRATION DURING THE SUMMER OF 1970

Duration of Running Average	Formula	Correlation Coeff (r)	Coeff of Determination (r^2)	t-value
One Day	Makkink	0.0963	0.0093	0.743
	Turc	0.1341	0.0.80	1.039
	Penman	0.1281	0.0164	0.992
N=61	Blaney & Morin	0.1627	0.0265	1.266
	Blaney & Criddle	0.1438	0.0207	1.116
Three Day	Makkink	0.4522	0.2045	2.090*
	Turc	0.3268	0.1068	1.426
	Penman	0.3835	0.1471	1.712
N =19	Blaney & Morin	0.2732	0.0746	1.171
	Blaney & Criddle	0.0999	0.0100	0.414
Five Day	Makkink	0.3594	0.1292	1.155
	Turc	0.2782	0.0773	0.869
	Penman	0.3236	0.1047	1.065
N =11	Blaney & Morin	0.2825	0.0798	0.883
	Blaney & Criddle	0.1110	0.0123	0.335
Ten Day	Makkink	0.1211	0.0146	0.244
	Turc	0.2245	0.0504	0.461
	Penman	0.1909	0.0364	0.389
N =6	Blaney & Morin	0.0205	0.0004	0.041
	Blaney & Criddle	0.2619	0.0686	0.543

*Significant at P = 0.05 level

N = number of cases

TABLE 4

COMPARISON BETWEEN CALCULATED POTENTIAL EVAPOTRANSPIRATION AND MEASURED POTENTIAL EVAPOTRANSPIRATION DURING THE SUMMER OF 1971

Duration of Running Average	Formula	Correlation Coeff (r)	Coeff of Determination (r^2)	t.value
One Day	Makkink	-0.1418	0.0201	-1.128
	Turc	-0.0065	0.0000	-0.051
	Penman	-0.1192	0.0142	-0.945
N =64	Blaney & Morin	0.0875	0.0077	0.692
	Blaney & Criddle	-0.0165	0.0002	-0.130
Three Day	Makkink	0.0025	0.0000	0.010
	Turc	0.0699	0.0049	0.305
	Penman	0.0350	0.0012	0.153
N =21	Blaney & Morin	0.0899	0.0081	0.393
	Blaney & Criddle	-0.0221	0.0004	-0.096
Five Day	Makkink	0.1451	0.0211	0.415
	Turc	-0.0142	0.0002	-0.040
	Penman	0.1680	0.0282	0.482
N =10	Blaney & Morin	-0.0348	0.0012	-0.098
	Blaney & Criddle	-0.1768	0.0313	-0.508
Ten Day	Makkink	-0.0201	0.0004	-0.040
	Turc	-0.1067	0.0114	-0.215
	Penman	0.0347	0.0012	0.069
N =6	Blaney & Morin	-0.1346	0.0181	-0.272
	Blaney & Criddle	-0.2366	0.0560	-0.487

*Significant at P = 0.05 level

N = number of cases

The value r^2 is called the coefficient of determination. This value (r^2) indicates the proportion of variance in the dependent variable accounted for by (explained by) the independent variable. For example, an r^2 of 0.72 means that seventy-two percent (72%) of the variation in the dependent variable is associated with changes in the independent variable. It is frequently desired to know if relationships found in the sample exist in the population as a whole (i.e. whether two variables have a correlation other than zero in a vast population from which the sample was drawn). In order to indicate if the population correlation coefficient differs from zero, the Student's t-distribution is utilized. In order to use this method it is assumed that both variables follow normal distribution patterns. It is possible to test, by use of the sample correlation coefficient, whether the population coefficient differs significantly from zero, the null hypothesis being that the population correlation coefficient is zero.

In order to carry out this test the t-value must be calculated as shown below:

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}} \qquad (8)$$

where: r = correlation coefficient.

r^2 = coefficient of determination.

N = number of cases.

If r equals zero then the t-value is equal to zero. If r is near +1.0 then the t-value is large and positive and if r is near -1.0 then the t-value is large and negative. Thus, the null hypothesis of no correlation should be rejected if the t-value is large, positive or negative. The Student t-distribution depends on the number of degrees of freedom, which for this type of test is (N-2), where N is the number of pairs of observations.

The degrees of freedom determine the shape or the t-distribution (Weinberg and Schumaker, 1969). Another way of putting it is that, for any given number of degrees of freedom there is a particular t-distribution with its own unique set of critical values for significance. Under the assumption that the distribution is normal, the task is to define the critical value which would separate the region of acceptance of the null hypothesis from the region of rejection, at a given level of significance. Tables of these critical values of t are illustrated in a number of statistics texts, including Weinberg and Schumaker (1969) and Remington and Schork (1970).

For example, if the t-value exceeds the critical value (in the Student's t-value table), at the five percent (5%) significance level (i.e. $p = 0.05$) and at the number of degrees of freedom in question (i.e. N-2), it is concluded that there is some real relationship between two sets of variables and the null hypothesis of no relationship may be

rejected (i.e. there is a ninety-five percent [95%] chance that the $\underline{r}$ value of the population as a whole is not zero). The t-test works equally well if the t-value is negative (Moroney, 1951).

The above concepts of $\underline{r}$, $\underline{r}^2$ and the t-distribution were utilized in the analysis of the data over the study period. The results of this analysis are shown in Tables 3 and 4. Results from 1970 (Table 3) indicate that the three and five day running averages are more suited to the study site than the daily data or the ten day running average. In the three and five day analyses, the results of the Makkink and Penman formulae show the highest correlation with measured potential evapotranspiration. For the three day running average, the correlation coefficient for the Makkink formula is significant at the 0.05 level. Generally, results from the analyses of 1970 data are scattered and no trends may be recognized.

Analysis of 1971 data (Table 4) indicates that little or no correlation exists between calculated potential evapotranspiration and measured potential evapotranspiration, for any formula or any time period.

It may be concluded from a composite view of Tables 3 and 4 that none of the tested methods of calculating potential evapotranspiration suitably predict potential

evapotranspiration at the study site. Conditions producing these results may be related to two main factors: climatic conditions and soil/crop types.

First, climatic conditions under which the tested methods were developed were different than those existing at the study site. The Blaney and Morin, and Blaney and Criddle formulae were developed utilizing measurements from Texas and New Mexico. The Blaney methods have been shown, however, to be good indicators of potential evapotranspiration in Florida and also in areas more humid than that in which they were developed. Stephens and Stewart (1963) found that, in Florida, the Blaney and Criddle method correlated well with evaporation pan and lysimeter data ($\underline{r}$ = 0.833 and $\underline{r}$ = 0.912 respectively). McGuinness and Bordne (1972) found that, in Ohio, total yearly estimates of potential evapotranspiration by the Blaney and Criddle method were 38.11 inches compared with lysimeter readings of 40.14 inches.

Due to the poor results using the Blaney formula at the Koksilah nursery, it may be concluded that humidity and temperature are not as important in determining potential evapotranspiration as they are in the warmer, drier climate for which the formulae were developed.

The Turc method of calculating potential evapotranspiration was derived in Rothamste d and Versailles and, like the Makkink method, it utilizes solar radiation and air temperature factors. McGuinness and Bordne (1972) found

that the Turc method underestimated yearly evapotranspiration because, like other methods, it utilizes a temperature factor that does not work below freezing. Over the rest of the year, however, the Turc method satisfactorily estimated potential evapotranspiration. The Turc method has worked well in arid climates. Ahmad (1962) showed that in West Pakistan the Turc method gave good estimates of water balance over bare as well as cropped soil. At Koksilah, however, the results of the Turc method do not correlate well with measured potential evapotranspiration. It may be concluded that solar radiation and air temperature, as used in both the Turc and Makkink methods, are either not good indicators of the amount of energy available for evaporation at Koksilah or that other climatic parameters are more important.

The Penman method was derived with data from Lake Hefner. McGuinness and Bordne (1972) showed that, in Ohio, the Penman method gave a good indication of actual potential evapotranspiration (i.e. Penmann = 37.74 inches and measured = 40.14 inches). Pelton and Korven (1969) found that on the Canadian Prairies the Penman method accounted for only 65% of the variation in daily potential evapotranspiration. They suggested that considerable modifications would be necessary before the Penman method could be utilized extensively in semi-arid regions. However, Stanhill (1961) found that in semi-arid Israel, the Penman method correlated well

with measured potential evapotranspiration on a monthly basis ($\underline{r}$ = 0.96) but not as well on a weekly basis ($\underline{r}$ = 0.76). In Denmark, Aslyng (1965) found that the Penman method overestimated potential evapotranspiration for the early summer and showed good agreement during the rest of the year. Papadakis (1965) criticized the Penman method for its underestimation of potential evapotranspiration in dry climates, overestimation in spring, underestimation in the autumn, and overestimation on windy days.

In general, it may be concluded that the tested formulae may be valid for the climatic conditions under which they were developed but are not necessarily valid when used in areas with different climatic conditions.

A second condition relating to the tested formulae is the difference between soil and crop types under which they were developed and the soil and crop type at the Koksilah nursery. At Koksilah, the crop is not a complete cover. The Blaney methods were developed for use with a number of crops. A crop factor index is included in the equation in recognition that the potential evapotranspiration of an area may vary greatly with the physical condition in the stand. There is, however, no crop index factor that has been developed for tree seedlings in a nursery situation.

The other formulae tested, except the Penman method, were derived for continuous cover of short grass. The Penman method was derived for an open water surface.

These physical conditions vary greatly from the forest nursery situation of the Koksilah nursery. The soil-crop factor is, therefore, a second variable which may lead to the poor correlation between calculated and measured potential evapotranspiration.

It may be concluded, therefore, that the tested formulae do not show good correlations between calculated and measured potential evapotranspiration due to conditions relating to their origin that are different than corresponding conditions at the study site. In the following section, the relationship between individual climatic variables and measured potential evapotranspiration in the Koksilah nursery is studied.

C. Relation of Measured Potential Evapotranspiration to Individual Climatic Variables

This section compares the measured potential evapotranspiration with certain climatic variables in order to determine if relationships exist. Climatic variables used in this analysis include hours of sunshine, windspeed, temperature (daily mean, maximum and minimum) and relative humidity (daily mean, maximum and minimum). As in the previous section, a correlation analysis is used.

Results of the correlation analysis are shown in Tables 5 and 6. Data are tested using individual daily values and three, five and ten day running averages. The results are analyzed in two steps: i) analysis to deter-

mine the best time period, and ii) analysis to determine which, if any, of the climatic variables have consistently high correlations with measured potential evapotranspiration.

Results using 1970 data (Table 5) show no definite trends or improvements as the time span is lengthened from one day values to a ten day running average. Results using 1971 data (Table 6), however, show that the use of a ten day running average gives consistently higher correlations than other time spans. The correlation coefficient of hours of sunshine is significant at the 0.05 level while the correlation coefficients of all other variables are significant at the 0.01 level, for the ten day running average.

The ten day running average, in 1971, only utilized seven sets of data (degrees of freedom = 5). This was due to the difficulty in procuring data over ten day periods without interruption in one or more of the variables. Despite this drawback, it was concluded that the ten day running average showed significant improvement over other time intervals tested and that it should be utilized in the further analysis of data. Based on Table 6, the ten day running average best smooths out minor fluctuations in lysimetric results so that general trends may be noted (i.e. it smooths out lag effects and percolation differences).

In general, the three humidity factors gave the best correlation with measured potential evapotranspiration in

TABLE 5

COMPARISON OF CLIMATIC VARIABLES WITH MEASURED POTENTIAL EVAPOTRANSPIRATION IN 1970

Duration of Running Ave.	Statistical Parameter	Wind Speed	Hours of Sun	Average Temp.	Maximum Temp.	Minimum Temp.	Average Relative Humidity	Maximum Relative Humidity	Minimum Relative Humidity
1 Day	r	0.1939	0.3340	0.1730	0.2903	-0.0029	-0.2337	0.0750	-0.2396
N = 48	r^2	0.0376	0.1115	0.0299	0.0843	0.0000	0.0546	0.0056	0.0574
	t-value	1.340	2.403*	1.191	2.057*	-0.016	-1.630	0.510	-1.674
3 Day	r	0.2223	0.4615	0.1009	0.2072	-0.0498	-0.3088	0.2855	-0.2863
N = 19	r^2	0.0494	0.2130	0.0102	0.0429	0.0025	0.0954	0.0815	0.0820
	t-value	0.940	2.145*	0.418	0.873	-0.206	-1.339	1.228	-1.232
5 Day	r	0.5324	0.3437	0.1483	0.2135	-0.0121	-0.3210	0.2971	-0.3142
N = 11	r^2	0.2834	0.1181	0.0220	0.0456	0.0001	0.1030	0.0883	0.0987
	t-value	1.887*	1.098	0.450	0.656	-0.036	-1.017	0.933	-0.993
10 Day	r	0.5571	0.0632	0.2650	0.1715	0.3260	0.2391	-0.1177	0.2340
N= 6	r^2	0.3104	0.0040	0.0702	0.0244	0.1063	0.0572	0.0139	0.0547
	t-value	1.342	0.127	0.550	0.348	0.690	0.492	-0.237	0.481

*Significance Level p = 0.05

N = Number of Cases

TABLE 6

COMPARISON OF CLIMATIC VARIABLES WITH MEASURED POTENTIAL EVAPOTRANSPIRATION IN 1971

Duration of Running Av	Statistical Parameter	Wind Speed	Hours of Sun	Average Temp.	Maximum Temp.	Minimum Temp.	Average Relative Humidity	Maximum Relative Humidity	Minimum Relative Humidity
1 Day	r	0.1005	0.1406	0.0113	0.0528	-0.0554	-0.0157	0.0725	0.0161
N = 59	r^2	0.0101	0.0198	0.0001	0.0028	0.0031	0.0002	0.0053	0.0003
	t-value	0.763	1.072	0.085	0.399	-0.419	-0.119	0.549	0.122
3 Day	r	0.0591	-0.0056	0.0935	-0.0068	0.2312	0.3401	-0.3654	0.2984
N = 21	r^2	0.0035	0.0000	0.0087	0.0000	0.0535	0.1157	0.1335	0.0890
	t-value	0.0258	-0.024	0.409	-0.030	1.036	1.576	-1.711	1.363
5 Day	r	0.3122	0.1158	-0.0864	-0.0986	-0.0646	0.2385	- .5609	0.4495
N =12	r^2	0.0975	0.0134	0.0075	0.0097	0.0042	0.0569	0.3146	0.2021
	t-value	1.039	0.369	-0.274	-0.313	-0.205	0.777	-2.142*	1.591
10 Day	r	0.9480	0.8133	0.848o	0.9423	0.9551	0.9835	0.9873	0.9637
N = 7	r^2	0.8987	0.6615	0.7193	0.8879	0.9122	0.9673	0.9748	0.9287
	t-value	6.660**	3.126*	3.579**	6.293**	7.207**	12.161**	13.907**	8.070**

*Significance Level p = 0.05
**Significance Level p = 0.01
N = Number of Cases

the 1971 data. At the other end of the scale, hours of sunshine has the lowest correlation of the climatic variables tested. One important result is the high correlation of windspeed with measured potential evapotranspiration.

Of the three relative humidity terms (average, maximum and minimum), maximum relative humidity appears to be more important to potential evapotranspiration at Koksilah than does average or minimum relative humidity. Under conditions of consistent radiation and temperature, the ability of air to absorb vapour will increase with a decrease in humidity (Chang, 1968). It would be expected, therefore, that minimum relative humidity would be negatively related to potential evapotranspiration. During 1971, both maximum and minimum relative humidity have a strong positive relationship with measured potential evapotranspiration. In 1970, however, there were no significant relationships between relative humidity and evapotranspiration.

The strong relationship of maximum relative humidity and measured potential evapotranspiration in 1971 should be noted as an unexplained factor that must be considered in any formulation of a model for predicting evapotranspiration at the Koksilah nursery.

Temperature variables are not as highly correlated with measured potential evapotranspiration, at Koksilah, as the relative humidity variables. The average temperature

shows the poorest correlation with measured potential evapotranspiration of the three tested temperature variables. This correlation is an illustration that average daily temperature is a poor indicator of energy available for evapotranspiration.

As pointed out by Mather (1974), maximum and minimum temperatures might be better indicators of evapotranspiration trends than average temperature. Maximum temperature generally occurs during the daytime, a time of minimum evapotranspiration. This would indicate that the maximum temperature should bear a closer relationship to evapotranspiration than should minimum temperature. At Koksilah, however, this is not true. In both 1970 and 1971, results indicate that minimum temperature plays a more important role in determining potential evapotranspiration than does maximum or average temperature. This suggests that substantial evapotranspiration takes place at night, as well as during the daytime, at the Koksilah site. This might be related to the ability of the soil to hold heat energy for use in the evaporation process at nighttime. This ability to hold heat energy is closely related to soil texture, moisture content and tilth. The heat capacity of soil is increased when water is added to it, which means the temperature rise produced by a given quantity of heat is reduced. Tillage of the soil increases the temperature extremes at the surface (i.e. hotter during the day and

cooler during the night). These are just a few examples of how conditions at the study site might affect heat storage in the soil and subsequently minimum temperatures. Further investigations into the relationships of minimum temperature, potential evapotranspiration, physical properties of the soil, and other climatic variables are required before a more detailed explanation of these relationships at the study site may be made.

In both 1970 and 1971, analysis of the data shows that hours of sunshine (as an indicator of solar radiation) had the lowest correlation with measured potential evapotranspiration of all climatic variables tested. Solar radiation is the source of all energy needed in the evapotranspiration process, but is not well represented by measuring hours of sunshine. This is supported by the results of this analysis.

The relatively high correlation of windspeed with measured potential evapotranspiration indicates the importance of wind in evapotranspiration trends at the study site. During 1970, windspeed had the highest correlation with measured potential evapotranspiration of all variables tested. The importance of wind in evapotranspiration has been recognized by numerous researchers including Fritschen (1966), Rosenberg and Hart (1967), and Decker (1962). The results of this study indicate that windspeed is an important climatic variable in the determination of potential evapotranspiration at the Koksilah nursery.

From this analysis, it is difficult to ascertain any one climatic variable that predominates. The 1971 data analysis shows strong positive correlations for all variables tested. However, 1970 data results are weaker and more varied and in some instances they do not agree with trends shown in the 1971 results. It is thought that by combining several climatic variables a more reliable method of predicting potential evapotranspiration at the Koksilah nursery might be obtained. This process might reduce yearly fluctuations and discrepancies even though correlation levels between measured and calculated potential evapotranspiration might not reach the levels of 1971.

The following section uses certain of the tested climatic variables in differing combinations in an effort to determine a reliable, accurate, and simple means of calculating potential evapotranspiration at the Koksilah nursery.

D. Derivation of Evapotranspiration Formula for the Koksilah Nursery.

This section looks at various combinations with the specific purpose of identifying one or more combinations of climatic variables which might be used to predict potential evapotranspiration at the Koksilah nursery. Climatic variables used in this analysis are windspeed (WNDSPD), hours of sunshine (HRSSUN), daily mean temperature (TAVGC), maximum temperature (TMAXF), minimum temperature (TMINF), daily mean relative humidity

(RHAVG), maximum relative humidity (RHMAX), and minimum relative humidity (RHMIN). The type of analysis used in this section is multiple linear regression.

The results of this multiple linear regression analysis are listed in Table 7. Combinations listed in this table represent the best twelve of a large selection that were tested. All data used in this study were based on ten day running averages.

In explaining the results, it is useful to define the values represented. $\underline{R}$ is the coefficient of multiple correlation. This refers to the degree of relationship between the dependent variable, measured potential evapotranspiration ($\underline{Y}$), and the independent variables, the various climatic parameters. $\underline{R}^2$ is the coefficient of multiple determination or the proportion of the total variation in observed potential evapotranspiration ($\underline{Y}$) which is accounted for by the regression equation. This value varies between zero (0) and one (1).

The closer $\underline{R}^2$ gets to one (1) the better the regression line fits the data.

The t-value, as used in the Student's t-distribution, was outlined in a previous section.

The correlation coefficients of all twelve formulae listed in Table 7 are significant at the 0.01 level. $\underline{R}^2$ values range from 0.1750 to 0.3894 (i.e. 17% to 39% of the variation in $\underline{Y}$ is accounted for by the regression equation).

TABLE 7

COMPARISON OF VARIOUS CLIMATIC ELEMENT COMBINATIONS

No.	Regression Equation	R	R^2	t-value
3-1	Y = 11.0801 - 0.0631 RHMIN + 0.0224 TMAXF + 0.6512 WNDSPD ± 0.3499	0.6240	0.3894	5.051**
3-2	Y = 7.8908 + 0.5805 WNDSPD + 0.0970 TMAXF + 0.0890 TMINF ± 0.3506	0.6221	0.3870	5.025**
3-3	Y = 13.0507 + 0.333 TAVGC - 4.0825 RHAVG + 0.4189 WNDSPD ± 0.3684	0.5683	0.3230	4.368**
3-4	Y = 9.2983 + 0.2929 WNDSPD + 0.0322 TMAXF ± 0.3770	0.5226	0.2731	3.877**
3-5	Y = 9.1827 + 0.0389 RHMIN + 0.0084 TMAXF + 0.1511 HRSSUN ± 0.3840	0.5142	0.2644	3.792**
3-6	Y = 9.4424 + 0.1809 HRSSUN + 0.0414 RHMIN ± 0.3816	0.5052	0.2552	3.702**
3-7	Y = 11.1168 + 0.0712 HRSSUN + 0.0113 TMAXF ± 0.3915	0.4648	0.2160	3.320**
3-8	Y = 11.4450 - 0.6711 RHAVG + 0.0213 TMAXF ± 0.4008	0.4219	0.1780	2.943**
3-9	Y = 12.5043 + 0.0960 TAVGC + 0.0021 TMAXF - 0.0327 TMINF ± 0.4062	0.4208	0.1771	2.939**
3-10	Y = 12.6397 + 0.0413 TAVGC - 1.1877 RHAVG ± 0.4062	0.4208	0.1771	2.934**
3-11	Y = 10.8386 + 0.0293 TMAXF - 0.0075 TMINF ± 0.4012	0.4200	0.1764	2.927**
3-12	Y = 10.7785 + 0.0009 RHMIN + 0.0247 TMAXF ± 0.4016	0.4183	0.1750	2.913**

R = coefficient of multiple correlation
R^2 = coefficient of multiple determination
* = significance level p = 0.05
** = significance level p = 0.01
Sample Size (N) = 42
Y = potential evapotranspiration

Coefficients of correlation range from 0.4183 to 0.6240. These correlation coefficients indicate that a relationship does exist between measured potential evapotranspiration and the climatic variables. These correlation coefficients far exceed those between measured potential evapotranspiration and potential evapotranspiration as calculated from existing formulae (See Tables 3 and 4). This difference in results may be due to numerous factors. As previously mentioned, formulae developed under certain climatic conditions do not necessarily work well in areas with different climatic conditions. It is logical, therefore, that a formula derived from data collected at the study site would produce a better prediction of potential evapotranspiration trends at that site, than one derived under different climatic conditions. Secondly, the conditions of soil and crop cover for which the tested formulae were developed do not correspond to the particular type of conditions found at the Koksilah nursery.

These are only two reasons why the results of the multiple regression analysis are more highly correlated with measured potential evapotranspiration than the results utilizing existing formulae. The following analysis studies the twelve (12) derived formulae in order to determine a practical and accurate one for use in determining potential evapotranspiration trends at the Koksilah nursery.

Formulae 3-1, 3-5 and 3-12 all utilize minimum relative humidity and maximum temperature as a base. This

represents the typical daytime situation when moist evaporation should occur. Equation 3-5 also utilizes hours of sunshine while equation 3-1 utilizes windspeed. The addition of hours of sunshine to maximum temperature and minimum relative humidity increases the correlation coefficient from 0.4183 to 0.5142 and increases the R^2 value from 0.1750 to 0.2644 (comparison of equations 3-12 and 3-5). This increase in $\underline{R}^2$ value indicates that the amount of explained variation in observed potential evapotranspiration is increased by nine percent (9%).

This increase in the R^2 value, accounted for by hours of sunshine, is small when compared with the increase in the R^2 value accounted for by windspeed. The latter increase is represented by a comparison of equations 3-12 and 3-1. In this case, the R^2 value more than doubled from 0.1750 to 0.3894. This represents an increase in the explained variation in observed potential evapotranspiration of twenty-one percent (21%). By comparing equations 3-5 and 3-1 it may be noted that when windspeed is substituted for hours of sunshine, the R^2 value increase from 0.2644 to 0.3894 (an increase in explained variation in potential evapotranspiration of twelve and one-half percent [12½%]). This would indicate that during the daytime, windspeed is more important in determining variations in potential evapotranspiration than is hours of sunshine. These findings are a reflection of results indicated in the previous section, where it was

noted that hours of sunshine had the lowest correlation with measured potential evapotranspiration and that windspeed had a relatively high correlation with measured potential evapotranspiration.

The relative contribution of radiation and windspeed to evapotranspiration was studied in Kansas by Skidmore, Jacobs and Powers (1969). They noted that on consecutive non-windy days and windy days (windspeed 0.88 m/sec and 2.26 m/sec respectively) windspeed contributed one hundred thirteen percent (113%) more to evapotranspiration than did radiation. The function of the wind in the evapotranspiration process is one of maintaining vapour pressure gradients and temperature gradients above the evaporating surface as well as directly moving vapour away from the evaporating surface (i.e. turbulent transfer). This is accomplished by bringing fresh parcels of air into contact with the evaporating surface. At Koksilah, it appears that this process is more closely associated with variations in potential evapotranspiration than is solar radiation. A review of data shows that windspeed varies with changes in potential evapotranspiration while hours of sunshine varies randomly and by a greater amount. The fluctuations in hours of sunshine are large when compared to fluctuations in potential evapotranspiration and windspeed. These comparative variations are subjects which require more detailed study.

The observed potential importance of windspeed in determining potential evapotranspiration variations at the study site is further evidenced by studying equations 3-11 and 3-2, as well as equations 3-10 and 3-3.

Equation 3-11 uses maximum and minimum temperature to calculate potential evapotranspiration. When a windspeed factor is added to equation 3-11, $\underline{R}^2$ increases from 0.1764 to 0.3870. This represents an increase in the explained variation in observed potential evapotranspiration of twenty-one percent (21%).

A similar increase in $\underline{R}^2$ value is noted when windspeed is added to equation 3-10. This equation utilizes average temperature and average relative humidity to calculate potential evapotranspiration. In this case, the $\underline{R}^2$ value increases from 0.1771 (equation 3-10) to 0.3230 (equation 3-3), representing an increase in explained variation of fourteen and one-half percent (14½%). Both of these comparisons further indicate the importance of windspeed in determining potential evapotranspiration at the study site.

In review, all of the existing formulae tested, with the exception of the Penman (1956) method, failed to include any factor relating to the influence of windspeed. Although the Penman method included a wind component, it did not adequately predict potential evapotranspiration trends at the Koksilah nursery. It may be concluded that the Penman

method utilized internal constants that were not valid at the study site.

It has been shown that windspeed has a greater influence on potential evapotranspiration than do hours of sunshine (i.e. solar radiation), at the study site. It was concluded that the presence of windspeed along with good statistical results, should be paramount in the final selection of a formula for prediction of potential evapotranspiration at the Koksilah nursery.

As well as the importance of windspeed, an analysis of the twelve formulae listed in Table 7 indicates other interesting factors relating to the importance of certain climatic variables at the study site.

The importance of minimum relative humidity is illustrated when equations 3-7 and 3-5, and equations 3-4 and 3-1 are compared.

Equation 3-7 utilizes hours of sunshine and maximum temperature to calculate potential evapotranspiration. The addition of a minimum relative humidity term to this equation (see equation 3-5) raises the $\underline{R}^2$ value from 0.2160 to 0.2644. This represents an increase in explained variation of approximately five percent (5%).

A large impact is noted when minimum relative humidity is added to equation 3-4 (see equation 3-1). In this case, $\underline{R}^2$ values rise from 0.2731 (equation 3-4) to 0.3894 (equation 3-1), an increase in explained variation of eleven and one-half percent (11½%).

Both of these comparative results indicate that minimum relative humidity does play an important role in determining potential evapotranspiration trends at the Koksilah nursery. In the previous section, it was noted that maximum relative humidity had the highest correlation with potential evapotranspiration of all variables tested (1971 data). The results of the multiple regression analysis, however, show that minimum relative humidity plays a more important role in potential evapotranspiration than does maximum relative humidity, when in combination with other climatic elements.

Temperature variables and their influence on potential evapotranspiration at the Koksilah nursery are varied. By comparing equations 3-11 and 3-9 the influence of average temperature may be noted. The addition of average temperature to an equation already using maximum and minimum temperature (equation 3-11) raises the R^2 value from 0.1764 (equation 3-11) to 0.1771 (equation 3-9), an increase in explained variation of less than one-half percent ($<\frac{1}{2}\%$). This is expected since average temperature is a product of minimum and maximum temperature.

By comparing equations 3-5 and 3-6, the effect of maximum temperature on potential evapotranspiration trends at the study site may be illustrated (when combined with RHMIN and HRSSUN). The $\underline{R}^2$ value increases from 0.2552 (equation 3-6) to 0.2644 (equation 3-5), an increase in

explained variation of one percent (1%). Although the observed effect of maximum temperature may appear small, when combined with windspeed it may help represent the amount of energy available for evapotranspiration better than when combined with hours of sunshine. This effect may be observed by reviewing equations 3-5 and 3-1.

As noted in the discussion of individual elements, minimum temperature was a better indicator of potential evapotranspiration trends than were either average or maximum temperature. It was concluded, at that time, that a substantial amount of evapotranspiration takes place during the nighttime, a time of minimum temperatures.

The observed importance of minimum temperature at the study site is emphasized by observing equations 3-4 and 3-2. Both of these equations utilize windspeed and maximum temperature to calculate potential evapotranspiration. The addition of the minimum temperature term to equation 3-4 increases the amount of explained variation by over eleven percent (11%). This is represented by an increase in $\underline{R}^2$ value from 0.2731 (equation 3-4) to 0.3870 (equation 3-2). This further substantiates the belief that nighttime evapotranspiration is a significant portion of the overall potential evapotranspiration at the Koksilah nursery.

The effects of various climatic variables on the ability of formulae to predict potential evapotranspiration

trends, may be summarized as follows. Windspeed plays a major role in adding to the predictive ability of various formulae. Its overall significance may be noted in that it is the only climatic variable present in the four most accurate formulae (equations 3-4 through 3-1). Comparative results also indicate that minimum relative humidity plays an important role in evapotranspiration trends at the study site. This is to be expected, due to the relation of potential evapotranspiration and relative humidity. Of the temperature variables tested, minimum temperature influences evapotranspiration trends to a large extent. Results indicate that the evaporation process during the nighttime is more substantial than would be expected. Finally, hours of sunshine at the study site did not greatly affect potential evapotranspiration trends.

In the above discussion, certain formulae have been shown to be improved through the addition of one variable or through the substitution of one variable for another. This is primarily true with respect to windspeed. Based on statistical results equations 3-1 and 3-2 were selected as most accurately predicting potential evapotranspiration trends at the Koksilah nursery. Both of these equations had correlation coefficient of 0.62 and R^2 value of 0.39. The next most accurate equation (equation 3-3) explained only thirty-two percent (32%) of the variation in the dependent variable. It was concluded that either equation 3-1 or

equation 3-2 would be suitably accurate for use at the study site.

In an effort to compare these two formulae, a brief review of basic aims is needed. A satisfactory method for determining water needs at the Koksilah nursery must be: i) quick and accurate, ii) practical for use in the nursery situation, and iii) simple enough for use by any nurseryman.

Both equations utilize windspeed and maximum temperature. Equation 3-1 also includes a minimum relative humidity term while equation 3-2 includes a minimum temperature term. As maximum temperature is required for both solutions the additional factor of minimum temperature is easily obtained with little or no added capital or maintenance costs. However, to obtain minimum relative humidity, a hygrograph must be purchased, installed and maintained. Also, as previously noted, minimum relative humidity and maximum temperature generally both occur during the middle of the day thereby reflecting each other's trends although their representative effects on evaporation may be different. It was decided that equation 3-2 would be the best formula for calculating potential evapotranspiration trends at the Koksilah nursery. Equation 3-2 is as follows:

$$Y = 7.8908 + 0.5805\ (WNDSPD) + 0.0970\ (TMAXF) + 0.0890\ (TMINF) \pm 0.3506 \qquad (9)$$

when $\underline{Y}$ = potential evapotranspiration (in mm.)

WNDSPD = windspeed in miles per hour.

TMAXF = maximum temperature in ^{o}F.

TMINF = minimum temperature in ^{o}F.

This method yields potential evapotranspiration for the lysimeter under experimental conditions. In the next section, steps will be taken to correct the results for the lack of an irrigated guard area. The result of this corrective action will give a value of potential evapotranspiration that is applicable to the nursery as a whole.

III. ADVECTIVE EFFECTS

Any area with one set of soil moisture conditions will be affected by horizontal energy and moisture transfer (advection), when surrounded by an area with different soil moisture conditions. The lack of a protective irrigated guard area at the study site tended to accentuate this sensitivity to advection and thereby greatly increased the recorded evapotranspiration. This experimental bias appears in two forms: the "oasis" effect and the "clothesline" effect (Chang, 1968).

The clothesline effect is the increase in evapotranspiration from a small area, resulting from the hori ontal transfer of heat in the air flowing over the surface. The oasis effect is the vertical transfer of this advected energy to the field surface.

At the test site, the advective effect was quite marked because of the dry surroundings and the small size of

the lysimeter. Evapotranspiration recorded with the lysimeter approximated that which would occur on the windward side of the nursery. In order to calculate potential evapotranspiration more applicable to the centre of the irrigated nursery, the advective effect must be reduced to a minimum.

Green (1959) and Chang (1965) both pointed out a method of alleviating the clothesline effect. Green stated that:

> . . . the total evaporation from a circular wet surface in completely dry surroundings, increases not according to thesquare of the radius, but according to the 1.88th power of the radius. This conclusion, although reflection shows that it can be applied within certain limits of areal dimension, appears in practice to be applicable within limits of 11 inches (diameter of the drum) and a 200 yard radius; . . .

Ward (1963) suggested dividing measured potential evapotranspiration by 2.177. He used this correction factor for a twenty-two inch (22 inch)(55.9 cm) diameter tank and found that results obtained were more reasonable than those otherwise obtained. The calculation factor used by Ward was used at Koksilah because of the similarity between the experimental site of Ward and the Koksilah nursery. The drainage lysimeter used at the study site was based on the same design as the one used by Ward and was about the same size.

By using Ward's correction in this study, estimated potential evapotranspiration was substantially reduced.

In the analysis of the data to this point, all measured evapotranspiration rates have been the potential

rate (i.e. surface never short of water). In reality this condition seldom occurs. Usually, as evapotranspiration takes place over a surface, the soil will dry out. The next section will look at some of the ramifications of soil drying and how actual evapotranspiration varies from potential evapotranspiration.

IV. A MODULATED SOIL MOISTURE BUDGET

In the experimental case, evapotranspiration takes place at the potential rate. This is because soil moisture is kept at the saturation level. In reality, however, the actual rate is less than the potential rate because the condition of a saturated soil is seldom met. Holmes and Robertson (1959) point out that as soil dries, available moisture decreases and the hydraulic tension increases. In such a situation, actual evapotranspiration falls far short of potential evapotranspiration. To account for this decrease, Holmes and Robertson (1959) developed a modulated soil moisture budget.

Assumptions used in the soil moisture budget are as follows: i) the 0.6 inches (15.24 mm.) of soil moisture in the top soil layer (zone of depletion) evaporates at the potential rate (100%), ii) the potential evapotranspiration is modulated so moisture in the ensuing depths is evaporated at a decreasing rate depending on the percentage of moisture remaining in the soil, iii) soil moisture in the topmost layer is exhausted before moisture in the lower layers is

tapped, and iv) percolation is complete. This method of modulating soil moisture budgets (Holmes and Robertson, 1959) should give a reasonable approximation of actual evapotranspiration.

A conversion graph was developed based on a series of graphs by Holmes and Robertson (1959) and using a soil moisture capacity of two and one-half (2.5) inches (63.5 mm.) for nine (9) inches (228.6 mm.) of soil depth (van den Driessche, 1969). It was assumed that this graph (Figure 11) adequately represented the decrease in evapotranspiration with decreasing soil moisture at the Koksilah nursery. The use of this graph is explained in the following section.

V. APPLICATION OF THE KOKSILAH MODEL

It is of prime concern that the nurserymen at the Koksilah nursery be able to calculate water needs easily. For this purpose, this section will lay out procedures for calculating irrigation needs and illustrate these procedures with examples for the purpose of clarification.

A. Nomograph

To eliminate the need for long calculations in the use of the derived formula (3-2), a nomograph has been developed. Through the use of this graph (Figure 12) the nurseryman can quickly and easily calculate potential evapotranspiration. The left side of the nomograph relates maximum temperature and windspeed to potential evapotranspiration. This potential evapotranspiration is noted on

Figure 11

Adjustment of P.E. for soil dryness

(after: Holmes & Robertson, 1959)

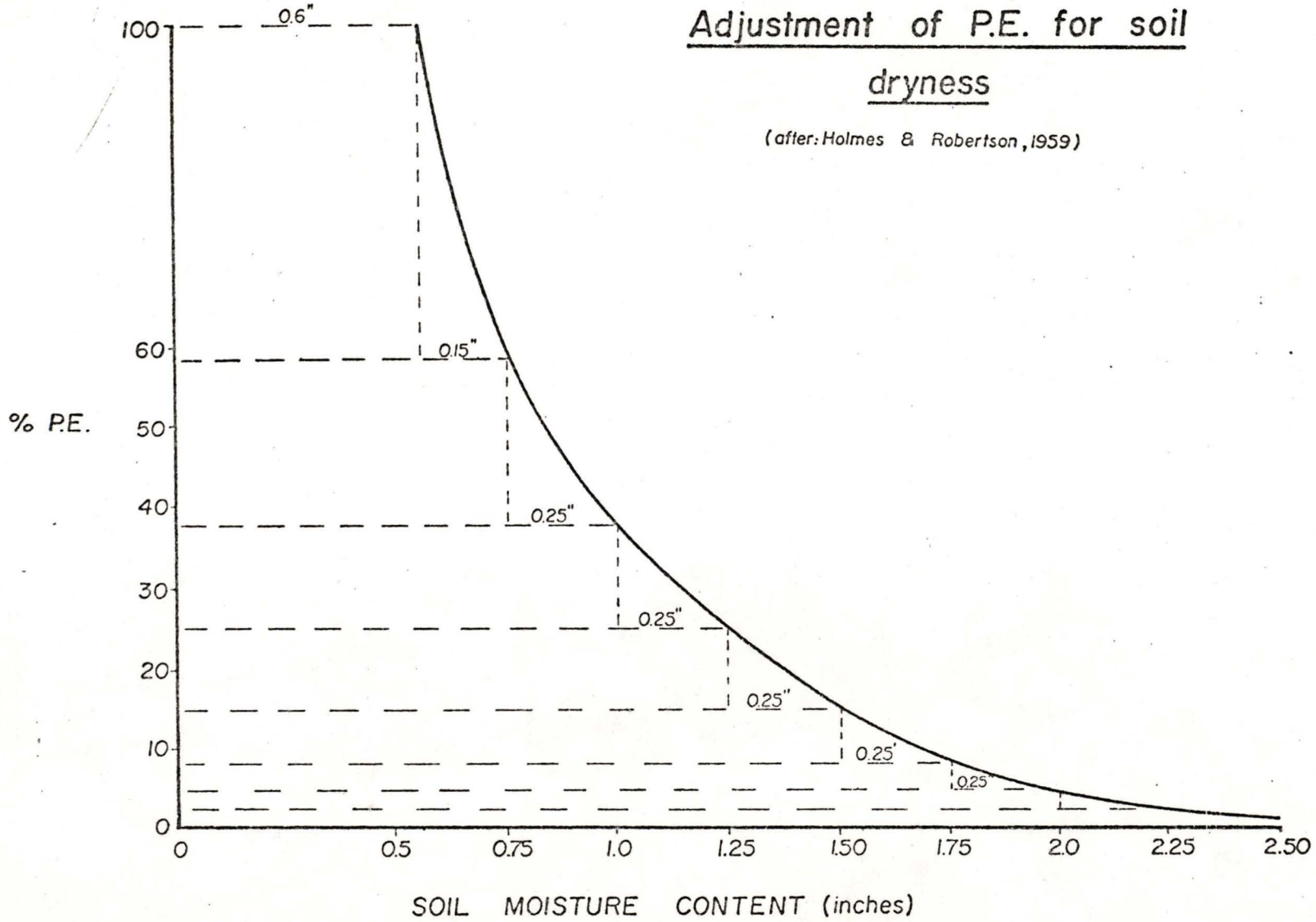
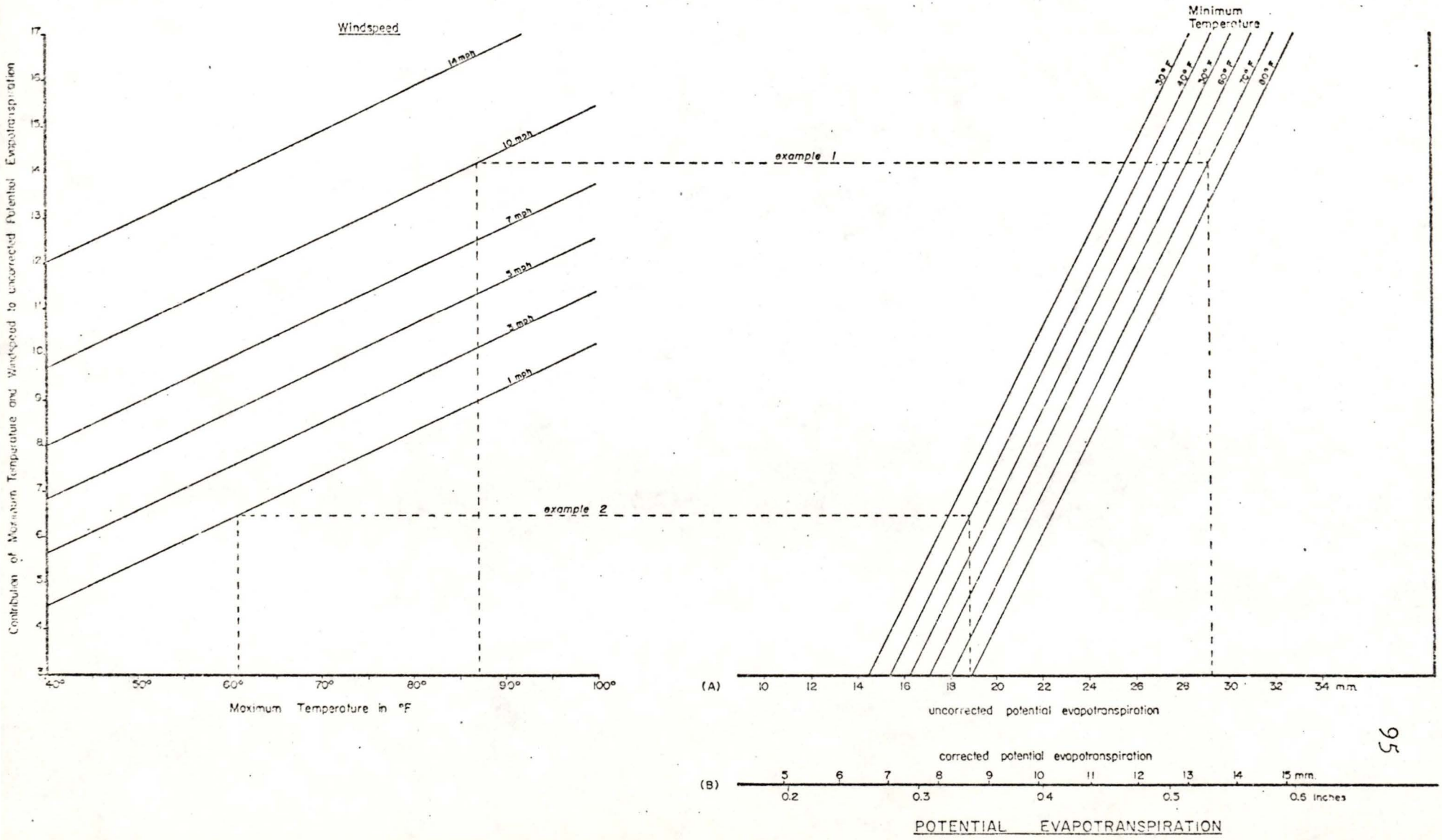


Figure 12

Nomograph for the Calculation of Potential Evapotranspiration at the Koksilah Nursery.



the extreme left of the nomograph. The right hand side of the nomograph includes the effect of minimum temperature. The resultant potential evapotranspiration is indicated in line (A) in the lower right hand quadrant of the nomograph (in mm. of moisture). The value represents potential evapotranspiration as calculated by equation 3-2. Using the Ward method (as previously described) for adjusting for the advective effect, the corrected potential evapotranspiration is indicated in line (B). Line (B) represents potential evapotranspiration in inches and millimeters.

The nomograph thereby gives an easy method of determining potential evapotranspiration from readings of maximum and minimum temperature, and average windspeed.

B. Calculation of Actual Evapotranspiration

Once the nurseryman has determined the corrected potential evapotranspiration, the actual evapotranspiration may be calculated. Table 8 relates the calculated potential evapotranspiration to the actual evapotranspiration. This table was developed by subjecting the potential evapotranspiration to the modulated soil moisture budget approach of Holmes and Robertson (Figure 11).

In Table 8, the process of soil moisture modulation has been taken into account. The actual evapotranspiration that is shown is the amount of moisture that has to be reapplied to the nursery to bring the soil moisture level back to the optimum. The nurseryman, at this point, must take into

TABLE 8

RELATION OF POTENTIAL EVAPOTRANSPIRATION TO MODULATED ACTUAL EVAPOTRANSPIRATION

PE(ins.)	AE(ins.)	AE(mm)
less than 0.6	0.6	15.24
0.7	0.66	16.76
0.8	0.72	18.29
0.9	0.77	19.56
1.0	0.80	20.32
1.1	0.84	21.34
1.2	0.88	22.35
1.3	0.92	23.37
1.4	0.95	24.13
1.5	0.99	25.15
1.6	1.01	25.65
1.7	1.03	26.16
1.8	1.06	26.92
1.9	1.08	27.43
2.0	1.11	28.19
2.1	1.13	28.70
2.2	1.16	29.46
2.3	1.18	29.97
2.4	1.21	30.73
2.5	1.23	31.24
2.6	1.26	32.00
2.7	1.28	32.51
2.8	1.29	32.77
2.9	1.31	33.27
3.0	1.32	33.53
3.1	1.34	34.04
3.2	1.35	34.29
3.3	1.37	34.80
3.4	1.38	35.05
3.5	1.40	35.56
3.6	1.41	35.81
3.7	1.43	36.32
3.8	1.44	36.58
3.9	1.46	37.08
4.0	1.47	37.34
4.1	1.49	37.85
4.2	1.50	38.10
4.3	1.51	38.35
4.4	1.52	38.61
4.5	1.52	38.61
4.6	1.53	38.86
4.7	1.54	39.12
4.8	1.55	39.37
4.9	1.56	39.62
5.0	1.56	39.62

consideration the percentage efficiency of the irrigation sprinklers and adjust time of irrigation to suit (i.e. sprinkler rate at the head minus evaporation before the water reaches the surface minus dispersion due to wind). The actual efficiency of the irrigation method may be measured through the use of a rain gauge.

The relation between potential and actual evapotranspiration is best explained through the use of an example (Table 9). In this example, the first 0.6 inches (15.24 mm.) of moisture is evaporated at the potential rate (100%). The next 0.15 inches (3.81 mm.) is evaporated at a rate approximately fifty-eight percent (58%) that of the potential rate (see Figure 11). In order to evaporate this 0.15 inches of moisture it takes a potential evapotranspiration of 0.26 inches (6.60 mm.). The next 0.25 inches (6.35 mm.) of moisture is evaporated at thirty-seven percent rate (37%), utilizing a potential evapotranspiration of 0.68 inches (17.27 mm.). This process continues until water is reapplied or until the assumed soil moisture capacity of 2.5 inches (63.5 mm.) has been exhausted. If water is reapplied in the form of precipitation or irrigation to the point of bringing it back to the optimum moisture level, the process repeats itself. In the example given in Table 9, 2.43 inches (61.72 mm.) of moisture has to be potentially evaporated in order to actually evaporate 1.27 inches (32.66 mm.) of moisture.

TABLE 9

DAILY P.E. AND SOIL MOISTURE

			SOIL MOISTURE STORAGE - % OF PE							
			100		58		37		25	
			SOIL ZONE CAPACITY							
			0.6"		0.15"		0.25"		0.25"	
DATE	PE	RAIN	AE	SM	AE	SM	AE	SM	AE	SM
Day 1				0.6		0.15		0.25		0.25
Day 2	.30		0.30	0.30						
Day 3	.28		0.28	0.02						
Day 4	.19	0.06"	0.08	0.00	0.06	0.09				
Day 5	.40				0.09	0.00	0.09	0.16		
Day 6	.42						0.16	0.00		
Day 7	.43								0.11	0.14
Day 8	.39								0.10	0.04
Total	2.43	0.06"	0.66	0.00	0.15	0.00	0.25	0.00	0.21	0.07
Total AE	1.27"									

After: Holmes & Robertson, 1959

C. Irrigation Procedure and Calculation

This section will outline the basic procedures that the nurserymen should follow in order to calculate irrigation needs.

Initially the nurseryman must record daily maximum and minimum temperature and windspeed (at approximately 2 metres above ground). After a given number of days, average maximum and minimum temperature, and average windspeed may be calculated for that period.

Using these average figures, the nurseryman would consult the nomograph (Figure 12) in order to determine the average daily potential evapotranspiration for the period. A more detailed format for this procedure is illustrated in the two examples that will be given. Total potential evapotranspiration over this period would be gained by multiplying the average potential evapotranspiration by the number of days in the observation period. Any rain that falls during that time span would be subtracted from the total potential evapotranspiration.

The most applicable method of determining the net potential evapotranspiration at Koksilah is through the daily logging of potential evapotranspiration as illustrated in Table 9. This process entails the execution of the procedure noted above on a daily basis rather than on a total average basis. This procedure would continue until it is determined that the cumulative total net potential evapotranspiration is at a point where irrigation is required.

Once the nurseryman has calculated the net potential evapotranspiration, by either of the above two methods, he refers to Table 8. This table relates potential evapotranspiration to actual evapotranspiration. Using net potential evapotranspiration calculated above, the nurseryman looks down Table 8 and determines the actual evapotranspiration. The actual amount indicated is the amount of water that has actually evaporated and must be reapplied in order to bring soil moisture back to field capacity. Dependent on sprinkler capacity, the nurseryman can calculate how long he must irrigate.

In order to clarify this procedure, two examples will be given. Using the nomograph provided (Figure 12) the maximum temperature is found and a line is drawn vertically to the windspeed indicated (10 mph). From this intersection, go horizontally to the 70°F (21.1°C) minimum temperature line. From this intersection, go vertically down to find the uncorrected potential evapotranspiration (line A) and the potential evapotranspiration as corrected for advective effects (line B). In this example, the value is 0.53 inches (13.5 mm.). Utilizing Table 8, a potential evapotranspiration of 0.53 inches (13.5 mm.) gives an actual evapotranspiration of 0.53 inches (13.5 mm.).

EXAMPLE 1

TABLE 10

Maximum Temperature	87°F (30.6°C)
Minimum Temperature	70°F (21.1°C)
Windspeed	10 mph (16 km/hr)
Precipitation	Nil
PE	0.53 inches (13.5 mm.)

The second example given is different from the first in that there is some rainfall (Table 11). Proceeding through the same routine as example 1, the nomograph shows that 0.34 inches (8.6 mm.) of moisture is potentially evaporated. Subtracting the rainfall from this value yields a net potential evapotranspiration, minus rainfall, of 0.19 inches (4.8 mm.). Using the conversion table (Table 8), the nurseryman has to reapply 0.19 inches (4.8 mm.) of water.

EXAMPLE 2

TABLE 11

Maximum Temperature	61°F (16.1°C)
Minimum Temperature	40°F (4.4°C)
Windspeed	1 mph (1.6 km/hr)
Precipitation	0.15 inches (3.81 mm.)
PE	0.34 inches (8.6 mm.)
Net PE	0.19 inches (4.8 mm.)

These two examples illustrate the simplicity of the method. Once the actual evapotranspiration is noted for a given time period, the calibration of how long to irrigate is all that the nurseryman has to do. It must be assumed that

evapotranspiration showed that: i) hours of sunshine had the lowest correlation with measured potential evapotranspiration of all variables tested, ii) relative humidity correlated most strongly with measured potential evapotranspiration, particularly maximum relative humidity, iii) maximum and minimum temperatures play a strong role in evapotranspiration trends, and iv) windspeed shows a strong correlation with measured potential evapotranspiration. It was concluded that no one individual climatic variable could be used to calculate potential evapotransporation at the study site and that a combination of variables might improve the reliability of evapotranspiration prediction at the study site. The unreliability of individual climatic variables stemmed from the lack of consistency in correlation between data from 1970 and 1971.

An analysis of various combinations of climatic variables and their ability to predict potential evapotranspiration, illustrated some important local relationships between these variables and potential evapotranspiration, of which some did not appear in the analysis of individual climatic variables. When considered in combination with other climatic variables, windspeed was a significant factor. When windspeed was added, the amount of explained variation in the dependent variable rose between nine percent (9%) and twenty-one percent (21%). Of the combinations tested, windspeed was the only variable that appeared in each of the four best formulae. It was

the amount of moisture actually evaporated gets back into the soil regime. A slight overirrigation will not substantially affect the plants or the soil but an underirrigation will. Underirrigation could lead to a cumulative soil moisture deficit. Always be sure not to underirrigate.

As a means of checking the progress of this new method of scheduling irrigation, periodic soil moisture tests should be conducted. This may either be done through resistance blocks or core sampling.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

The use of existing formulae for the calculation of water needs and potential evapotranspiration does not offer a good solution to irrigation problems at the Koksilah nursery. It was concluded that poor correlations between measured potential evapotranspiration and potential evapotranspiration as calculated by the tested formulae were due to two major factors: i) formulae tested may be valid for climatic conditions under which they were developed but are not valid for climatic conditions at the study site, and ii) formulae tested were developed under different soil and crop conditions than those experienced at the Koksilah nursery.

Based on the correlation analysis of individual climatic variables with measured potential evapotranspiration, it was concluded that the use of a ten day running average best smoothed out minor fluctuations in lysimetric and climatic data, so that general trends may be noted more easily.

The correlation analysis of the relationship between individual climatic variables and measured potential

concluded that windspeed at the study site was a major influencing factor in the determination of potential evapotranspiration.

It was also found that minimum relative humidity was an important factor at the Koksilah nursery. It was noted that when minimum relative humidity was added the amount of explained variation rose between five percent (5%) and eleven and one-half percent (11½).

Minimum temperature made a significant contribution to potential evapotranspiration at the Koksilah nursery. The addition of minimum temperature to equation 3-4 (maximum temperature and windspeed), increased the amount of explained variation in the regression equation by over eleven percent (11%). It was concluded that at the Koksilah nursery a considerable amount of evapotranspiration must take place at nighttime, a time of minimum temperature.

Hours of sunshine was not important in determining potential evapotranspiration trends at the study site, either singly or in combination with other variables. It is concluded that the effect of available energy is better represented by other climatic variables such as maximum temperature.

Based on the statistical results, two formulae were chosen for further study. Both of these formulae explained thirty-nine percent (39%) of the variation in the regression equation. The first formula used minimum relative humidity, maximum temperature, and windspeed to calculate potential

evapotranspiration. The second formula used minimum and maximum temperature, and windspeed. Based on practicality, the formula employing minimum and maximum temperature, and windspeed, as shown below, was selected:

$$Y = 7.8908 + 0.5805\ (WNDSPD) + 0.0970\ (TMAXF) + 0.0890\ (TMINF) \pm 0.3506 \quad (10)$$

This method gave more reliable results than any of the previously tested established formulae, as well as offering simplicity and practicality of data requirements and calculation.

Due to the effect of advection at the study site, a correction factor was applied to the results. Utilizing a factor developed by Ward (1963), estimated potential evapotranspiration was corrected for advective effects over the small lysimeter.

A modulated soil moisture budget was used to correct results from the experimental saturated condition, never short of water (potential evapotranspiration), to a practical field condition where soil drying greatly affects evapotranspiration rates (actual evapotranspiration).

A nomograph was developed by which potential evapotranspiration at the Koksilah nursery is easily calculated. A table is provided by which potential evapotranspiration is quickly and accurately converted to a modified actual evapotranspiration rate. Examples are provided to illustrate the use of the field calculation procedures in order that the user might familiarize himself with the procedure.

Based on the results of this study the following recommendations are made:

1) More detailed studies be undertaken to examine the contribution of minimum temperature and nighttime evapotranspiration to total evapotranspiration at the Koksilah nursery.

2) Further studies be conducted to determine the contribution of advection to the evapotranspiration process at the Koksilah nursery.

3) A complete radiation balance should be conducted to determine daytime and nighttime balances over the nursery beds.

4) Methods suggested in this study for the application of irrigation water be tested for a period of two years. During this period monitoring of soil moisture and crop growth should be conducted as a check. After such a test period a re-evaluation of methods and results be undertaken to assess what, if any, modifications are needed.

It is hoped that the results of this study and the techniques suggested, will prove of value in the scheduling of irrigation for Douglas fir seedlings at the Forest Nursery, Koksilah, British Columbia.

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APPENDIX I

EVAPOTRANSPIRATION FORMULAE

Thornthwaite (1948)

$$E = 1.69\ (10T/L)^{a}$$

where: E = potential water use in centimeters
T = mean monthly temperature in degrees Celsius
L = annual heat index
a = a locationally varying constant

Blaney and Morin (1942)

$$E = TKp\ (1.14-H)$$

where: E = evapotranspiration in mm./day
T = mean monthly air temperature in ^{o}F
K = crop coefficient
p = monthly % of daytime hours in the year
H = mean monthly relative humidity (%/100)

Blaney and Criddle (1950)

$$E = TKp$$

where: E = evapotranspiration in mm./day
T = mean monthly air temperature in ^{o}F
K = crop coefficient
p = monthly % of daytime hours in the year

Makkink (1957)

$$E = 0.61Q\ \frac{\Delta}{\Delta + \gamma} - 0.12$$

where: E = evapotranspiration in mm.
Q = incoming solar radiation in evaporation units
Δ = slope of saturated vapour-pressure-temperature curve at the mean air temperature
γ = psychrometric constant

Turc (1954)

$$E = 0.0437\ (T+2)Q$$

where: E = evaporative power of the air
T = mean air temperature in ^{o}C
Q = incoming solar radiation in langleys/day

Penman (1956)

$$E = \frac{Qn + \gamma Ea}{\Delta + \gamma}$$

where: E = evaporation from an open water surface in mm./day
Δ = slope of saturation vapour pressure-temperature curve in mbs./^{o}C at temperature T.
Qn = net radiation expressed in evaporation units
γ = psychrometric constant
Ea = an aerodynamic component

APPENDIX II

SOIL ANALYSIS

TABLE II - 1

MECHANICAL SOIL ANALYSIS

	Bin #1	Bin #2
Soil sample (wet)	200 grams	200 grams
Soil sample (dry)	155 grams	174 grams
Loss of Moisture	45 grams (23%)	36 grams (18%)

Grain Size (mm)	Bin #1 % of sample	Bin #2 % of sample
greater than 4	4.3	13.2
4 to 2	1.3	3.7
2 to 1	1.3	2.4
1 to 0.5	2.8	4.7
0.5 to 0.25	10.8	14.5
0.25 to 0.06	39.0	30.0
less than 0.06	40.5	30.9
	100%	100%

TABLE II - 2

WENTWORTH SCALE OF PARTICLE SIZE

Type	ϕ units	Wentworth scale (mm)
Boulder	more than -8.0	More than 256
Cobble	-8.0 to -6.0	256 to 64
Pebble	-6.0 to -2.0	64 to 4
Granule	-2.0 to -1.0	4 to 2
Very coarse sand	-1.0 to 0	2 to 1
Coarse sand	0 to 1.0	1 to 0.5
Medium sand	1.0 to 2.0	0.5 to 0.25
Fine sand	2.0 to 3.0	0.25 to 0.125
Very fine sand	3.0 to 4.0	0.125 to 0.0625
Coarse silt	4.0 to 5.0	0.0625 to 0.0312
Medium silt	5.0 to 6.0	0.0312 to 0.0156
Fine silt	6.0 to 7.0	0.0156 to 0.0078
Very fine silt	7.0 to 8.0	0.0078 to 0.0039
Coarse clay	8.0 to 9.0	0.0039 to 0.00195
Medium clay	9.0 to 10.0	0.00195 to 0.00098

- after King (1966), p. 277

TABLE II - 3

CLASSIFICATION OF SOILS ACCORDING TO PERCENTAGE COMPOSITION OF CLAY AND SAND

% clay	% sand	type
Up to 10	90 to 100	sandy soil
10 to 20	80 to 90	sandy loam
20 to 60	40 to 80	loam
60 to 80	15 to 40	clay

- after Nikol'skii (1959), p. 5

TABLE II - 4

CLASSIFICATION OF SOILS ACCORDING TO

MECHANICAL COMPOSITION

Type	Ratio clay/sand	Content (%) clay
Clay	1:1 to 1:2	above 50
Heavy loam	1:2 to 1:3	50 to 25
Medium loam	about 1:4	25 to 20
Light loam	1:5 to 1:6	20 to 14
Sandy loam	1:7 to 1:8-1:10	14 to 9
Clay loam	about 1:10 to 1:30	9 to 3
Sand	about 1:30 to 1:50	less than 3

- according to N. M. Sibistev
after Nikol'skii (1959), p. 46

TABLE II - 5

CLASSIFICATION OF SOILS ACCORDING

TO STONINESS

Classification	Content of particles 3 mm.+
Slightly stony	0.5 to 5.0%
Moderately stony	5.0 to 10.0%
Very stony	greater than 10.0%

+ - according to N. A. Kachinskii;
after Nikol'skii (1959), p. 47

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11th March, 1977

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