AN ABSTRACT OF THE THESIS OF

Craig Costello for the degree of Master of Science in Soil Science presented on December 22, 1986.

Title: A Water Balance Model for Reforestation Sites: Description and Sensitivity.

Abstract approved: Redacted for Privacy

Dr. Stuart W. Childs

A model was developed for analysis of the soil water balance of individual reforestation sites in western Oregon. The numerical procedure for this model was programmed in compiled BASIC language and calculations for an entire season are made in about 180 seconds on an IBM AT microcomputer.

The processes that define the water balance are represented in five model components: 1) An estimate of potential evapotranspiration using the energy-based Jensen-Haise method, 2) Partitioning of evapotranspiration from estimates of percentage cover by vegetation type and soil surface cover, 3) Actual evaporation at the soil surface, 4) Actual transpiration from calculations of soil water supply limit and the Nimah-Hanks uptake method, and 5) Soil water flow, including redistribution and drainage.

The input data requirement consists of 20 parameters for characterizing site variation of climate, soil, and ground cover.
Surface cover conditions (slash, mulch, and litter) and plant competition (grasses, forbs, and shrubs) are featured in the model because these ground cover variables are a major reforestation concern. The minimum input data requirement has been simplified in order to accommodate users with limited data for practical applications.

Output of the model includes estimates of solar radiation, soil water storage, total water loss, and water allocation. To test the validity of model output, calculations of water loss were compared to measured values from a detailed field study of the environmental effects of site management practices. The results confirm that the model performs reasonably well and that theory and assumptions of the model are appropriate.

Results of a sensitivity analysis are given in order to evaluate the importance of input parameters and to consider the effects of data error. The analysis demonstrates limitations and possible uses of the model. The predictive ability of the model was found to be most limited by the availability of precipitation data; this does not limit the model as a comparative tool. One important use of the model is the identification of harsh sites and potential water-limiting conditions. Model estimates will also facilitate the consideration of forest management options regarding type of harvest, modification of the seedling environment, species selection, and choice of stock characteristics.
A Water Balance Model for Reforestation Sites: Description and Sensitivity

by

Craig Costello

A THESIS

submitted to

Oregon State University

in partial fulfillment of the requirements for the degree of

Master of Science

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ACKNOWLEDGEMENTS

My respect and appreciation go to the members of my committee: Dr. Stuart Childs, for the opportunity to work in soil-water hydrology and for the perspective on environmental physics which he imparts to his students. Dr. Paul Adams, for guiding my water resources minor. Dr. David Myrold and Dr. Bernd Simoneit for their spirit of cooperation.

Thanks to Alan and Lorrie, for their example and friendship. Thanks Mom and Dad! To Becka, I owe it all.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INTRODUCTION</strong></td>
<td></td>
</tr>
<tr>
<td>Objectives</td>
<td>1</td>
</tr>
<tr>
<td><strong>REVIEW OF LITERATURE</strong></td>
<td>6</td>
</tr>
<tr>
<td>Transpiration and Plant Growth</td>
<td>7</td>
</tr>
<tr>
<td>Soil Water Balance Models Used in Forestry</td>
<td>8</td>
</tr>
<tr>
<td>Components of the Soil Water Balance</td>
<td>11</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>11</td>
</tr>
<tr>
<td>Estimates of potential evapotranspiration</td>
<td>12</td>
</tr>
<tr>
<td>Partitioning of evapotranspiration</td>
<td>15</td>
</tr>
<tr>
<td>Actual evaporation and transpiration</td>
<td>16</td>
</tr>
<tr>
<td>Soil water flow</td>
<td>19</td>
</tr>
<tr>
<td>Precipitation</td>
<td>20</td>
</tr>
<tr>
<td><strong>MODEL DESCRIPTION</strong></td>
<td>22</td>
</tr>
<tr>
<td>Estimate of Potential Evapotranspiration</td>
<td>24</td>
</tr>
<tr>
<td>Partitioning of Evapotranspiration</td>
<td>25</td>
</tr>
<tr>
<td>Actual Evaporation</td>
<td>26</td>
</tr>
<tr>
<td>Actual Transpiration</td>
<td>27</td>
</tr>
<tr>
<td>Soil Water Flow</td>
<td>29</td>
</tr>
<tr>
<td>Precipitation</td>
<td>31</td>
</tr>
<tr>
<td>Input Data Requirement</td>
<td>32</td>
</tr>
<tr>
<td>Climate</td>
<td>32</td>
</tr>
<tr>
<td>Soil</td>
<td>36</td>
</tr>
<tr>
<td>Ground cover</td>
<td>39</td>
</tr>
<tr>
<td>Output Data Types</td>
<td>40</td>
</tr>
<tr>
<td><strong>INITIAL TEST OF VALIDITY</strong></td>
<td>43</td>
</tr>
<tr>
<td>The Field Study</td>
<td>43</td>
</tr>
<tr>
<td>Methods</td>
<td>43</td>
</tr>
<tr>
<td>Results</td>
<td>44</td>
</tr>
<tr>
<td>Input Parameter Estimates</td>
<td>46</td>
</tr>
<tr>
<td>Simulation Results</td>
<td>47</td>
</tr>
<tr>
<td><strong>SENSITIVITY ANALYSIS</strong></td>
<td>51</td>
</tr>
<tr>
<td>Climate</td>
<td>51</td>
</tr>
<tr>
<td>Soil</td>
<td>57</td>
</tr>
<tr>
<td>Ground Cover</td>
<td>61</td>
</tr>
<tr>
<td><strong>SUMMARY AND CONCLUSIONS</strong></td>
<td>67</td>
</tr>
<tr>
<td><strong>REFERENCES</strong></td>
<td>71</td>
</tr>
<tr>
<td><strong>APPENDICES</strong></td>
<td></td>
</tr>
<tr>
<td>I. Program listing.</td>
<td>76</td>
</tr>
<tr>
<td>II. Program variables</td>
<td>90</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>1.</td>
<td>Components of the soil water balance.</td>
</tr>
<tr>
<td>2.</td>
<td>Flow chart of the soil water balance model.</td>
</tr>
<tr>
<td>3.</td>
<td>Calculated solar radiation for five site positions under clear skies.</td>
</tr>
</tbody>
</table>
| 4.     | a) Calculated water release curve. 
|        | b) Calculated unsaturated hydraulic conductivity. |
| 5.     | a) Field measurements for test of validity. 
|        | b) Comparison of model estimates for test of validity. Mean square errors for control, mulch, scalp, and herbicide are 0.16, 0.09, 0.04, and 0.11, respectively. |
| 6.     | Partitioning of water loss on control site. |
| 7.     | Transpiration ratio for site treatments. |
| 8.     | a) Effect of site position on calculated radiation. 
|        | b) Timing of daily radiation on east and west slopes and the relation to diurnal air temperature. 
|        | c) Effect of site position on potential evapotranspiration. Calculated by the Jensen-Haise method with radiation from Figure 8a and temperatures from NOAA Sexton Summit. |
| 9.     | a) Effect of competing vegetation on partitioning of water loss. 
|        | b) Effect of slash cover on partitioning of water loss. |
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Features of soil water balance models used in forestry.</td>
<td>10</td>
</tr>
<tr>
<td>2.</td>
<td>Data requirement for evapotranspiration equations.</td>
<td>13</td>
</tr>
<tr>
<td>3.</td>
<td>Input data requirement for the model.</td>
<td>33</td>
</tr>
<tr>
<td>4.</td>
<td>Output data types.</td>
<td>41</td>
</tr>
<tr>
<td>5.</td>
<td>Sensitivity of potential evapotranspiration calculation to errors in input values (Jensen-Haise, eqs. 1a-1e).</td>
<td>52</td>
</tr>
<tr>
<td>6.</td>
<td>Comparison of environmental conditions and soil water balance for different years and different, but nearby, sites.</td>
<td>56</td>
</tr>
<tr>
<td>7.</td>
<td>Effect of soil factors on water status and use.  The date column indicates the first day on which water becomes limiting. The parameters following the date column are evaluated on this day.</td>
<td>59</td>
</tr>
<tr>
<td>8.</td>
<td>Effect of plant root distribution on water status and use.</td>
<td>65</td>
</tr>
<tr>
<td>9.</td>
<td>Data options for the model input requirement.</td>
<td>69</td>
</tr>
</tbody>
</table>
A Water Balance Model for Reforestation Sites: 
Description and Sensitivity

INTRODUCTION

Soil water as a factor in plant growth has been an important focus of research since the beginning of the century (Briggs and Shantz, 1914). Water is essential for most physiological processes in plants, so water must be sufficiently available if they are to survive and grow. Soil is a natural reservoir for storage of plant available water.

The soil water balance represents a physical system in which a volume of soil water is continually being recharged and depleted. The complex processes of this local hydrologic cycle determine the net volume of plant available water. Most techniques for managing plant moisture conditions take into account the soil water balance, as in the irrigation of agricultural lands. In forestry and range management, where irrigation is usually impractical, the balance may be manipulated through control of water loss.

An important application of water balance information is the management of reforestation sites in harsh environments. When nursery seedlings are transplanted to a field site, favorable growth conditions are required for establishment. It is estimated that there must be "adequate" moisture for a period of 4 weeks following planting (Kreuger
and Trappe, 1967). Although seedlings are most vulnerable during the establishment period, moisture stress can cause reforestation failure at any time.

Adequate moisture in the seedling root zone may be limited by climate, soil water supply, competing vegetation, or all of these factors (Youngberg, 1959; Greaves et al., 1978). Common reforestation practices to conserve limited soil water include site treatments that control surface evaporation and vegetation that competes for moisture. Current research in southwest Oregon has provided a quantitative assessment of these environmental modifications (Flint and Childs, 1986; Childs and Flint, 1984). Evaluation of water use and growth on the study sites demonstrated the importance of the partitioning of water among evaporation, seedling, and competing vegetation components. Competing vegetation accounted for the greatest fraction of total water loss and its control significantly enhanced seedling growth.

Land managers have a need for routine assessment techniques for evaluating a large number of sites that have variable characteristics. In this case it is impractical to make extensive measurements. A conceptual model might be employed for qualitative judgement of site harshness such as predicting possible reforestation problems on a steep south slope with a shallow soil. Other techniques include: extrapolation of the results of case studies, field trials, calculations with a simple model, and calculations with an elaborate model. By choosing an appropriate model, the land manager can combine several of these techniques to increase the accuracy of prediction. Models may also provide estimates of quantities that are difficult to measure.
A model that is intended for site analysis in a reforestation environment should include at least three relevant features:

1) Effects of slope, aspect, and elevation. Calculations of evapotranspiration should be sensitive to these topographic variables that influence site moisture conditions.

2) A layered soil profile. Subsoil variation and soil layers influence the water supply for evapotranspiration and drainage.

3) Surface effects (slash, mulch, and litter) and competition (grasses, forbs, and shrubs). Manipulation of ground cover for water conservation is a major reforestation objective.

Available measurements that characterize this environment are limited, and they are often costly and time-consuming to obtain. Therefore, the data requirement for a practical model used in forestry should be simplified as much as possible.

The model presented in this thesis is appropriate for reforestation site analysis. It is designed to fill a gap between models of elaborate detail, which require extensive data, and approaches for watersheds, which generalize site characteristics. The model is based on a numerical analysis of water balance processes, rather than bookkeeping methods alone (deterministic models) or experimental correlation alone (regression models). Theoretical and experimental information is organized within a framework of equations representing a dynamic system.

The water balance method (Jensen, 1974) provides the mathematical framework for the model. Water balance components represented in the model are shown in Figure 1. The net change in soil water storage is calculated by accounting for all additions and losses of stored water.
Figure 1. Components of the soil water balance.
Precipitation is an addition of water to the soil profile and gravity drainage is a loss from the bottom of the profile. Evaporation and transpiration are the major components of water loss in summer. Evaporation occurs at the soil surface, while transpiration draws water from the profile by root water uptake. As water is used or lost, water potential gradients develop in the profile and internal flow redistributes the remaining soil water.

The physical environment which influences the soil water balance is represented by three categories: climate, soil, and ground cover. Climatic factors determine amounts of precipitation and energy available for evapotranspiration. Soil factors influence water storage and rate of movement. Ground cover factors affect the partitioning of water loss among vegetation and evaporation components.

Demonstration of the complete model includes analysis of model design and validity. Validation provides evidence that the theory and assumptions of the model are appropriate. It also indicates the limits of predictive ability imposed by model simplifications. A sensitivity analysis of the model data requirement provides an assessment of the relative importance of each parameter. This is intended to guide the user, who is responsible for obtaining the input values and who controls their precision.
Objectives

The objectives of this thesis are to:

1) Develop a model of the soil water balance appropriate to the scale of reforestation planning and field management.
   A) Include detail to account for site variation and site treatments.
   B) Provide information to address the constraint of minimal input data.

2) Demonstrate the performance and use of the model.
   A) Provide an initial test of validity.
   B) Provide a sensitivity analysis to indicate the relative importance of input parameters and to assess the effects of data error.
REVIEW OF LITERATURE

Several literature areas are pertinent and appear in this section as follows: 1) Transpiration and plant growth; 2) Soil water balance models used in forestry; and 3) Water balance component methods, which include: estimates of potential evapotranspiration, partitioning of evapotranspiration, actual evapotranspiration and root water uptake, soil water flow and drainage, and precipitation.

Transpiration and Plant Growth

The relation between moisture conditions and growth has been difficult to quantify because of the number, diversity, and interrelation of factors involved. Independent analyses of variables in the soil-plant-atmosphere continuum cannot be sufficiently integrated to represent the system under the dynamic conditions that occur in the field. Instead, the variables of climate, soil, and plants must be considered in the context of their effect on processes that occur in the water balance such as transpiration or soil water depletion.

A basic premise for this approach is the relationship of transpiration and plant growth (Briggs and Shantz, 1914). Arkley (1963) gave evidence for a direct relationship between transpiration and growth rate. He presented statistical analyses of data from
various world locations showing linear correlation of transpiration and yield.

The ratio of actual transpiration to potential transpiration has been used extensively to predict plant growth and yield (reviewed by Hanks, 1983). This relation agrees with the experimental data given by Arkley (1963) and also that of deWit (1958). Denmead and Shaw (1962) found that transpiration is reduced at low soil water potential, and the reduction in transpiration rate depends on both potential transpiration rate and soil water availability.

The transpiration ratio has been used in mathematical models to quantify the growth environment as a dynamic function of water demand and water supply. It is used in models for agriculture (Hanks, 1974) and forestry (Giles et al., 1985). Childs et al. (1977) used this ratio successfully in growth predictions for highly stressed crops.

Soil Water Balance Models Used in Forestry

Soil water balance models used in forestry differ from each other in several respects. Watershed models (reviewed by Baker and Rogers, 1983) are suited to water balance and yield predictions for large areas and relatively long time periods (i.e. monthly); reforestation planning requires greater attention to local site variation than these provide. Site models differ in mathematical detail and approach used to describe the soil-plant-atmosphere system. Bookkeeping models (e.g. Warrington and Weathered, 1983; Legard, 1977) are based on relatively simple
mathematical operations, regardless of the number of variables included. Process models (e.g. Black and Spittlehouse, 1981; Federer, 1979; Luxmoore et al., 1978) are based on theoretical analysis of one or more components of the physical system. These incorporate greater detail and allow interactions to occur during operation of the model. For example, a numerical procedure for soil water flow allows the hydraulic characteristics of the soil to change as soil water becomes limited, thus exerting control over the future rate of water loss.

Process type models vary in calculation detail and accompanying input data requirements. Most begin by dividing either the canopy-atmosphere zone or the root zone of the soil into layers. Layered canopy models (e.g. Ehleringer and Miller, 1975) require extensive measurements from the canopy-atmosphere boundary. Layered soil models (e.g. Black and Spittlehouse, 1981) assume that the canopy-atmosphere interaction can be represented by a simplified method of estimating potential evapotranspiration. Norman and Campbell (1983) have presented an integrated layered canopy and layered soil model; although this represents an advance in technique, the data requirement is extensive. They assert that the integrated model is needed to combine information from the several disciplines studying components of the soil-plant-atmosphere system, but that a simplified model (i.e. layered soil) is often appropriate for applied use.

Features of several current soil water balance models used in forestry are compared in Table 1. These represent a range of detail, component methods, and data requirements. The models that perform diurnal calculations are capable of simulating the development of plant stress through the day, including critical peak events. Representation
Table 1. Features of soil water balance models used in forestry.

<table>
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<tr>
<td>Time resolution</td>
<td>diurnal</td>
<td>diurnal</td>
<td>diurnal or daily</td>
<td>daily</td>
<td>monthly</td>
</tr>
<tr>
<td>Depth resolution</td>
<td>6 layer soil</td>
<td>2 layer soil</td>
<td>2 layer soil</td>
<td>2 layer soil</td>
<td>each soil horizon</td>
</tr>
<tr>
<td>Potential ET</td>
<td>Penman type</td>
<td>Penman type</td>
<td>Penman type</td>
<td>Priestley-Taylor</td>
<td>Thornthwaite</td>
</tr>
<tr>
<td>Actual ET</td>
<td>stomatal resistance</td>
<td>stomatal resistance</td>
<td>stomatal resistance</td>
<td>soil resistance</td>
<td>soil resistance</td>
</tr>
<tr>
<td>Separation of E and T</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Root water uptake</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Precipitation gross</td>
<td>gross</td>
<td>net</td>
<td>net</td>
<td>net</td>
<td>net</td>
</tr>
<tr>
<td>Drainage calculation</td>
<td>unit hydraulic gradient</td>
<td>amount &gt; storage capacity</td>
<td>amount &gt; storage capacity</td>
<td>unit hydraulic gradient</td>
<td>amount &gt; storage capacity</td>
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<tr>
<td>Redistribution</td>
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<td>no</td>
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<td>Climate Data</td>
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<tr>
<td>radiation</td>
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<td>x</td>
<td>x</td>
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<td>precipitation</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>wind</td>
<td>x</td>
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<td>Soil Data</td>
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<td>infiltr. rate</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>storage capacity</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>hydraulic prop.</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>soil type</td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>rock percentage</td>
<td></td>
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<td>Plant Data</td>
<td></td>
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<td>cover percentage</td>
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<td>leaf area index</td>
<td></td>
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<tr>
<td>stom. resist.</td>
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<tr>
<td>flow resist.</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>min. water pot.</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rooting density</td>
<td>x</td>
<td></td>
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</table>
of soil layers is another advantageous feature because the effective limit of water supply is influenced by each horizon in the profile. Methods used to model the components of the water balance are numerous and varied; common approaches will be identified and reviewed in the specific sections that follow.

The intended application of a model and the availability of input data determine the optimum combination of component features. The more complex models also have increased data requirements. There are definite tradeoffs in model performance that are associated with model input requirements and precision. This is one reason for performing sensitivity studies that compare input variation with output results. For instance, Luxmoore et al. (1981) analyzed the sensitivity of evapotranspiration calculations to meteorological data; the analysis indicated the type of data necessary for accurate results in eastern Tennessee. The model of Luxmoore et al. (1978) is comparable in detail to that of Federer (1982) in Table 1.

Components of the Soil Water Balance

Evapotranspiration. The process of evaporation or transpiration involves vaporization and vapor transport. This requires a simultaneous supply of water and energy. Actual evapotranspiration may be limited by available energy, available water, or both. The concept of "potential" evapotranspiration is used to describe the energy-limited rate of evapotranspiration.
Methods that are used to calculate or predict evapotranspiration can be classified into four types based on their approach to the process: aerodynamic, energy balance, combination, and simplified. The aerodynamic approach evaluates actual evapotranspiration from canopy resistances to the transfer of heat and vapor. The energy balance approach evaluates potential evapotranspiration from the proportion of net radiation that can be supplied for vaporization. The combination approach incorporates the two basic theoretical approaches to provide actual or potential rates depending on the number of resistances measured. Simplified methods estimate potential evapotranspiration from fewer parameters and use empirical corrections for effects such as advection or inadequate soil water supply.

Examples of the data requirement for the various approaches are shown in Table 2. The aerodynamic, energy balance, or combination methods provide a necessary basis for representing the physics involved, but the data requirement is not feasible for routine land management. Reduced data requirements are shown in the table by common examples of the simplified approach. Reviews of the numerous methods and modifications are given by Burman et al. (1983) and the American Society of Civil Engineers (Jensen, 1974).

Estimates of potential evapotranspiration. Simplified methods that are radiation-based are practical in forestry applications because radiation and air temperature data are more easily acquired or estimated than stomatal resistance data. The following methods are widely used equations for estimating potential evapotranspiration with limited data.
Table 2. Data requirement for evapotranspiration equations.

<table>
<thead>
<tr>
<th>Method</th>
<th>Radiation</th>
<th>Air temp</th>
<th>Rel. humid</th>
<th>Wind speed</th>
<th>Stomatal resist.</th>
<th>Data freq</th>
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<tbody>
<tr>
<td>AERODYNAMIC</td>
<td></td>
<td>5 hts.</td>
<td>5 hts.</td>
<td>3 dim.</td>
<td></td>
<td>millisec ave.</td>
</tr>
<tr>
<td>ENERGY BALANCE</td>
<td>net</td>
<td>2 hts.</td>
<td>2 hts.</td>
<td>option</td>
<td></td>
<td>0.5 hr ave.</td>
</tr>
<tr>
<td>COMBINATION</td>
<td>net</td>
<td>1 ht.</td>
<td>1 ht.</td>
<td>yes</td>
<td></td>
<td>0.5 hr ave.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2 m)</td>
<td></td>
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<tr>
<td>SIMPLIFIED:</td>
<td></td>
<td>ave.</td>
<td>ave.</td>
<td>yes</td>
<td>daily</td>
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<td>Canopy resistance</td>
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<td>ave.</td>
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<td>daily</td>
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<tr>
<td>Priestley-Taylor</td>
<td>net</td>
<td>ave.</td>
<td>option</td>
<td></td>
<td>daily</td>
<td></td>
</tr>
<tr>
<td>Jensen-Haise</td>
<td>incoming</td>
<td>ave.</td>
<td>option</td>
<td></td>
<td>daily</td>
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</tr>
<tr>
<td></td>
<td>solar</td>
<td></td>
<td></td>
<td></td>
<td>monthly</td>
<td></td>
</tr>
<tr>
<td>Thornthwaite</td>
<td></td>
<td>ave.</td>
<td></td>
<td></td>
<td>monthly</td>
<td></td>
</tr>
</tbody>
</table>
The Priestley-Taylor method (1972) is a truncation of the Penman (1948) combination method in which the aerodynamic term is not present. The primary factor is net radiation, which is multiplied by a coefficient. Values of this coefficient for various environmental, crop, and soil water conditions may be obtained from literature (Stewart, 1983; Flint, 1986). The Priestley-Taylor method has been applied primarily where there is relatively complete canopy cover or bare soil (Black and Spittlehouse, 1981). Reforestation sites, however, are characterized by variable and incomplete cover conditions.

In the method of Jensen and Haise (1963), the primary factors are solar radiation and air temperature. This equation assumes that net radiation is well correlated with evapotranspiration, that net radiation is proportional to total radiation and air temperature, and that the mechanism for removal of water vapor by turbulent transfer is not a limiting factor (well ventilated canopy). These assumptions were evaluated with 35 years of data representing variable and incomplete cover conditions (crops and orchards). Two coefficients were determined in correlating the data, one associated with radiation and the other with air temperature. A modification by Jensen et al. (1970) allows for the determination of the coefficients using site elevation and a vapor deficit characteristic based on site temperature data.

Thornthwaite (1948) presented one of the many methods which correlate mean air temperature and evapotranspiration. This equation has been used in field-scale models (e.g. Warrington and Weatherred, 1983) because air temperature data are commonly available. The procedure is also straightforward in the event that climatic conditions must be estimated.
Estimates of the radiation-based equations are similar to the theoretical combination method estimates because radiation generally dominates the aerodynamic influence and there is an underlying correlation between vapor deficit and net radiation (Stewart, 1983). Experimental studies have demonstrated repeatedly that net radiation is more closely related to evapotranspiration than air temperature, humidity, or any other single variable (Jensen and Haise, 1963).

Partitioning of evapotranspiration. A collective estimate of water loss through evapotranspiration is often the extent of general hydrology models (Baker and Rodgers, 1983). The variability of cover conditions on reforestation sites requires that the process be subdivided for resolution of evaporation and transpiration water loss. Soil surface cover can reduce bare soil evaporation; this varies by the amounts of slash, mulch, and litter present. Vegetation cover and component transpiration rates vary by species and amounts present on a particular site.

Partitioning is estimated initially by the separation of potential evaporation and potential transpiration. Calculation of actual evaporation or transpiration from the potential rates is a second step in partitioning. A commonly used approach to partitioning is to arbitrarily set evaporation and transpiration percentage. For instance, Nimah and Hanks (1973) chose 10% and 90% respectively. This approach would not suffice for the reforestation environment because actual ground cover distribution is highly variable. A complex approach for partitioning is given by Norman and Campbell (1983). They incorporate a detailed description of the energy balance of each
surface and the penetration of radiation through ground cover. The data requirement is rigorous and they do not recommend the technique for routine analysis.

A practical approach, which is approximately correct, is to assume that the ratio of transpiration to evapotranspiration is the same as the ratio of radiation intercepted by vegetation to total incident radiation (Campbell, 1985). Variations of this approach all employ the assumption that the distribution of soil surface cover, vegetative cover, and bare soil characterizes the distribution of energy on a site. Waring and Running (1976) used leaf area; this technique requires data for individual species. Ritchie and Burnett (1971) and Tanner and Jury (1976) used empirical relationships based on percentage cover and leaf area index. Childs and Hanks (1975) used the stage of crop growth to calculate cover area. Rasmussen and Hanks (1978) used percentage plant cover, litter, and bare soil. An estimate of cover percentage would be the most practical parameter to use for reforestation management where data are limited.

**Actual evaporation and transpiration.** There are two fundamental approaches commonly used in forestry to determine the limits of actual evaporation and transpiration:

1) The canopy resistance method focuses on the role of stomatal resistance in the diffusion of water vapor from the canopy (Black and Spittlehouse, 1981). The gradient for diffusion is the vapor pressure deficit (VPD; the difference between vapor concentration in plant substomatal cavities and the ambient atmospheric vapor concentration). Actual evaporation and transpiration are
calculated directly and require data for stomatal resistance. Some type of assessment of soil water supply is also required.

2) Soil water supply limitation methods focus on the role of soil resistance to water flow. As water content decreases, water supply begins to dominate the actual rate of evaporation and transpiration. This condition occurs rapidly in the shallow root zone of seedlings and when summer weather is harsh. Actual evaporation and transpiration are calculated as the lesser of potential evapotranspiration and a soil water supply rate.

The following discussion is limited to water supply limitation methods because: A) stomatal resistance data are not expected to be available for most field situations, and B) the model is intended for incomplete cover in harsh environments where soil water is expected to be limiting for much of the growing season.

Simple functions for predicting actual evapotranspiration from the estimate of potential evapotranspiration relate supply to a single soil water parameter such as water content (Waring and Running, 1976). The coefficient in the Priestley-Taylor equation may also be corrected for water-limited conditions in this manner (Flint, 1986). This approach lacks detail, however, and has not been calibrated for the variety of soil and cover characteristics encountered in general use.

Water supply for evaporation from bare soil can be described by Darcy's Law. This relation is widely used, and is particularly appropriate when used in models (e.g. Childs et al., 1977) that calculate the parameters for soil water flow (water potential and unsaturated hydraulic conductivity) throughout the entire profile. Water supply for transpiration can also be described by a form of
Darcy's Law, though additional flow resistance factors must be incorporated to describe water uptake by roots.

Numerous approaches have evolved for representing the complex process of root water uptake. These can be categorized as either microscopic, focused on single roots, or macroscopic, focused on the root profile. A microscopic model (Gardner, 1960) describes radial flow to a hollow cylindrical root which has uniform hydraulic properties. A flow equation is solved which requires resistance data at the root surface and in the nearby soil. A macroscopic model (Gardner, 1964) broadens the analysis; the integrated properties of the root system over a volume of soil are considered. In this case a flow equation is solved where uptake is proportional to an effective root density, the sum of the resistances in the pathway from the soil to the leaf, and the matric potential difference between the soil and the leaf.

The macroscopic approach avoids excessive detail yet it can be used to incorporate root distribution, a general characteristic important to the separation of uptake by different plant species. The macroscopic model of Molz and Remson (1970) based water uptake solely on transpiration and root distribution. Distribution over four equal depth increments in the root zone was assumed to be 40%, 30%, 20%, and 10%. Results from this model showed moderate agreement with laboratory data.

The macroscopic model of Nimah and Hanks (1973a) incorporated depth variation of soil water potential and of plant and soil properties. Their approach involved a modification of the Gardner (1964) model coupled with the unsaturated soil water flow equation. In
the modification they introduce a plant flow resistance term and a mathematical solution procedure for transpiration based on plant water potential (Gardner required a known transpiration rate). A minimum allowable plant water potential is required for the modified solution; this value corresponds to the concept of plant wilting point. In the model this is related to the point at which actual transpiration becomes less than the potential transpiration rate (Lopushinski and Klock, 1974). Nimah and Hanks (1973b) demonstrated a strong ability to predict actual transpiration in a field test of this model. Accurate calculations are also documented with plants under conditions of moisture stress (Feddes et al., 1975).

Soil Water Flow. The process of soil water flow is simplified in many layered-soil models (Table 1) by considering the soil layers to be fixed reservoirs. The available water content is measured or estimated from soil texture. In each layer the volume of available water is adjusted by addition of precipitation, or depletion by evapotranspiration. This bookkeeping method is generally useful for long-term (monthly or longer) water balance and yield applications that do not attempt to describe moisture dynamics in the plant root zone.

More detailed methods incorporate a layered profile of soil water potential, unsaturated conductivity, and a mathematical solution of the soil water flow equation for redistribution fluxes. The equation for transient state soil water flow is not readily solved as a boundary value problem because the relationship of conductivity to water potential is nonlinear. Numerical methods are therefore used to give approximate solutions. In the method of Hanks and Bowers (1962), a
A system of linearized equations is written for the depth increments. A tridiagonal coefficient matrix is created for the system of equations at one time increment. Initial and boundary conditions must be specified, as well as unsaturated hydraulic conductivity and a moisture release curve.

The solution of the flow equation using numerical methods would introduce additional complexity to the model if soil hydraulic properties had to be supplied by the user. Fortunately, the required hydraulic functions can be simplified. Methods for estimation of these on the basis of texture work well in practical applications (Saxton et al., 1986). Campbell (1974; 1985) gave one method (review by Ahuja et al., 1985) of determining hydraulic functions based on simple hydraulic parameters and has provided values for these parameters for 10 classes of soil texture (Campbell and Campbell, 1982).

When the process of transient state soil water flow is included in a model there is more output information available to examine the causes of moisture stress. The calculated profiles of water potential and unsaturated conductivity over depth and time indicate water storage limitations and water supply rate limitations, and allow these to be distinguished in further data analysis.

Precipitation. Precipitation entering the soil may be less than the total rain gauge measurement due to interception by ground cover and surface water runoff. Interception in forests is dependent upon a large number of vegetative and weather factors that are not often measured; the importance of interception loss is the subject of much debate (Hewlett and Nutter, 1969). Elaborate interception submodels
are available (Stewart, 1977), but data requirements are extensive. Simplified coefficients may only be appropriate when calibration data are available. McNaughton and Black (1973) found that, in a young forest in British Columbia, only 17% of interception could be considered net loss because transpiration was reduced when intercepted water was present.

The soil infiltration rate on undisturbed forested lands throughout most of Oregon is so high that surface runoff can be considered negligible (Greaves et al., 1978). The detailed input requirement for infiltration routines (including parameters such as surface conductivity and rainfall intensity) can therefore be avoided in a simplified model.

Practical models used in forestry generally rely on the reservoir concept for entering precipitation (Warrington and Weatherred, 1983). Models that incorporate the soil water flow process, however, include redistribution of precipitation over time and soil depth (Federer, 1979).
MODEL DESCRIPTION

A soil water balance model was developed to simulate the processes that affect moisture conditions for seedling growth and survival. The numerical procedure is programmed in compiled BASIC language and calculations for an entire season are made in about 180 seconds on an IBM AT microcomputer.

The framework for numerical analysis of water flux with respect to depth and time consists of a depth profile, a daily loop, and a diurnal loop. The depth profile is a series of soil layers with designated soil hydraulic properties, root densities, initial water status, and boundary conditions. The number of layers varies with total soil depth (for example, a 0.6 m soil is divided into 7 layers, a 1.2 m soil is divided into 10 layers). The time sequence for a growing season advances by increments of 1 day for input of weather data and daily calculations. Each day advances by increments of 2 hrs (the increment can be varied) for diurnal calculations. Diurnal cycles are included in the simulation because of their importance in the development of plant moisture stress through the day.

A flow chart of the program is shown in Figure 2. Data for site description are entered by the user and a series of subroutines initializes the mathematical framework. Weather data are entered in the daily cycle, and precipitation is distributed in the soil profile. The diurnal cycle performs the water balance calculations over time and over depth. Five component methods are incorporated within this routine: 1) An estimate of potential evapotranspiration using the
INPUT CLIMATE, SOIL, AND GROUND COVER DATA

INITIALIZE DEPTH PROFILE FOR
SOIL PROPERTIES, WATER CONTENT,
AND ROOT DISTRIBUTION

DAILY CYCLE

Daily weather

Distribute precipitation to soil profile and drainage

DIURNAL CYCLE

Estimate potential evapotranspiration

Separate potential evaporation and transpiration

Calculate actual evaporation from surface

Calculate actual transpiration from profile

Calculate soil water redistribution and drainage

END OF DIURNAL CYCLE

PRESENT DAILY OUTPUT

END OF DAILY CYCLE

PRESENT FINAL OUTPUT DATA AND GRAPHS

Figure 2. Flow chart of the water balance model.
energy-based Jensen-Haise method, 2) Partitioning of evapotranspiration from estimates of percentage cover by vegetation type and soil surface cover, 3) Actual evaporation at the soil surface, 4) Actual transpiration from calculations of soil water supply limit and Nimah-Hanks uptake method, and 5) Soil water flow, including drainage. These components are described in detail in the following paragraphs.

**Estimate of Potential Evapotranspiration**

The modified Jensen-Haise method (Jensen et al., 1970) is used to estimate potential evapotranspiration. It was chosen because it is a simplified radiation-based method, temperature is included in the correlation, and model coefficients are calibrated for site conditions (Eqs. 1b-1e). The complete data requirement is daily solar radiation, daily maximum and minimum air temperatures, and elevation. The equations are:
\[ \text{ETP} = \frac{\text{RS}}{\text{CT}(\text{T-TX}) \times \text{c}} \]  
\[ \text{CT} = \frac{1}{(\text{Cl} + 7.6 \times \text{CH})} \]  
\[ \text{CL} = 38 - (2 \times \text{EL}/305) \]  
\[ \text{CH} = \frac{5}{(e_2 - e_1)} \]  
\[ \text{TX} = -2.5 - 1.4(e_2 - e_1) - \frac{\text{EL}}{550} \]

where

- ETP = potential evapotranspiration \( (\text{m}^3 \text{ m}^{-2} \text{ s}^{-1}) \)
- T = air temperature (°C)
- RS = solar radiation \( (\text{MJ m}^{-2} \text{ s}^{-1}) \)
- EL = elevation (m)
- e = saturation vapor pressure at mean minimum \( (e_1) \) and mean maximum \( (e_2) \) temperature for the warmest month in the year \( (\text{kPa}) \); calculated from the temperature data
- c = conversion from energy to equivalent evaporation, \( (4.1 \times 10^{-4} \text{ m}^3 \text{ water MJ}^{-1}) \)

**Partitioning of Evapotranspiration**

Potential evaporation and potential transpiration are separated from total potential evapotranspiration based on the distribution of cover on a site. Ground cover estimates are used to assign values to five cover percentages: bare soil, non-transpiring surface cover (slash, mulch, or litter), and three categories of vegetation (commercial tree seedlings, grasses and forbs, and shrubs).
Potential evaporation from bare soil is calculated using:

\[ EP = CO(0) \times ETP \]  \hspace{1cm} (2)

where

- \( EP \) = potential evaporation \( (m^3 \ m^{-2} \ s^{-1}) \)
- \( CO(0) \) = fraction of site area that is bare soil

Potential transpiration by each vegetation category is:

\[ TP(s) = CO(s) \times ETP \]  \hspace{1cm} (3)

where

- \( s \) = species, or vegetation type
- \( TP(s) \) = transpiration by vegetation type \( (m^3 \ m^{-2} \ s^{-1}) \)
- \( CO(s) \) = fraction of site area covered by vegetation type

Actual Evaporation

The water supply limited rate of evaporation is determined by a Darcy's Law expression using the unsaturated conductivity of a 0.02 m surface layer of soil:
Actual evaporation is equal to the lesser of the potential rate (eq. 2) and the soil water supply rate (eq. 4).

Actual Transpiration

The actual rate of transpiration for each vegetation type is determined by the potential rate and water uptake by roots, calculated using the macroscopic model of Nimah and Hanks (1973):

\[
EA = \frac{(H-(h-g*z))Ku}{p_w*z}
\]  

(4)

where:

- **EA**: actual evaporation \((m^3 m^{-2} s^{-1})\)
- **H**: atmospheric water potential \((-1E+5 \text{ J kg}^{-1})\)
- **h**: surface soil matric potential \((\text{J kg}^{-1})\)
- **g**: gravitational acceleration \((9.8 \text{ m s}^{-2})\)
- **p_w**: density of water \((1000 \text{ kg m}^{-3})\)
- **z**: distance for water flow \((0.02\text{m})\)
- **Ku**: unsaturated hydraulic conductivity \((\text{kg s m}^{-3})\)
\[
\text{TA}(s) = \left( \text{Hroot} - (h(z) - \text{Rres} \cdot g \cdot z) \right) \cdot \text{K}(z) \cdot \text{Rdf}(s, z) \cdot p_w \cdot x
\]  

(5)

where

\begin{align*}
\text{TA}(s) & \quad \text{actual transpiration for each of three vegetation categories (m}^3 \text{ m}^{-2} \text{ s}^{-1}) \\
\text{Hroot} & \quad \text{effective plant water potential at the soil surface (J kg}^{-1} \text{)} \quad (0 > \text{Hroot} > \text{Hmin}(s); \text{ Hmin}(s) = \text{minimum allowable plant water potential for a species}) \\
h(z) & \quad \text{soil matric potential as a function of depth (J kg}^{-1} \text{)} \\
\text{Rres} & \quad \text{root resistance term (1.03 assumed)} \\
g & \quad \text{gravitational acceleration (9.8 m s}^{-2} \text{)} \\
z & \quad \text{depth from surface (m)} \\
\text{K}(z) & \quad \text{unsaturated hydraulic conductivity as a function of depth (kg s m}^{-3} \text{)} \\
\text{Rdf}(s, z) & \quad \text{effective root density as a function of species and depth (fraction)} \\
p_w & \quad \text{density of water (1000 kg m}^{-3} \text{)} \\
x & \quad \text{distance of effective root water extraction (0.01 m assumed)}
\end{align*}

The root density function is determined in a model procedure that superimposes a root depth distribution over the soil profile for the total depth of rooting; the result is a calculated percentage of total roots present in each soil layer.
The calculation of actual transpiration then proceeds as follows. Potential transpiration is substituted for TA and the equation is solved for $H_{\text{root}}$. Next, two conditions are possible. If the value of $H_{\text{root}}$ is greater than the minimum allowable plant water potential then transpiration is determined by the potential rate (eq. 3). If the value of $H_{\text{root}}$ is less than the minimum allowable plant water potential then transpiration is limited by the ability of the soil to supply water to the plant roots. This supply-limited rate is calculated by substituting the minimum allowable plant water potential for $H_{\text{root}}$ and solving equation 5 for TA.

**Soil Water Flow**

Once the components of water loss have been calculated for each depth, they are collected in a sink term. The sink term is combined with the soil water flow equation (Richards, to compute the new water balance of the soil profile: **
\[
\frac{dWC}{dt} \frac{dh}{dz} = \frac{d}{dh} \frac{d(h-gz)}{dz} - S(z,t) \tag{6}
\]

where

- WC = water content \( \left( m^3 m^{-3} \right) \)
- h = matric potential \( \left( J kg^{-1} \right) \)
- t = time \( (s) \)
- g = gravitational acceleration \( (9.8 m s^{-2}) \)
- \( p_w \) = density of water \( (1000 kg m^{-3}) \)
- z = depth \( (m) \)
- \( K(h) \) = unsaturated conductivity \( (kg s m^{-3}) \)
- \( S(z,t) \) = sink term: fluxes due to gravity drainage at bottom of profile, soil surface evaporation, and water uptake by roots

The equation for each node is expanded over depth and time using a finite difference technique. Weighted averages for the nonlinear hydraulic functions, unsaturated hydraulic conductivity and water supply capacity \( dWC/dh \), are integrated to represent effective values over time (Campbell, 1985). The system of equations for the entire profile is then ordered in matrix form and solved using a numerical algorithm.

Nodes for calculation of fluxes and storage are centrally located in each layer of the profile. Two additional nodes outside the soil profile are required; these are the upper and lower boundary conditions. The upper boundary condition is atmospheric water potential and assumes a high vapor deficit. The lower boundary
condition assumes that the matric potential at the bottom node of the profile and at the boundary node are equal (unit hydraulic gradient assumption). Therefore only gravity drainage flow proceeds:

\[
DR = K \frac{d(g*z)}{p_w} dz - \frac{K*g}{p_w}
\]  

where

- \(DR\) = drainage (\(m^3 m^{-2} s^{-1}\))
- \(K\) = unsaturated hydraulic conductivity (\(kg s m^{-3}\))
- \(g\) = gravitational acceleration (9.8 \(m s^{-2}\))
- \(p_w\) = density of water (1000 \(kg m^{-3}\))
- \(z\) = depth (m)

**Precipitation**

An interception submodel is not used, although this component could be readily incorporated for applications in which data are available to calibrate the net effect of interception. It is assumed that surface runoff does not occur.

Additions to soil water from precipitation are entered during a nightly time increment. Extra calculation cycles are added for this period by subdividing the time increment; the number of subdivisions is proportional to the amount of precipitation. Larger changes in water content have a greater effect on the nonlinear hydraulic
functions, so more calculation cycles will reduce mathematical error in the linearized system of equations in the model.

Daily precipitation is added to the surface layer of the soil profile until field capacity (estimated by $-30 \text{ J kg}^{-1}$) for that layer is reached. If there is more precipitation than can be stored in the surface layer, the procedure is repeated in the next layer of the profile. If there is sufficient precipitation to fill all soil layers to field capacity, the excess becomes drainage from the bottom of the profile.

**Input Data Requirement**

The input data requirement for the model is summarized in Table 3 with sample values for a simulation run. Calculations are usually made for a summer growing season. Climate in this example is represented by data from Sexton Summit, a high-elevation weather station in southern Oregon operated by the National Oceanic and Atmospheric Administration (NOAA). The soil shown is isotropic; a layer would be created by changing the values in any horizon. The four sets of ground cover percentages will be used in model simulations to compare reforestation site treatments that control water loss.

**Climate.** Daily solar radiation, daily maximum and minimum air temperatures, elevation, and daily precipitation are the parameters required for climatic characterization. The diurnal radiation cycle
Table 3. Standard input requirement and sample values.

<table>
<thead>
<tr>
<th>INPUT</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growing season</td>
<td>June 1 to August 31</td>
</tr>
<tr>
<td><strong>Climate:</strong></td>
<td>1981 Sexton Summit, OR.</td>
</tr>
<tr>
<td>Solar Radiation:</td>
<td></td>
</tr>
<tr>
<td>Latitude</td>
<td>42 deg N</td>
</tr>
<tr>
<td>Longitude</td>
<td>123 deg W</td>
</tr>
<tr>
<td>Slope</td>
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</tr>
<tr>
<td>Aspect</td>
<td>180 deg</td>
</tr>
<tr>
<td>Elevation</td>
<td>1170 m</td>
</tr>
<tr>
<td>Sky cover</td>
<td>daily</td>
</tr>
<tr>
<td>Air Temperature:</td>
<td>daily C</td>
</tr>
<tr>
<td>Maximum</td>
<td>daily C³ m⁻²</td>
</tr>
<tr>
<td>Minimum</td>
<td></td>
</tr>
<tr>
<td>Precipitation</td>
<td>daily m³ m⁻²</td>
</tr>
<tr>
<td><strong>Soil:</strong></td>
<td>A horizon B horizon C horizon</td>
</tr>
<tr>
<td>Texture</td>
<td>sandy loam</td>
</tr>
<tr>
<td>Cumulative Depth</td>
<td>0.12 m 0.30 m⁻³ 0.60 m</td>
</tr>
<tr>
<td>Rock fragment volume</td>
<td>0.35 m m⁻³</td>
</tr>
<tr>
<td>Initial water content</td>
<td>0.21 m³ m⁻³ (-30 J kg⁻¹)</td>
</tr>
<tr>
<td><strong>Ground Cover:</strong></td>
<td>Control Mulch Scalp Herbicide</td>
</tr>
<tr>
<td>Cover percentages:</td>
<td></td>
</tr>
<tr>
<td>Slash or mulch</td>
<td>10 80 0 20</td>
</tr>
<tr>
<td>Seedlings</td>
<td>10 10 10 10</td>
</tr>
<tr>
<td>Grass and forbs</td>
<td>30 0 0 0</td>
</tr>
<tr>
<td>Shrubs</td>
<td>30 5 1 0</td>
</tr>
<tr>
<td>Bare soil</td>
<td>20 5 89 70</td>
</tr>
<tr>
<td>Characteristics of vegetation types:</td>
<td></td>
</tr>
<tr>
<td>Seedling root depth</td>
<td>0.25 m</td>
</tr>
<tr>
<td>Grass root depth</td>
<td>0.18 m</td>
</tr>
<tr>
<td>Shrub root depth</td>
<td>0.60 m</td>
</tr>
<tr>
<td>Root profiles</td>
<td>40/30/20/10, %</td>
</tr>
<tr>
<td>Minimum plant water potential</td>
<td>-1500 J kg</td>
</tr>
</tbody>
</table>
can be estimated from measured daily radiation fit to a half sine function (12 P.M. maximum), or calculated from input values of latitude, slope, aspect, elevation, and sky cover. Input data for air temperature, precipitation, and sky cover may be obtained from local climatological data publications (NOAA). Other regional sources may also be available (Satterlund, 1981). Daily minimum and maximum air temperatures are fit to a sine function (3 A.M. minimum, 3 P.M. maximum) to simulate the diurnal temperature cycle.

Calculated radiation values are supplied by a model subroutine using the following methods. First, a value for potential radiation (outside the earth's atmosphere) is calculated as a function of site orientation to the sun (Kaufmann and Weatherred, 1982). Latitude, slope, and aspect are the required parameters to determine the position of the site in relation to the daily path of the solar beam. Next, direct beam radiation at a site is calculated as a function of potential radiation, atmospheric transmissivity, and sky cover percentage (Garnier and Ohmura, 1968). The method of Campbell (1977) is used to calculate the diffuse component of radiation; this procedure reduces direct beam and increases diffuse radiation for cloudy conditions. In the model, atmospheric transmissivity is assumed to be approximately 0.7 (Garnier and Ohmura, 1968).

The annual cycle of solar radiation for five representative site positions is shown in Figure 3. The effects of slope and aspect, calculated by the model subroutine, agree with the predictions of others (Lee, 1978) that also account for atmospheric transmissivity. The horizontal position has the highest peak which occurs in mid-summer. The south slope, however, receives the highest seasonal
Figure 3. Calculated solar radiation for five site positions under clear skies.
average. East and west slope values are identical; differences in the water balance for these slopes are due to the timing of daily radiation and temperature, to be discussed later.

Three alternatives have been used to create climatic input data files for model analysis:

1) Complete data: Experimental data for insolation, air temperatures, and precipitation.

2) Partial data: Calculated insolation; air temperatures, precipitation, and sky cover from NOAA weather data.

3) No data: Calculated insolation; simulated weather with estimated mean monthly temperatures fit to annual sine function and assumed clear sky conditions.

Other data options are possible when the user creates the climatic input data file.

Soil. The properties of the soil profile that must be known are typically obtained in a site visit. The minimum requirement is a representative profile description, including depth and texture of the master horizons, and an estimate of initial water content.

The hydraulic functions needed to solve the unsaturated flow equation (water release and unsaturated hydraulic conductivity) may be estimated from fine soil texture (Campbell, 1974; 1985) for each horizon. The model incorporates example literature values (Campbell and Campbell, 1982) for hydraulic properties (air entry water potential, saturated hydraulic conductivity, saturated water content, and a regression constant); ten soil textural classes are represented.
Data for soil hydraulic characteristics may also be supplied by the user.

Estimated hydraulic functions may be adjusted for secondary effects (e.g. organic matter, density, or clay type) by slight adjustment of the texture (Saxton et al., 1986). An adjustment for the effect of rocks, based on the porosity of a rocky soil (bulk total) relative to the fine-earth fraction, was developed for the model:

$$\frac{X_B - X_A}{P_B} = X_A \left( \frac{P_R + P_A(1-R)}{P_A} \right)$$

(8)

where

- $X_B$ = hydraulic variable for bulk soil (water content or hydraulic conductivity)
- $X_A$ = hydraulic variable value for fine-earth fraction (water content or hydraulic conductivity)
- $P_B$ = porosity of bulk soil
- $P_A$ = porosity of fine-earth fraction (equal to saturated water content)
- $P_R$ = porosity of rock fragments
- $R$ = volume fraction of rock fragments

Examples of the water release function and unsaturated hydraulic conductivity function for several soil textures are shown in Figure 4a and Figure 4b, respectively. These were calculated from the example literature values incorporated in the model. Among the soils shown, there exists a relatively large variation in water content for a given
Figure 4. a) Calculated water release curve.
   b) Calculated unsaturated hydraulic conductivity.
water potential over the "available" range of potential (estimated by -30 J kg$^{-1}$ to -1500 J kg$^{-1}$). The variation in unsaturated soil hydraulic conductivity is less with several textures having about the same curve. An estimate of the effect of rocks is shown in each figure by curves for a sandy loam versus a sandy loam with 32% rocks. Rock fragments reduced the water content of the bulk soil to a greater degree than they reduced the unsaturated hydraulic conductivity.

The water content profile of the soil at the beginning of the season is required. If no data are available, the model will calculate an equilibrium hydraulic profile (total potential = matric + gravitational = constant) from an input value of subsoil water content. If there is no measurement or other desired assumption, the value may be set arbitrarily (field capacity at maximum depth and hydraulic equilibrium for spring conditions).

Ground Cover. Vegetation and soil surface cover on the site are characterized in the model by five cover coefficients. These variables represent the distribution of transplanted seedlings, grasses and forbs, shrubs, litter and mulch, and bare soil. Cover values are visually estimated as a percentage of total site area.

It is expected that the cover percentages will always be input by the user, while root distribution and water use characteristics have default values available in the model. In the absence of available data, root depths are set to 0.25 m for seedlings, 0.18 m for grasses and forbs, and the the depth of the soil profile for shrubs. Total root depth is divided into four equal depth increments and the root density profile is set to 40%, at the soil surface, 30%, 20%, and 10%
Minimum plant water potential, the point at which transpiration is limited by the plant, is set to -1500 J kg\(^{-1}\). Other estimates of this water use characteristic may be obtained in Lopushinsky and Klock (1974) for several forest tree species.

Output Data Types

A summary of types of output data provided by the model is shown in Table 4. The minimum output of the model is a summary of water balance components: evaporation from bare soil surface, transpiration by vegetation type, drainage out of the soil profile, precipitation, and soil water storage. The units of water loss for general applications are cm, in deference to common usage (SI units for water loss are m\(^3\) m\(^{-2}\)). The units of unsaturated hydraulic conductivity for general use are cm hr\(^{-1}\) (SI units are kg s m\(^{-3}\)); time increments in the model are measured in hours. The program code is organized to make modification of output or units a simple matter for the user.

Other calculations of the model can be output for recordkeeping or specific additional analyses. Three parameters commonly used to predict site conditions for seedling growth and survival are: plant available water, the ratio of plant available water to the available water capacity, and the transpiration ratio (T/TP). Although the model calculates all three, the transpiration ratio is the best representation of the dynamic conditions that result in plant moisture stress (Denmead and Shaw, 1962). The transpiration ratio is related to
Table 4. Output data types

<table>
<thead>
<tr>
<th>OUTPUT</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar radiation:</td>
<td></td>
</tr>
<tr>
<td>Direct</td>
<td>MJ m(^{-2})</td>
</tr>
<tr>
<td>Diffuse</td>
<td>MJ m(^{-2})</td>
</tr>
<tr>
<td>Precipitation (m(^3) m(^{-2}))</td>
<td>cm</td>
</tr>
<tr>
<td>Evapotranspiration calculations</td>
<td></td>
</tr>
<tr>
<td>Potential evapotranspiration (m(^3) m(^{-2}))</td>
<td>cm</td>
</tr>
<tr>
<td>Potential evaporation (m(^3) m(^{-2}))</td>
<td>cm</td>
</tr>
<tr>
<td>Potential transpiration (m(^3) m(^{-2}))</td>
<td>cm</td>
</tr>
<tr>
<td>Water loss components:</td>
<td></td>
</tr>
<tr>
<td>Evaporation from bare soil surface (m(^3) m(^{-2}))</td>
<td>cm</td>
</tr>
<tr>
<td>Transpiration by seedlings (m(^3) m(^{-2}))</td>
<td>cm</td>
</tr>
<tr>
<td>Transpiration by grass and forbs (m(^3) m(^{-2}))</td>
<td>cm</td>
</tr>
<tr>
<td>Transpiration by shrubs (m(^3) m(^{-2}))</td>
<td>cm</td>
</tr>
<tr>
<td>Drainage (m(^3) m(^{-2}))</td>
<td>cm</td>
</tr>
<tr>
<td>Soil water storage:</td>
<td></td>
</tr>
<tr>
<td>Soil water content depth profile</td>
<td>m(^3) m(^{-1})</td>
</tr>
<tr>
<td>Soil water potential depth profile</td>
<td>J kg(^{-1})</td>
</tr>
<tr>
<td>Unsaturated hydraulic conductivity (kg s m(^{-3}))</td>
<td>cm hr(^{-1})</td>
</tr>
<tr>
<td>Other parameters:</td>
<td></td>
</tr>
<tr>
<td>Available water (m(^3) m(^{-3}))</td>
<td>cm</td>
</tr>
<tr>
<td>Available water/ available water capacity</td>
<td></td>
</tr>
<tr>
<td>Transpiration ratio (actual/potential)</td>
<td></td>
</tr>
</tbody>
</table>
all of the soil and plant variables used in equation 5 to calculate actual transpiration, as well as the climatic and plant variables in Eq. 1a-le and Eq. 3 for the estimate of potential transpiration. Moisture stress and reduced growth are the outcome of water supply that is less than potential demand (T/TP less than one), rather than an independent result of limited supply or high demand.
INITIAL TEST OF VALIDITY

The initial test of validity is done to confirm that theory and assumptions of the model provide a reasonable approximation of the system. Model calculations of cumulative water loss are compared to measured values from a detailed field study of the environmental effects of site management practices (Flint, 1985). Model estimates of water loss partitioning and transpiration ratio are compared to partitioning and growth analyses from the field report.

The Field Study

Methods. The field study was conducted near Wolf Creek in southwest Oregon (Flint and Childs, 1986). The overall study was the basis for the thesis of Flint (1985) where further detail is provided. In a randomized experimental design, five hundred bareroot Douglas-fir seedlings were planted in spring, 1982. Measurements of transpiration, growth, site water loss, and meteorological variables were made during two consecutive growing seasons. The weather was mild, with no extreme temperature events, and survival of planted seedlings was greater than 95%.

Twelve treatments were established including currently used operational techniques for controlling high soil temperatures or water loss. A group of untreated seedling locations was used as an
experimental control. Soil water loss was measured to a depth of 0.6 m (or shallower bedrock) using the gamma ray attenuation technique. Results from four treatments are modeled here: control, mulch, surface scalp, and herbicide. These were selected because they show the range of treatment effects on soil water loss, and the other treatments had primary effects on the soil temperature environment rather than soil water.

The mulch treatment consisted of 0.76 m x 0.76 m plastic that was used to reduce competing vegetation and surface evaporation. In the scalp treatment the soil surface layer and accompanying vegetation were scraped away in a 1.2 m x 1.2 m area around the seedling. This eliminated most competing vegetation, but slash and surface litter were also removed. In the herbicide treatment a 3.3 m x 3.3 m area was sprayed to eliminate competing vegetation, leaving slash and litter intact. The variation in area treated corresponds with standard management techniques.

Results. The 1983 field data indicate that these treatments significantly affected water use over the growing season (Figure 5a). The mulch, scalp, and herbicide treatments decreased water loss by reducing competition from grass and shrubs. Lower water loss by the herbicide treatment relative to the scalp indicates the effectiveness of an undisturbed soil surface layer in controlling evaporation. Although the mulch could control evaporation more effectively, it was not as effective at reducing competition because of physical deterioration and lateral invasion of competing root systems.
Figure 5. a) Field measurements for test of validity.

b) Comparison of model estimates for test of validity. Data points are the measured values. Lines are drawn between the calculated values (points omitted) for each measurement date. Mean square errors for control, mulch, scalp, and herbicide are 0.16, 0.09, 0.04, and 0.11, respectively.
The study concluded that competing vegetation is the most important influence on water available to seedlings, and that surface evaporation is also clearly important. Partitioning of water among seedling, competing vegetation, and soil surface evaporation was important in explaining growth differences among treatments. This was demonstrated by water use efficiencies, calculated as seedling shoot volume divided by water loss. The herbicide treatment demonstrated the best growth and highest water use efficiency. In addition to conserving water, this treatment allocated water to seedlings most effectively.

Input Parameter Estimates

The Wolf Creek site is located at 42 degrees north latitude, 123 degrees west longitude, and 715 m elevation. The site slopes 17 degrees at 190 degrees aspect. Precipitation and air temperature data were supplied from site measurements. Solar radiation was calculated using the model subroutine previously described.

The soil is a moderately deep, loamy-skeletal, mixed, Typic Xerocrept of 0.65 m average depth. Estimated average rock fragment content was 35 %; estimated rock fragment porosity was 15 %. The initial water content profile was calculated from an estimate of water potential at the bottom of the profile: $-60 \text{ J kg}^{-1}$. (Analysis of model results showed that this parameter should be known or calibrated, so
adjustment of an original estimate of \(-30 \text{ J kg}^{-1}\) was made which improved accuracy).

Cover percentages for each treatment were obtained from the author of the field study report (Flint, 1985), based on notes from periodic visual estimates of ground cover. The ground cover input values are shown in Table 3. Root depths were 0.25 m for seedlings, 0.18 m for grass, and 0.45 m for shrubs. Root profiles were given the model default values, and minimum plant water potential was set to \(-1200 \text{ J kg}^{-1}\).

**Simulation Results**

Model estimates of cumulative water loss for the control, mulch, scalp, and herbicide plots are compared with measured data in Figure 5b. These are in generally good agreement. The relative patterns of water loss are the same and magnitudes are similar (mean square errors range from 0.04 to 0.16). Where lack of fit occurs, the model estimate was usually higher than the measured value. Model simplifications of climatic characteristics, soil hydraulic properties, and plant responses are undoubtedly responsible. A plant growth subroutine could be added to reduce the tendency of the model to overestimate plant water use early in the season. The overall goodness of fit, however, indicates that primary influences on the system are well represented.

The model is designed to provide additional information that cannot be directly measured. An example is the partitioning of water
loss among seedlings, competing vegetation, and evaporation (Figure 6). The analysis supports the qualitative conclusions of the field study that: 1) competing vegetation was the most important site management factor, and 2) soil surface evaporation was also an important mechanism for water loss on the reforestation site.

The transpiration ratio for seedlings can be used to relate treatment effects on water loss to growth (Hanks, 1983). The ratio is less than one when soil water supply limits transpiration. This corresponds to stomatal closure and, presumably, decreased growth. The ranking of treatments according to T/TP (Figure 7) corresponds with the growth data of Flint (1986), which showed that the largest seedling diameters were recorded on the herbicide plot and the smallest on the control plot. Actual differences were not great for the mild season that occurred during this study.

Relative water use efficiency can also be determined by comparing total water loss with the transpiration ratio or growth. In the above results, the herbicide treatment demonstrated maximum water use efficiency; this experimental plot had the least amount of water loss and greatest seedling diameters, thus demonstrating the most productive allocation of water.
Figure 6. Partitioning of water loss on control site.
Figure 7. Transpiration ratio for site treatments.
SENSITIVITY ANALYSIS

The model sensitivity analysis is performed to show the relative importance of input parameters and to consider the effects of data error. These results indicate uses and limitations of the model.

Climate

Precipitation and evapotranspiration are major components of the water balance in Oregon forests where drainage is minimal in summer and runoff is limited to areas that have been severely disturbed. Evapotranspiration is more difficult to measure directly than rainfall and usually exceeds summer rainfall. Estimates of evapotranspiration are therefore a very important component of the model.

The modified Jensen-Haise method (Jensen et al., 1970) is used to estimate potential evapotranspiration. The data requirement is daily solar radiation, daily maximum and minimum air temperatures, and elevation. The sensitivity of each factor is shown in Table 5. A partial derivative is given for ETP with respect to each factor, which is a raw value of sensitivity. A range is given to indicate the magnitude and variation that could be expected for each input factor. Sensitivity is examined by choosing an arbitrary, but reasonable, value for input error and determining the effect of this error on the estimate of potential evapotranspiration. The resultant error column
Table 5. Sensitivity of the potential evapotranspiration calculations to errors in input values (Jensen-Haise, Eqs. 1a-1e).

Standard conditions used in calculations:
(Variables defined in Eqs. 1a-1e)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Partial derivative</th>
<th>Common range</th>
<th>Input error</th>
<th>ETP error (cm d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rs (MJ m⁻² d⁻¹)</td>
<td>0.23</td>
<td>5-35</td>
<td>5</td>
<td>0.12</td>
</tr>
<tr>
<td>Ta (C)</td>
<td>0.18</td>
<td>0-40</td>
<td>5</td>
<td>0.09</td>
</tr>
<tr>
<td>Constant:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT</td>
<td>320</td>
<td>0.015-0.025</td>
<td>0.005</td>
<td>0.16</td>
</tr>
<tr>
<td>TX</td>
<td>-0.18</td>
<td>0-(-10)</td>
<td>5</td>
<td>0.09</td>
</tr>
<tr>
<td>Calibration:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EL (m)</td>
<td>0.0007</td>
<td>0-2000</td>
<td>500</td>
<td>0.04</td>
</tr>
<tr>
<td>e2-el (kPa)</td>
<td>3.8</td>
<td>1-4</td>
<td>0.5</td>
<td>0.19</td>
</tr>
</tbody>
</table>

*Partial derivative of ETP with respect to one factor, evaluated with the remaining factors at standard conditions.

**Chosen arbitrarily from within the range to represent an error that could be made. Other possibilities can be tested by multiplying a sample input error by the partial derivative to obtain the error in ETP that would occur.
shows the relative importance of each input factor in producing error. Of the environmental factors, radiation is most sensitive, followed by temperature. The vapor deficit characteristic for calibration of the constants is more sensitive than elevation. Elevation may be easily obtained, but the vapor deficit characteristic must be estimated from temperature data. Although this source of error could be reduced by providing measured data for direct calibration, model predictions in the test of validity were successful using the simplified calibration method.

The effect of site position on summertime clear-sky radiation is shown in Figure 8a. These effects are well known (Lee, 1978). For the example of 42 degrees north latitude and 30 degree slopes, a north aspect receives less radiation than any other position. East and west are higher and not distinguishable from each other. The horizontal position and south aspect have the highest values; these two exhibit a change in relative rank over the season. In June the horizontal position receives greater total radiation than south due to high sun angle and a longer solar day. These effects diminish following the summer solstice, and in August the south slope receives the greatest total radiation. Timing also contributes to the relative harshness of south slopes; in Oregon, solar radiation load in August is accompanied by maximum seasonal temperature and minimum seasonal soil water supply.

Differences in the water balance of east and west slopes are due to timing. In the model, the distinction between east and west is based on the timing of radiation with respect to the diurnal cycle of air temperature (Figure 8b). Total radiation on the east slope is received earlier in the day, coinciding with lower temperatures.
Figure 8. a) Effect of site position on calculated radiation.
   b) Timing of daily radiation on east and west slopes and the relation to diurnal air temperature.
   c) Effect of site position on potential evapotranspiration.
   Calculated by the Jensen-Haise method with radiation from Figure 8a and temperatures from NOAA Sexton Summit.
Radiation on the west slope is received later in the day and so coincides with higher temperatures. Radiation and temperature are both sensitive factors in the calculation of potential evapotranspiration.

The influence of site position on summer potential evapotranspiration is shown in Figure 8c. The climatic characteristics of east and west are now represented in the model as a function of two interacting variables, radiation and temperature. Potential evapotranspiration on the west slope is greater than east throughout the season; west is also greater than south early in the season due to the effect of temperature. In August, the south slope is the most severe position of all (as in Figure 8a).

Potential radiation and potential evapotranspiration estimates are the first step in evaluating water loss. Actual water loss as a function of slope and aspect follows the same patterns but the magnitude of the effect is often diminished (Satterlund, 1981) by: 1) sky cover, which reduces direct beam and increases diffuse radiation, and 2) limited water supply, affected by soil factors and precipitation.

General climatic variation with time and space is considered in the two comparisons in Table 6. The first is an example of temporal variability. Weather data from Sexton Summit (NOAA station) were used to contrast the water balance during two summer growing seasons: 1981 was a moderately harsh year, while 1983 represented a mild year for this region due to high precipitation. If a field study was conducted at Sexton Summit in 1983, the seasonal potential evapotranspiration would be within 15% of that in 1981. Precipitation in 1983 was 10 cm more than in 1981. This factor alone presents a very different system
Table 6. Comparison of environmental conditions and soil water balance for different years and different, but nearby, sites.

<table>
<thead>
<tr>
<th>Climate Data</th>
<th>Environment</th>
<th>Water balance</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rs $\text{MJ} \text{m}^{-2}$</td>
<td>ETP $\text{cm}$</td>
<td>PPT $\text{cm}$</td>
<td>- ET $\text{cm}$</td>
<td>- DR $\text{cm}$</td>
</tr>
<tr>
<td>SEXTON SUMMIT 1981</td>
<td>1767</td>
<td>34</td>
<td>3.63</td>
<td>6.27</td>
<td>0.78</td>
</tr>
<tr>
<td>SEXTON SUMMIT 1983</td>
<td>1609</td>
<td>29</td>
<td>13.87</td>
<td>10.55</td>
<td>3.44</td>
</tr>
<tr>
<td>Difference</td>
<td>158</td>
<td>5</td>
<td>-10.24</td>
<td>-4.28</td>
<td>-2.66</td>
</tr>
<tr>
<td>% Rel. Diff.</td>
<td>9</td>
<td>15</td>
<td>-282</td>
<td>-68</td>
<td>-341</td>
</tr>
<tr>
<td>WOLF CREEK 1983</td>
<td>1746</td>
<td>32</td>
<td>4.60</td>
<td>6.46</td>
<td>0.08</td>
</tr>
<tr>
<td>SEXTON SUMMIT 1983</td>
<td>1609</td>
<td>29</td>
<td>13.87</td>
<td>10.55</td>
<td>3.44</td>
</tr>
<tr>
<td>Difference</td>
<td>137</td>
<td>3</td>
<td>-9.278</td>
<td>-4.09</td>
<td>-3.38</td>
</tr>
<tr>
<td>% Rel. Diff.</td>
<td>8</td>
<td>9</td>
<td>-201</td>
<td>-63</td>
<td>-4225</td>
</tr>
</tbody>
</table>

Rs = solar radiation; ETP = potential evapotranspiration
PPT = precipitation; ET = evapotranspiration; DR = drainage
*($(a-b)/a$)
for soil-plant-atmosphere interaction. 1983 did not have the water limited conditions that produce moisture stress.

Differences in precipitation also made it impossible to extrapolate data from the Sexton Summit NOAA weather station to the nearby Wolf Creek site. Seasonal potential evapotranspiration at the Wolf Creek site was less than 10% different, but actual evapotranspiration was 63% less than predicted by the extrapolation due to water supply conditions. These results indicate that on-site precipitation data are required if the model is to be used to accurately predict water balance components.

If the model is used for a relative ranking of sites, it is only necessary to select weather data from a year on record that represents the conditions of interest such as a harsh, average, or mild year. Another option would be to repeat model simulations with several years of weather data; this approach would indicate the probability of unfavorable site moisture conditions for reforestation.

Soil

Soil texture is used in the model to estimate soil hydraulic properties. Soil hydraulic properties determine plant available water in two ways: 1) by the amount of water in the "available" range of water potential (estimated by -30 J kg\(^{-1}\) to -1500 J kg\(^{-1}\)) and 2) by the maximum water supply rate at a given water potential (unsaturated hydraulic conductivity). Depth of the soil profile and the presence of
layers are the other soil factors that determine the effective magnitude and depth distribution of plant available water.

A series of model simulations were run with the inputs given in Table 3 and variations of the soil profile conditions. Results are shown in Table 7. For each soil texture profile a value for available water capacity is given to indicate the relative amount of water held in these soils on June 1. The next column is the first day that seedling transpiration becomes limited (T/TP less than 1). The five columns to the right are information provided by the model to describe water status on this day: T/TP, the ratio of available water to available water capacity (AW/AWC), water loss total, average water potential, and average hydraulic conductivity.

In the model, as in the natural soil-plant-atmosphere system, the soil water limited rate of water use is determined in the total plant environment. The T/TP ratio may therefore be considered an environmental parameter for plant moisture conditions. The other parameters in Table 7 are widely used soil water parameters. Their values in the table generally exhibit a high degree of variability among soils compared at nearly the same value of T/TP. The exception is unsaturated hydraulic conductivity. This column corresponds well with soil water limitations estimated by T/TP. Unsaturated hydraulic conductivity is perhaps a better single estimator of soil water availability than "available water".

As an example of the effect of texture, seedling transpiration became soil water limited in the sandy loam after 3 weeks. This condition occurred in the loam soil after 4 weeks. In the very coarse soils (loamy sand, sand) water supply is limited from the beginning of
Table 7. Effects of soil factors on water status and use. The date column indicates the first day on which water becomes limiting. The parameters following the date column are evaluated on this day.

<table>
<thead>
<tr>
<th>Texture</th>
<th>AWC</th>
<th>Date</th>
<th>T/TP</th>
<th>AW/AWC</th>
<th>Water loss total</th>
<th>Water potential</th>
<th>Hydraulic conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cm</td>
<td>J kg^-1</td>
<td>cm hr</td>
</tr>
<tr>
<td>UNIFORM PROFILE:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(depth= 60 cm, iwc at -30 J kg^-1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>clay</td>
<td>0.12</td>
<td>6.28</td>
<td>0.98</td>
<td>0.13</td>
<td>7.2</td>
<td>-1210</td>
<td>1E-7</td>
</tr>
<tr>
<td>silty clay</td>
<td>0.12</td>
<td>6.24</td>
<td>0.98</td>
<td>0.43</td>
<td>5.7</td>
<td>-420</td>
<td>1E-7</td>
</tr>
<tr>
<td>silty clay loam</td>
<td>0.14</td>
<td>6.28</td>
<td>0.99</td>
<td>0.37</td>
<td>6.5</td>
<td>-500</td>
<td>1E-7</td>
</tr>
<tr>
<td>clay loam</td>
<td>0.12</td>
<td>6.24</td>
<td>0.99</td>
<td>0.42</td>
<td>5.7</td>
<td>-430</td>
<td>1E-7</td>
</tr>
<tr>
<td>sandy clay loam</td>
<td>0.12</td>
<td>6.24</td>
<td>0.99</td>
<td>0.38</td>
<td>6.9</td>
<td>-480</td>
<td>2E-7</td>
</tr>
<tr>
<td>loam</td>
<td>0.14</td>
<td>6.28</td>
<td>0.99</td>
<td>0.33</td>
<td>6.7</td>
<td>-520</td>
<td>1E-7</td>
</tr>
<tr>
<td>silt loam</td>
<td>0.16</td>
<td>6.29</td>
<td>0.98</td>
<td>0.09</td>
<td>7.8</td>
<td>-1250</td>
<td>2E-7</td>
</tr>
<tr>
<td>sandy loam</td>
<td>0.10</td>
<td>6.21</td>
<td>0.98</td>
<td>0.56</td>
<td>4.3</td>
<td>-230</td>
<td>1E-7</td>
</tr>
<tr>
<td>loamy sand</td>
<td>0.08</td>
<td>6.03</td>
<td>0.99</td>
<td>0.81</td>
<td>0.6</td>
<td>-80</td>
<td>9E-8</td>
</tr>
<tr>
<td>sand</td>
<td>0.04</td>
<td>6.01</td>
<td>0.22</td>
<td>0.98</td>
<td>0.1</td>
<td>-40</td>
<td>7E-9</td>
</tr>
<tr>
<td>LAYERED PROFILE:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s1/scl/s1</td>
<td>0.11</td>
<td>6.24</td>
<td>0.97</td>
<td>0.43</td>
<td>5.1</td>
<td>-530</td>
<td>1E-7</td>
</tr>
<tr>
<td>DEEPER SOIL PROFILE:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(depth= 100 cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sandy loam</td>
<td>0.10</td>
<td>6.21</td>
<td>0.99</td>
<td>0.77</td>
<td>4.3</td>
<td>-220</td>
<td>1E-7</td>
</tr>
<tr>
<td>WETTER INITIAL WATER CONTENT:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iwc= 0.25 at -10 J kg^-1 (vs. 0.21 above)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sandy loam</td>
<td>0.14</td>
<td>6.28</td>
<td>0.98</td>
<td>0.39</td>
<td>6.1</td>
<td>-290</td>
<td>7E-8</td>
</tr>
</tbody>
</table>

AWC= available water capacity; AW= available water
iwc= initial water content
the growing season. The error associated with estimating texture is indicated by these comparisons. An additional week of non-limiting moisture conditions is significant to seedling establishment, so the differentiation of a sandy loam from a loam would be important in a model simulation. In some cases, differences between textures are less significant than in the above example. Missing texture by 1 class between a clay loam and a sandy clay loam would not make a difference in the date of initial water limitation. Extended water use patterns, however, could differ because the sandy clay loam has a higher water loss total on this date and has used a greater percentage of available water capacity. When water is nearly depleted from the sandy clay loam, the supply rate will rapidly diminish to a negligible value.

An example of the effect of missing a layer of clay accumulation in the profile is given by comparing the layered profile with the uniform sandy loam. In this case, the onset of water limited conditions was delayed several days by the presence of a sandy clay loam layer in the root zone. The effects of other variations of soil layers cannot be generalized from this example because they are conditional upon hydraulic properties, position of the layer, root distributions, and seasonal climatic patterns. Layers should be identified as accurately as possible in the field because of these interactions.

Soil depth variation produced expected results. An increase in total soil depth increased total available water as a result of the greater storage volume. Greater amounts of stored water will benefit the seedling if the supply rate is not severely limited. If the rate of drying is moderate, hydraulic conductivity can be maintained at a
higher rate and the deeper soil can maintain water supply for a longer period of time than the shallow soil. Also, the effect of restrictive soil layers on the redistribution of soil water is important when much of the storage volume is below the root zone.

Variation of the initial water content was simulated by assuming a higher estimate of field capacity, -10 J kg\(^{-1}\) versus -30 J kg\(^{-1}\), and beginning the season at this value. The result was a 1 week difference in the timing of initial water limitation for the seedlings. This indicates the importance of the estimate of field capacity, or initial water content, and demonstrates the possibility of significant error resulting from this estimate. The input for initial water conditions should therefore be based on representative estimates of field capacity for a soil series (Flint and Childs, 1984) or site measurements of initial water content profile.

**Ground Cover**

Seedling water use is typically a small component of water loss on reforestation sites (Figure 6); in the field study, competing vegetation was the largest component, followed by evaporation from bare soil. An example of the effect of competing vegetation in the model is shown in Figure 9a. Site conditions for the simulation were characterized by high potential evapotranspiration, 0.6 m loam soil, 10% seedling cover, and 10% slash cover. The figure shows estimates of total seasonal water use by each component where input cover
Figure 9. a) Effect of competing vegetation on partitioning of water loss.
   b) Effect of slash cover on partitioning of water loss.
percentages of competing vegetation are varied over a range of 0 to 60%.

The emergence of competing vegetation has an immediate effect on both total water loss and partitioning of water loss. Total water loss increases as the percentage of competing vegetation increases. There is a negative response by the seedlings, which are deprived of water as competition increases. The immediate effect is greatest (0 to 10% competing vegetation); this increment is also the easiest change in cover percentage to identify in the field. Once competing vegetation is well established, it becomes the major component of water loss and the estimate of cover is not critical within a 10% margin of error.

An example of the effect of soil surface cover is shown in Figure 9b. Climate and soil conditions are unchanged from the previous figure. For this test the competing vegetation factor remained a constant 10%, while the percentage of slash left after harvest is increased over the range of 0 to 60%. Seasonal water loss estimates show that as slash cover increases the evaporation component decreases and total water loss decreases. This results in a favorable response by the seedlings, which used a little more water. The soil surface cover input is less sensitive than vegetation because water supply is limited and water is only extracted at the soil surface (less effective than well distributed roots). The range of greater sensitivity is at high slash cover percentage; therefore, a benefit to seedling water supply can only be obtained by leaving a large amount of slash on a reforestation site.

The error resulting from poor precision in visually estimating the ground cover percentages (Figures 9a and 9b) should not be a problem. The average effect of a 10% increase in any estimate is not very great
for the given conditions, which include high potential evapotranspiration and limited water. This can be explained by considering the two limits on water loss, water and energy. The input cover percentages directly affect potential evaporation or potential transpiration, which represent available energy. For the dry summer climate being discussed, the water supply rate is exerting a dominant influence on the actual values of evaporation and transpiration.

The root distribution inputs for site vegetation can only be roughly estimated; however, some visual inspection is possible when a pit is dug for the soil profile description. The transplanted seedling is the most predictable, its depth having been determined by nursery processing. In the model default values, seedling roots are described by a 0.25 m depth and a distribution profile over depth of 40%, 30%, 20%, and 10%. A hypothesis is given for grass to 0.18 m depth with a vertical profile and shrubs to 0.40 m depth with a profile of 20%, 40%, 30%, and 10%.

The effect of variation of the root depth and profile input data are shown in Table 8. Values for the remaining inputs were obtained from Table 3 (cover percentages are from the control column in Table 3). Changes in transpiration ratio, absolute transpiration, and total site water loss are given for different root distributions representing combinations of root depth and profile. Greater root depth increased all output values as expected. The seasonal transpiration ratio for a seedling with roots to 0.40 m depth was 34% higher than one with roots to 0.18 m depth. One root profile comparison produced no significant difference although another, the
Table 8. Effect of plant root distribution on water status and use.

<table>
<thead>
<tr>
<th>Root distribution</th>
<th>T/TP</th>
<th>Transpiration (cm)</th>
<th>Total water loss (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>--- seasonal cumulative ---</td>
</tr>
<tr>
<td><strong>Depth</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) 0.18 m</td>
<td>0.35</td>
<td>2.38</td>
<td>5.62</td>
</tr>
<tr>
<td>b) 0.25 m</td>
<td>0.40</td>
<td>2.74</td>
<td>6.01</td>
</tr>
<tr>
<td>c) 0.40 m</td>
<td>0.47</td>
<td>3.21</td>
<td>6.51</td>
</tr>
<tr>
<td><strong>Profile</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d) 25/25/25/25%</td>
<td>0.47</td>
<td>3.20</td>
<td>6.44</td>
</tr>
<tr>
<td>e) 40/30/20/10%</td>
<td>0.40</td>
<td>2.74</td>
<td>6.01</td>
</tr>
<tr>
<td>f) 20/40/30/10%</td>
<td>0.40</td>
<td>2.72</td>
<td>6.02</td>
</tr>
<tr>
<td><strong>Seedling</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>2.74</td>
<td>6.01</td>
</tr>
<tr>
<td>(depth b, profile e)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Grass</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.39</td>
<td>2.67</td>
<td>5.87</td>
</tr>
<tr>
<td>(depth b, profile e)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Shrubs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.47</td>
<td>3.17</td>
<td>6.53</td>
</tr>
<tr>
<td>(depth b, profile e)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* (profile: e)

** (depth: b)
vertical profile, did show a difference because of more roots in the bottom increment where more water was available.

Variation of the minimum plant water potential within a common range is not critical in the model. For instance, the value might be estimated to be -1500 J kg\(^{-1}\) or as low as -3000 J kg\(^{-1}\). This represents about a 1% difference in water content for a sandy loam texture, so a reasonable estimate of the input suffices.
SUMMARY AND CONCLUSIONS

A mathematical model of the soil water balance has been summarized which is appropriate to the scale of reforestation planning and field management. The processes that define the water balance have been treated in five component methods: 1) An estimate of potential evapotranspiration using the energy-based Jensen-Haise method, 2) Partitioning of evapotranspiration from estimates of percentage cover by vegetation type and soil surface cover, 3) Actual evaporation at the soil surface, 4) Actual transpiration from calculations of soil water supply limit and the Nimah-Hanks uptake method, and 5) Soil water flow, including redistribution and drainage.

Variables in the soil-plant-atmosphere system which influence the soil water balance are represented by three categories: climate, soil, and ground cover. Data for these variables are required to solve equations in the component methods above. A major concern in model development is the simplification of the data requirement to suit the intended use of the model. This simplification was achieved without eliminating components that are important in applications of the model.

Three relevant features were included to suit reforestation applications specifically: 1) Calculation of evapotranspiration with the effects of slope, aspect, and elevation included. 2) A layered soil technique to account for different hydraulic characteristics within the soil profile. 3) Evaluation of surface effects (slash, mulch, and litter) and competition (grasses, forbs, and shrubs),
because they vary among individual sites and manipulation of ground cover is a major reforestation concern.

The input data necessary to characterize the environment and produce satisfactory results was assessed in a sensitivity analysis. Several options are possible depending on the expected level of model performance (Table 9). The maximum data requirement includes representative site measurements of climatic parameters and soil hydraulic properties. If these data are available, accurate prediction of water balance components, such as actual evaporation and transpiration, is possible. The minimum data requirement for identification of harsh sites and potential water-limiting conditions assumes that sites can be visited for an inspection of topography, soil profile, and ground cover. This information would be adequate for a relative ranking of specific sites with regard to the probability of reforestation success. The temporal and spatial variability of precipitation is the greatest limit on the predictive ability of this option. If no data are available, the model can still be used to evaluate reasonable hypotheses. The most important inputs could be estimated, based on selected assumptions, and model default values could be used for parameters that do not vary greatly. This approach can be used to assess management options in advance planning.

Output of the model includes estimates of solar radiation, soil water storage, total water loss, and water allocation. To test the validity of model output, calculations of water loss were compared to measured values from a detailed field study of the environmental effects of site management practices. The results confirm that the model performs reasonably well and that theory and assumptions of the
Table 9. Data options for the model input requirement.

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>MAXIMUM predictive</th>
<th>MINIMUM predictive</th>
<th>NO DATA comparative</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M=measured E=estimated A=assumed)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Climate:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Radiation:</td>
<td>M</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>Latitude</td>
<td>M</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>Longitude</td>
<td>E</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>M</td>
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</tr>
<tr>
<td>Aspect</td>
<td>M</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Elevation</td>
<td>E</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Sky cover</td>
<td>M</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Air Temperature:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>M</td>
<td>M</td>
<td>A</td>
</tr>
<tr>
<td>Minimum</td>
<td>M</td>
<td>M</td>
<td>A</td>
</tr>
<tr>
<td>Precipitation</td>
<td>M</td>
<td>M</td>
<td>A</td>
</tr>
<tr>
<td><strong>Soil:</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Master horizons:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic properties</td>
<td>M</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>Texture</td>
<td></td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>Depth</td>
<td>M</td>
<td>M</td>
<td>A</td>
</tr>
<tr>
<td>Rock fragment volume</td>
<td>M</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>Initial water content</td>
<td>M</td>
<td>M</td>
<td>A</td>
</tr>
<tr>
<td><strong>Ground Cover:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cover percentages:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slash or mulch</td>
<td>M</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>Seedlings</td>
<td>M</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>Grass and forbs</td>
<td>M</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>Shrubs</td>
<td>M</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>Bare soil</td>
<td>M</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td><strong>Vegetation Characteristics:</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Seedling root depth</td>
<td>M</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>Grass root depth</td>
<td>M</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>Shrub root depth</td>
<td>M</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>Root profiles</td>
<td>E</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>Minimum plant water potential</td>
<td>E</td>
<td>E</td>
<td>A</td>
</tr>
</tbody>
</table>
model are appropriate. Although model simplifications (of climate, soil, and plant characteristics) resulted in slightly higher estimates than measured values on several dates, the overall fit indicates that primary influences on the system are well represented.

The test of validity is an initial evaluation, which is done prior to a more extensive validation of the model. Comparison of model estimates with measured data must be performed for a full range of site conditions before the model can be widely applied by managers. These tests are usually conducted for each region in which the model will be applied. A cooperative research project begun in 1985 is nearing completion that will validate the model for use in the Pacific Northwest.
REFERENCES


Denmead, O.T. and R.H. Shaw. 1962. Availability of soil water to


Some measured and simulated plant water relations of yellow-poplar. Forest Sci. 24:327-341.


APPENDICES
Appendix I. Program listing.

10 '***********************************************************************
20 'SOIL WATER BALANCE PROGRAM: FILENAME "SOILWAT.BAS"  *****
30 '***********************************************************************
40 'OPENING ROUTINE
50
60 DIM B(13),B1(13),BR(13),C(13),CC$(9),CD$(9),CO(3),CP(13)
70 DIM D(13),DF(3,13),HW(3),ID(13),K(13),KS(13),LB(13),N(13),N1(13)
80 DIM P(13),PE(13),PH(13),PN(13),RD(3),RFV(13),RP(3,4),SC(13)
90 DIM TH(13),TL(13),TX$(12),T(3,13),TBD(13),TOV(10)
100 DIM TPL(3),TPD(3),TPW(3),TPS(3) 110 DIM TAL(3),TAD(3),TAW(3),TAS(3)
120 DIM UI(13),US(3),V(13),W(13),WFC(13),WS(13),WWP(13),XH(13),Z(13)
130 DEF FNV(T)-6.11*EXP(17.27*T/(237.3+T))
140 DEF FNC(F)-5/9*(F-32)
150 DEF FNM(EL)-((288-.0065*EL)/288)^.5256
160 DEF FNS(E,E1)-E+(E1-E)*DM/(ID(M0)-ID(M0-1))
170 GOSUB 3470
180 GOSUB 3950
190 IF BS-1 THEN GOTO 4110
200 PRINT"***** SOIL WATER BALANCE PROGRAM  *****";LEFT$(DATE$,12)
210
220 '***********************************************************************
230 'INPUT CLIMATE, SOIL, AND GROUND COVER DATA  *****
240 '***********************************************************************
250
260 'CLIMATE ENTRIES
270 CLS
280 INPUT"START OF GROWTH SEASON (MM.DD)";D1
290 INPUT"END OF GROWTH SEASON (MM.DD)";D2
300 PRINT " 1 - CAVE JUNCTION 1981 1280 FT. JOSEPHINE CO."
310 PRINT " 2 - SEXTON SUMMIT '81 3836 FT. JOSEPHINE CO."
320 PRINT " 3 - RUCH '81 1550 FT. JACKSON CO."
330 PRINT " 4 - PROSPECT '81 2485 FT. JACKSON CO."
340 PRINT " 5 - HOWARD PRAIRIE '81 4567 FT. JACKSON CO."
350 PRINT " 6 - WOLF CREEK 1983 2346 FT."
360 PRINT " 7 - SEXTON SUMMIT '83 3836 FT."
370 INPUT" ENTER NUMBER OF REPRESENTATIVE CLIMATE ";CLIM
371 INPUT"SLOPE (%)";SL: INPUT"ASPECT (DEGREES)";AZ
380 GOSUB 410: GOTO 660
390 GOSUB 410: GOTO 660
400 'CLIMATE INITIALIZATION SUBROUTINE
410"DAY-D1;GOSUB 3920:J1-JND: DAY-D2;GOSUB 3920:J2-JND
420 JJ+(J2-J1-1)/7:IF JJ>FIX(JJ) THEN JJ=FIX(JJ)+1
430 JJ=J2+7*JJ-1
440 OPEN "I",2,CD$(CLIM)
450 IF TOV= 1 THEN OPEN "I",4,"RAINRAD"
460 IF TOV= 1 THEN OPEN "I",4,"RAINRAD"
470 IF TOV= 1 THEN OPEN "I",4,"RAINRAD"
480 IF TOV= 1 THEN OPEN "I",4,"RAINRAD"
490 IF TOV= 1 THEN OPEN "I",4,"RAINRAD"
500 IF TOV= 1 THEN OPEN "I",4,"RAINRAD"
510 IF TOV= 1 THEN OPEN "I",4,"RAINRAD"
520 IF TOV= 1 THEN OPEN "I",4,"RAINRAD"
530 LA=42.43 :LN=123.17 :EL=2346 :H8=79.3 :L8=55.2 :GOTO 540
540 EL=EL*:3048 :H8=FNC(H8) :L8=FNC(L8)
560 ' (SOLRAD)
570 Q1=CO(SL) :Q2=CO(SL) :Q3=CO(SL)+Q1*CO(SL)
580 Q4=Q2*CO(SL)+Q1*CO(SL)+Q5=CO(SL)
590 NOON=12+LN*RAD/15-15-1-1/(C1+7.3*CH)
600 (JENSEN-HAISE COEFFICIENTS)
610 V1=FNV(L8):V2=FNV(H8)
620 C1=38-2*EL/305:CH=50/(V2-V1):CT=1/(C1+7.3*CH)
630 TX=2.5-.14*(V2-V1)-EL/550
640 RETURN
650 'SOIL ENTRIES
660 CLS
670 INPUT"LOWER BOUNDARY OF THE A HORIZON (CM) ";AD
680 INPUT"LOWER BOUNDARY OF B (CM) ";BD
690 INPUT"LOWER BOUNDARY OF C (CM) ";CD
700 PRINT "TEXTURE (SOIL WATER PROPERTIES)"
710 PRINT "1. CLAY"
720 PRINT "2. SILTY CLAY"
730 PRINT "3. SILTY CLAY LOAM"
740 PRINT "4. CLAY LOAM"
750 PRINT "5. SANDY CLAY LOAM"
760 PRINT "6. LOAM"
770 PRINT "6. Silt Loam"
780 PRINT "7. Silt Loam"
790 PRINT "8. SANDY LOAM"
800 PRINT "9. LOAMY SAND"
810 PRINT "10. SAND"
820 INPUT"TEXTURE OF HORIZON A";AX
830 INPUT"ROCK FRAGMENTS (% VOL.) HORIZON A";RFVA
840 INPUT"TEXTURE OF HORIZON B";BX
850 INPUT"ROCK FRAGMENTS (% VOL.) HORIZON B";RFVB
860 INPUT"TEXTURE OF HORIZON C";CX
870 INPUT"ROCK FRAGMENTS (% VOL.) HORIZON C";RFVC
880 INPUT"INITIAL WATER POTENTIAL AT BOTTOM OF PROFILE, BAR ";IWCM
890 IWCM=ABS(IWCM) 850 GOSUB 870: GOTO 1250
900 'SOIL INITIALIZATION SUBROUTINE
910 RFP=.17 'ROCK FRAGMENT POROSITY
920 K=INT(SQR(AD)):L=INT(SQR(BD)):M=INT(SQR(CD))
930 FOR I=0 TO M+1:Z(I)-IA2:NEXT
940 FOR I=1 TO M:V(I)-(Z(I+1)-Z(I-1))/2: LB(I)-V(I)+LB(I-1): NEXT
950 XX-AX :FOR I=1 TO K :GOSUB 1120 :RFV(I)- RFVA: NEXT
960 XX-BX :FOR I=K+1 TO L :GOSUB 1120 :RFV(I)- RFVB: NEXT
970 XX-CX :FOR I=L+1 TO M :GOSUB 1120 :RFV(I)- RFVC: NEXT
980 TAWCT=0
990 FOR I=1 TO M
1000 IF RFV(I)>1 THEN RFV(I)-RFV(I)/100
1010 KS(I)=KS(I)*(1-(1-RFP/WS(I))*RFV(I))
1020 WS(I)=WS(I)*(1-(1-RFP/WS(I))*RFV(I))
1030 B1(I)=1/BR(I) :N(I)=2+3/BR(I) :N1(I)=1-N(I)
1040 WFC(I)=WS(I)*(PE(I)/(-300-(Z(M)-Z(I))*GR))AB1(I)
1050 WWP(I)=WS(I)*(PE(I)/(-15000-(Z(M)-Z(I))*GR))AB1(I)
1060 TAWCT-TAWCT+(WFC(I)-WWP(I))*V(I)
1070 NEXT
1080 RETURN
1090 'INITIAL SOIL WATER PROFILE
1100 P(M)=IWCM*10000 :SW=0
1110 FOR I=1 TO M
P(I) = P(M) - (Z(M) - Z(I)) * GR: PN(I) = P(I); PH(I) = P(I)

W(I) = (PE(I) / P(I)) * B(I) * WS(I): SW = SW + W(I) * V(I)

NEXT: IW = SW

RETURN

' (PHYSICAL PROPERTIES DATA SUBROUTINE)

ON XX GOTO 1140, 1150, 1160, 1170, 1180, 1190, 1200, 1210, 1220, 1230

PE(I) = -48.4: BR(I) = 11.7: WS(I) = .52: KS(I) = 3600 * .000069: RETURN

PE(I) = -21.2: BR(I) = 10.1: WS(I) = .5: KS(I) = 3600 * .000038: RETURN

PE(I) = -25.4: BR(I) = 7.5: WS(I) = .48: KS(I) = 3600 * .000047: RETURN

PE(I) = -15.9: BR(I) = 8.5: WS(I) = .47: KS(I) = 3600 * .00011: RETURN

PE(I) = -12.4: BR(I) = 7.5: WS(I) = .45: KS(I) = 3600 * .00038: RETURN

PE(I) = -22.5: BR(I) = 5.4: WS(I) = .43: KS(I) = 3600 * .00018: RETURN

PE(I) = -21.2: BR(I) = 10.1: WS(I) = .41: KS(I) = 3600 * .00007: RETURN

PE(I) = -5.5: BR(I) = 6.3: WS(I) = .39: KS(I) = 3600 * .00047: RETURN

PE(I) = -1.6: BR(I) = 5.6: WS(I) = .38: KS(I) = 3600 * .001: RETURN

PE(I) = -.5: BR(I) = 4.1: WS(I) = .36: KS(I) = 3600 * .0014: RETURN

1240 ' GROUND COVER ENTRIES

1260 CLS

1270 INPUT "% SLASH COVER "; CO(0): IF CO(0)>1 THEN CO(0)=CO(0)/100

1280 INPUT "% SEEDLING COVER "; CO(1): IF CO(1)>1 THEN CO(1)=CO(1)/100

1290 INPUT "% EXPECTED GRASS COVER "; CO(2): IF CO(2)>1 THEN CO(2)=CO(2)/100

1300 INPUT "% EXPECTED SHRUB COVER "; CO(3): IF CO(3)>1 THEN CO(3)=CO(3)/100

1310 INPUT "ROOT DEPTH OF TREE SEEDLINGS (CM) "; RD(1)

1320 INPUT "ROOT DEPTH OF GRASS (CM) "; RD(2)

1330 INPUT "ROOT DEPTH OF SHRUBS (CM) "; RD(3)

1340 'INPUT" MINIMUM ALLOWABLE PLANT WATER POTENTIAL (-BARS) "; HW

1350 'INPUT" BASAL AREA OF SHELTER TREES, M2/HA "; BA

1360 GOSUB 1380: GOTO 1570

1370 ' GROUND COVER Initialization SUBROUTINE

1390 ' (COVER)

1400 TC = CO(0)+CO(1)+CO(2)+CO(3)

1410 ' (ROOTS)

1420 FOR S = 1 TO 3: FOR I = 2 TO M: DF(S,I) = 0: NEXT: NEXT

1430 FOR S = 1 TO 3: QU = (RD(S)-2)/4: QZ = QU + 2: RZ = 2

1440 RP(1,1) = .25: RP(1,2) = .25: RP(1,3) = .25: RP(1,4) = .25

1450 RP(2,1) = .1: RP(2,2) = .4: RP(2,3) = .3: RP(2,4) = .2

1460 RP(3,1) = .1: RP(3,2) = .4: RP(3,3) = .3: RP(3,4) = .2

1470 R = 1 'ROOT DEPTH INCREMENT

1480 I = 2 'SOIL DEPTH INCREMENT

1490 IF LB(I) < QZ THEN DF(S,I) = DF(S,I) + (LB(I) - RZ) / QU * RP(S,R)

1491 : RP(S,R) = RP(S,R) * (1 - (LB(I) - RZ) / QU) : RZ = LB(I) : I = I + 1: GOTO 1490

1500 DF(S,I) = DF(S,I) + RP(S,R) : R = R + 1: IF R > 4 THEN NEXT S: GOTO 1530

1510 IF LB(I) < QZ THEN I = I + 1

1520 RZ = QZ: QZ = QZ + QU: GOTO 1490

1530 ' (MINIMUM PLANT WATER POTENTIAL)

1540 HW = -8: HW(1) = HW * 1000: HW(2) = HW * 1000: HW(3) = HW * 1000

1550 RETURN

1560 ' OTHER

1580 GOSUB 3720 ' SR 2.2 SET ACCUMULATING VARIABLES
1590gosub4450'sr3inputprintout
1600ifgs-1thengosub4750'sr3setupgraphs
1610fori-1toj1-91:lineinput#2,c$d$:nexti
1620ifthov-1thenfori-1toj1-91:lineinput#4,rara$:nexti
1630'
1640'**************************************************************************
1650'BEGIN DAILY CYCLE
1660*****
1670'
1680forjd-j1toj2
1690i$=inkeys$:ifi$="q"thenclose:end
1700ifi$="g"thenlocate25,1:inputg
1710jndjd:gosub3860:modi(day):dm(day-mo)*100
1720'
1730'solrad
1740decl=23.45/rad*sin(360/365*(284+jd)/rad):q6=sin(decl)
1750k1=q6*1:k2=q7*2:k3=q6*3:k4=q7*4:k5=q7*q5
1760ifabs(decl)+abs(la)<pi/2thenw1=-tan(la)*tan(decl):w1=-
1770atan(w1/sqrt(w1*w1+1))+pi/2elseifdecl*la>0thenw1=pielse
1780w1=0
1790l2=atan(q3/sqrt(-q3*q3+1)):ifabs(decl)+abs(l2)<pi/2thenw2=
1800tan(l2)*tan(decl):w2=-atan(w2/sqrt(-w2*w2+1))+pi/2elseifdecl*la
1810>0thenw2=pielsew2=0
1820al=atan(q5/q4):ifaz<0then1800elseifaz<piandal<0
1830thenal+pi:goto1810
1840ifaz>=piandal>0thenal=al-pi:goto1810elsegoto1810
1850if(abs(la)+sl)>pi/2thenal=pielseal=0
1860if-w1>-w2-althenrise=noon-w1*rad/15else
1870rise=noon-(w2+al)*rad/15
1880ifw1<(w2-al)thensenoon+w1*rad/15else
1890sennoon+(w2-al)*rad/15
1900'
1910'time
1920nl=fix((set-rise)/timestep+.5)
1930rc=rise+(set-rise-nl*timestep)/2
1940angincr=timestep*15/rad
1950tt=(rc-noon)*15/rad+angincr/2
1960time=rc+timestep/2:mt=(rise+set)/2
1970'
1980'daily weather
1990'if suny-1thenth=fns(th(mo),th(mo+1)):tl=fns(tl(mo),tl(mo+1)):
2000sc=fns(sc(mo),sc(mo+1)):prd=0:goto
2010ifthov-1theninput#4,date,rday,rain:rday=rday*24*3600
2020input#2,dat,th,tl,prd,sc
2030th=fnc(th):tl=fnc(tl):prd=prd+2.54:cl=1-sc/100
2040prw=prw+prd:prs=prs+prd
2050'
2060'rain
2070'if rx>jhthenrx-rx-jh:er=er+jh:eps=eps+jh:eas=eas+jh:
2080etps=etps+jh:epw=epw+jh:eaw=eaw+jh:etpw=etpw+jh:jh=0
2090rx=prd
2100if rx<0thenfr:xl=4+int(rx*2)else f=fr:xl=1:goto2080
2110fori-1tom:if(wfc(i)-w(i))*v(i)>rxthenw(i)=w(i)+rx/v(i)
\[ P(I) = PE(I) \times (WS(I)/W(I)) \times BR(I) \times RX-O \times I-M \times GOTO 2040 \]

\[ RX = RX - (WFC(I) - W(I)) \times V(I) \times WFC(I) \]

\[ P(I) = PE(I) \times (WS(I)/W(I)) \times BR(I) \]

\[ NEXT: SAWSW; SW = 0; FOR I = 1 TO M: SW = SW + V(I) \times W(I) \]

\[ PN(I) = P(I); PH(I) = P(I) \]

\[ NEXT \]

\[ DR = DR + RX \]

\[ 2060 ' OTHER \]

\[ 2070 ' OTHER \]

\[ 2080 G = 1 - F \ 'TIME WEIGHTING FACTOR \]

\[ 2090 TIMINCR = (24 - NL \times TMESTEP)/XL; FOR X = 1 TO XL: \]

\[ 2100 \]

\[ 2110 T = ((TH - TL) + (TH - TL) \times SIN(0.2618 \times (MT + 15)) / 2 ' MEAN TEMPERATURE OF SOLAR DAY \]

\[ 2120 ATM = 1.37 \times 10^6 \times LOG(FN(TL)/FN(T)) 'ATMOSPHERIC WATER POTENTIAL \]

\[ 2130 ' \]

\[ 2140 '****************************' \]

\[ 2150 'BEGIN DIURNAL CYCLE ' \]

\[ 2160 '****************************' \]

\[ 2170 ' \]

\[ 2180 FOR J = 1 TO NL \]

\[ 2190 ' \]

\[ 2200 'SOLAR RADIATION \]

\[ 2210 XX = K3 + COS(TT) \times K4 - K5 \times SIN(TT); IF XX < 0 THEN XX = 0; PRINT "XX < 0" \]

\[ 2220 ES = COS(TT) \times K2 - K1 'SOL ELEV. ANGLE \]

\[ 2230 RSL = CL + IO / (0.999847 + 0.001406 \times DECL \times RAD) \times PO^5 (LP/ES) \times (XX + O) 'DIRECT RAD \]

\[ 2240 RSL = RSL + 5 \times IO / (0.999847 + 0.001406 \times DECL \times RAD) \times (1 - PO^5 (LP/ES)) \times XX 'DIFFUSE RAD \]

\[ 2250 RSL = RSL \times TMESTEP \times 3600 \]

\[ 2260 IF TOV = 1 THEN RSLOOP = RSDAY \times (COS((TIME-RISE) \times 3.14 / (SET-RISE)) - \]

\[ 2270 \]

\[ 2280 'POTENTIAL EVAPOTRANSPIRATION ESTIMATE \]

\[ 2290 ETPL = CT \times (T-TX) \times RSL / 697 / 60 / 585 \]

\[ 2300 IF TOV = 1 THEN ETPL = CT \times (T-TX) \times RSLOOP / 697 / 60 / 585 \]

\[ 2310 ' \]

\[ 2320 'TRANSPIRATION \]

\[ 2330 FOR I = 2 TO M: K(I) = KS(I) \times (PE(I)/P(I))^N(I); NEXT \]

\[ 2340 FOR S = 1 TO 3 \]

\[ 2350 TPL(S) = CO(S) \times ETPL \times US(S): TPL = TPL + TPL(S) \]

\[ 2360 FOR I = 2 TO M: UI(I) = 1; NEXT \]

\[ 2370 TP = TPL(S) / TIMINCR; IF TP < HW(S) / 17760! THEN TP = HW(S) / 17760! \]

\[ 2380 HRM = HW(S) - TP / 17760! \]

\[ 2390 HR = TP; RSR = 0; U = 1 \]

\[ 2400 FOR I = 2 TO M: HR = HR + (P(I) - 1.05 \times Z(I)) \times DF(S,I) \times K(I) \times UI(I) / 1; \]

\[ 2410 IF RSR = 0 THEN US(S) = 0; GOTO 2500 \]

\[ 2420 HR = HR / RSR \]

\[ 2430 IF HR < HRM THEN HR = HRM \]

\[ 2440 FOR I = 2 TO M: IF HR < P(I) - 1.05 \times Z(I) AND UI(I) = 1 THEN UI(I) = 0; U = 0 \]

\[ 2450 NEXT; IF U = 0 THEN GOTO 2390 \]

\[ 2460 FOR I = 2 TO M \]

\[ 2470 T(S,I) = (HR - P(I) - 1.05 \times Z(I)) \times K(I) \times DF(S,I) \times UI(I) / 1; \]

\[ T(S,I) = T(S,I) \times TIMINCR \]
2480 TAL(S) = TAL(S) + T(S,I) : TBD(I) = TBD(I) + T(S,I) : TAL = TAL + T(S,I)
2490 NEXT
2500 NEXT
2510 ' EVAPORATION
2520 EPL = (1 - TC) * (ETPL)
2530 IF ETPL > .9 * W(1) * V(1) THEN EAL = .9 * W(1) * V(1) ELSE EAL = EPL
2540 P(0) = ATMP: IF P(1) < P(0) THEN P(0) = P(1)
2550 IF P3 = PE(1) * ((W(1) * V(1) - EAL) / V(1) / WS(1)) ^ -BR(1) THEN KU = ABS(KS(1) * PE(1) / P3) ^ N(1) ELSE
2560 KU = (PE(1) ^ N(1) - (PE(1) ^ N(1) - (-P(1) ^ N(1))) / (P3 - P(1)))
2570 E3 = KU * (F * P3 + G * P(1) - P(0) + Z(1) * GR) / 2 * TIMINCR: IF E3 < EAL THEN EAL = E3:
2580 IF EAL < 0 THEN EAL = 0
2590 ' REDISTRIBUTION OF SOIL WATER
2600 GOSUB 2990 ' SR 1
2610
2620 ' ACCUMULATING VARIABLES
2630 RSD = RSD + RSL: RSW = RSW + RSL: RSS = RSS + RSL
2640 ETPD = ETPD + ETPL: ETPW = ETPW + ETPL: ETPS = ETPS + ETPL
2650 TPW = TPW + TPL: TPS = TPS + TPL
2660 TAD = TAD + TAL: TAW = TAW + TAL: TAS = TAS + TAL
2670 EPW = EPW + EPL: EPS = EPS + EPL
2680 EAD = EAD + EAL: EAW = EAW + EAL: EAS = EAS + EAL
2690 FOR S = 1 TO 3: TPD(S) = TPD(S) + TPL(S): TPW(S) = TPW(S) + TPL(S):
2700 TPS(S) = TPS(S) + TPL(S): TAD(S) = TAD(S) + TAL(S): TAW(S) = TAW(S) + TAL(S):
2710 ' (RESET DIURNAL VARIABLES)
2720 EAL = 0: TPL = 0: TAL = 0: ETPL = 0: FOR I = 2 TO M: TBD(I) = 0: NEXT
2730 ' (TIME)
2740 TT = TT + TNCNCR: TIME = TIME + TIMESTEP
2750 NEXT J
2760
2770 '************************************************************
2780 ' END DIURNAL CYCLE
2790 '************************************************************
2800 GOSUB 4740 ' DAILY PRINTOUT
2810 IF GS = 1 THEN GOSUB 6290 ' DAILY GRAPHICS
2820 DC = DC + 1: IF DC < 7 THEN GOTO 2860 ' DAY COUNTER
2830 GOSUB 5100 ' WEEKLY PRINTOUT
2840 IF GS = 1 THEN GOSUB 6440 ' WEEKLY GRAPHICS
2850 NEXT JD
2860
2870 GOSUB 5620 ' SEASON PRINTOUT
2880 IF GS = 1 THEN BEEP: LOCATE 25, 1: INPUT G ' HOLD GRAPH
2890 ' PRINT #3, CHR$(12) ' FORM FEED
2900 IF BS = 1 THEN CLOSE 2: CLOSE 4: GOTO 4140 ' NEXT BATCH
82

2960 CLOSE: END

2970

2980 '******************************************************************************

2990 'SOIL WATER FLOW SUBROUTINE (SR 1) 

3000 '******************************************************************************

3010

3020 DRM = KS(M)*(PE(M)/P(M))^N(M): DR = DR + DRM*TIMINCR

3030 IF PN(1)>PE(1) THEN PRINT #3,"QPN SETBACK ";"PN(1)= ";PN(1) 

3040 Q = F*PN(1)+G*P(1)

3050 IF PN(1)-P(1) THEN CP(1) = - W(1)*V(1)/(TIMINCR*PN(1)*BR(1)) ELSE 

3060 

3070 FOR I=2 TO M :P=Q

3080 IF PN(I)>PE(I) THEN PRINT #3,"QPN SETBACK ";"I= ";PN(1) 

3090 Q = F*PN(I)+G*P(I)

3100 IF PN(I) = P(I) THEN CP(I) = - W(I)*V(I)/(TIMINCR*PN(I)*BR(I)) ELSE 

3110 

3120 K(I-1) = SQR(KS(I-1)*(P/PE(I-1))^N(I-1)*KS(I)*(Q/PE(I))^N(I)) 

3130 / (Z(I)-Z(I-1)):NEXT I

3140

3150 P(0) = P(1) -(Z(1)-Z(0))*GR :PN(0) = PN(1) -(Z(1)-Z(0))*GR 

3160 P(M+1) = P(M) + (Z(M+1)-Z(M))*GR :PN(M+1) = PN(M) + (Z(M+1)-Z(M))*GR 

3170

3180 FOR I=1 TO M :C(I) = - K(I)*F

3190 B(I) = F*(K(I-1)+K(I))+CP(I)

3200 D(I) = G*K(I-1)*P(I-1) + (CP(I) - G*(K(I-1)+K(I)))*P(I) + G*K(I)*P(I+1) 

3210 NEXT I: D(M) = D(M) + K(M)*F*PN(M+1)

3220 D(I) = D(I) - EAL/TIMINCR :FOR I=2 TO M: D(I) = D(I) - TBD(I)/TIMINCR: NEXT 

3230 D(M) = D(M) - DRM

3240 FOR I=1 TO M-1

3250 C(I) = C(I)/B(I)

3260 D(I) = D(I)/B(I)

3270 B(I+1) = B(I+1) + K(I)*F*C(I)

3280 D(I+1) = D(I+1) + K(I)*F*D(I) :NEXT I

3290 PN(M) = D(M)/B(M)

3300 FOR I=M-1 TO 1 STEP -1

3310 PN(I) = D(I) - C(I)*PN(I+1):NEXT I

3320

3330 FOR I=1 TO M:XH(I) = PN(I) - PH(I):PH(I) = PN(I):NEXT 

3340 FOR I=1 TO M:IF ABS(XH(I))>LX THEN IX=1:IL=IL+1 

3350 NEXT:IF IX=1 THEN IX=0:GOTO 3030 ELSE IL=0

3360

3370 SA = SW; SW = 0: FOR I=1 TO M :IF PN(I)<PE(I) THEN 

3380 W(I) = WS(I)*(PE(I)/PN(I))^B(I) ELSE W(I) = WS(I);PRINT #3,"PN SETBACK DEPTH ";"PN 

3390 

3410 RETURN
3420 'SR 2.1 CONSTANTS
3480 TOV(1)=139:TOV(2)=149:TOV(3)=157:TOV(4)=167:TOV(5)=194:TOV(6)=215:
   TOV(7)=224:TOV(8)=237
3490 ID(1)=32:ID(2)=60:ID(3)=91:ID(4)=121:ID(5)=152:ID(6)=182:
   ID(7)=213:ID(8)=244:ID(9)=274:ID(10)=305:ID(11)=335:
   ID(12)=366:ID(13)=999
3500 A$="##.##":AR$="#####.#":B$="####.#":C$="###.##":D$="##.##":E$="####.##":R$="####.##":S$="#####":W$="##.##"
3510 ' (CLIMATE)
3520 CC$(1)="CAVE JUNCTION '81":CD$(1)="CAVE81"
3530 CC$(2)="SEXTON SUMMIT '81":CD$(2)="SEXTON81"
3540 CC$(3)="RUCH '81":CD$(3)="RUCH81"
3550 CC$(4)="PROSPER '81":CD$(4)="PROSP81"
3560 CC$(5)="HOWARD PRAIRIE '81":CD$(5)="HOWARD81"
3570 CC$(6)="WOLF CREEK '83":CD$(6)="WOLF83"
3580 CC$(7)="SEXTON SUMMIT '83":CD$(7)="SEXT83"
3590 ' (SOIL)
3600 TX$(1)="CLAY":TX$(6)="LOAM"
3610 TX$(2)="SILTY CLAY":TX$(7)="SILT LOAM"
3620 TX$(3)="SILTY CLAY LOAM":TX$(8)="SANDY LOAM"
3630 TX$(4)="CLAY LOAM":TX$(9)="LOAMY SAND"
3640 TX$(5)="SANDY CLAY LOAM":TX$(10)="SAND"
3650 ' (OTHER)
3660 GR=I!:PI=4!*ATN(1!):RAD=180/PI
3670 FR=1:F=1:LX=175
3680 IO=1360:PO=.7
3690 TIMESTEP=2
3700 RETURN
3710 'SR 2.2 SET ACCUMULATING VARIABLES
3730 VD=1
3740 EAL=0: EAD=0: EAW=0: EAS=0
3750 EPL=0: EPD=0: EPW=0: EPS=0
3760 TAL=0: TAD=0: TAW=0: TAS=0
3770 TPL=0: TPD=0: TPW=0: TPS=0
3780 FOR I=2 TO M:TBD(I)=0:NEXT
3790 RSD=0: RSW=0: RSS=0: PRW=0
3800 ETPD=0:ETPW=0:ETPS=0
3810 FOR S=1 TO 3:TAL(S)=0:TAD(S)=0:TAW(S)=0:TAS(S)=0:TPL(S)=0:
   TPD(S)=0:TPW(S)=0:TPS(S)=0:US(S)=1:NEXT
3820 CF=0: CW=0: PRS=0: DR=0: ER=0: DC=0
3830 RETURN
3840 'SR 2.3 DAY OF YEAR TO MO.DA
3850 FOR JJ=1 TO 13: IF ID(JJ)-JND<.1 THEN 3880
3860 DAY=(JND-ID(JJ-1)+1)/100+JJ: JJ=13
3870 NEXT JJ
3880 RETURN
```
84
3900 'SR 2.4  MO.DA TO DAY OF YEAR
3920 JF-FIX(DAY): JND-ID(JF-1)-1+(DAY-JF)*100
3930 RETURN
3940 'SR 2.5  INPUT/OUTPUT OPTIONS
3960 CLOSE:BS=0:GS=0:PS=0:DS=0:WK=0:PLOT=0:SCREE=0
3970 INPUT"INPUT 1 FOR GRAPHS";GS
3980 INPUT"INPUT 1 FOR DATA TO SCREEN (OUTPUT CAN BE SCREEN ONLY)"; SCREE
3990 INPUT"INPUT 1 TO STOP DAILY OUTPUT";DS
4000 INPUT"INPUT 1 TO STOP WEEKLY OUTPUT";WK
4010 INPUT"INPUT 1 FOR VALUES TO PLOT";PLOT
4020 INPUT"INPUT 1 FOR BATCH";BS
4030 INPUT"INPUT 1 FOR VALID";TOV
4040 CLS
4050 IF PS=1 THEN O$="LPT1:" ELSE O$="DATA"
4060 IF SCREE=1 THEN O$="CON"
4070 'IF TOV=1 THEN OPEN "O",5,"RAD"
4080 OPEN "O",3,O$
4090 RETURN
4100 '
4110 'SR 2.6  BATCH OPTION
4120 PRINT #3,"D1,D2,CLIM,SL,AZ,AD,BD,CD,Ax,Bx,Cx,IWCM,CO(0),CO(1), CO(2),CO(3),RD(1),RD(2),RD(3)"
4130 OPEN "I",1,"SITE.DAT"
4140 B=B+1:IF GS=0 THEN PRINT"BATCH RUN # ":B, TIME$
4150 IF EOF(1) THEN 2960
4160 INPUT #1,D1,D2,CLIM,SL,AZ,AD,BD,CD,Ax,Bx,Cx,IWCM,CO(0),CO(1), CO(2),CO(3),RD(1),RD(2),RD(3)
4170 PRINT #3,D1;D2;CLIM;SL;AZ;AD;BD;CD;Ax;Bx;Cx;IWCM;CO(0);CO(1); CO(2);CO(3);RD(1);RD(2);RD(3)
4180 RFVA-.3:RFVB-.3:RFVC-.3
4190 GOSUB 410: GOSUB 870: GOSUB 1380
4200 GOTO 1570
4210 '
4220 'SR 2.7  SUNY SEXTON CLIMATE
4230 TH(1)=39.8: TL(1)=29.2: SC(1)=7.8
4240 TH(2)=43.1: TL(2)=31.4: SC(2)=7.6
4250 TH(3)=44.9: TL(3)=30.7: SC(3)=7.5
4260 TH(4)=51.9: TL(4)=33.7: SC(4)=6.8
4270 TH(5)=59.6: TL(5)=39.3: SC(5)=5.9
4280 TH(6)=66.3: TL(6)=44.7: SC(6)=4.7
4290 TH(7)=75.7: TL(7)=51.4: SC(7)=2.1
4300 TH(8)=74.7: TL(8)=51.4: SC(8)=2.7
4310 TH(9)=70.2: TL(9)=49.2: SC(9)=3.4
4320 TH(10)=58.3: TL(10)=42.6: SC(10)=5.6
4330 TH(11)=47.1: TL(11)=35.2: SC(11)=7.3
4340 TH(12)=41.7: TL(12)=32: SC(12)=7.7
4350 TH(13)=39.8: TL(13)=29.2: SC(13)=7.8
4360 RETURN
4370 '
4380 '******************************************************************************
4390 'PRINTOUT SUBROUTINES (SR 3)  *****
```
'OPENING PRINTOUT

PRINT #3,"***** SOIL WATER BALANCE PROGRAM *****

";LEFT$(DATE$,12)

IF PLOT=1 THEN RETURN

'PRINTOUT OF INPUT VALUES SELECTED

PRINT #3,"":PRINT #3,"CONDITIONS FOR THIS RUN:";PRINT #3,""

PRINT #3, "BEGIN SEASON ";D1,"END SEASON ";D2

PRINT #3, "WEATHER STATION DATA FROM ";CC$(CLIM);" ELEV. ";EL/.3048;" FT.

PRINT #3, "SLOPE (%): ";TAN(SL)*100,"ASPECT (DEGREES): ";AZ*RAD

PRINT #3, "DEPTH OF HORIZON A (CM): ";AD,"TEXTURE: ";TX$(AX)

PRINT #3, "DEPTH OF HORIZON B (CM): ";BD,"TEXTURE: ";TX$(BX)

PRINT #3, "DEPTH OF HORIZON C (CM): ";CD,"TEXTURE: ";TX$(CX)

PRINT #3, "INITIAL WATER POTENTIAL: ";IWCM," BAR"

PRINT #3, "SHELTERWOOD COVER, M2/HA ";CO(3)

PRINT #3, "SEEDLING ROOT DEPTH: ";RD(1);"GRASS ROOT DEPTH: ";RD(2);

PRINT #3, "SHRUB ROOT DEPTH: ";RD(3)

PRINT #3,"UNITS: RS [MJ/M^2], RAIN [CM], ETP [CM], P [BAR], EVAP & TRANS [CM]"

PRINT #3," INITIAL SOIL WATER CONTENT


PRINT #3,"% WATER     ";

FOR I=1 TO 7

PRINT #3, USING E$;W(I);

NEXT: PRINT #3,

RETURN

'DAILY PRINTOUT

'*INITIAL SOIL WATER CONTENT


PRINT #3,"% WATER     ";

FOR I=1 TO 7

PRINT #3, USING E$;W(I);

NEXT: PRINT #3,

RETURN

'DAILY PRINTOUT

'*INITIAL SOIL WATER CONTENT


PRINT #3,"% WATER     ";

FOR I=1 TO 7

PRINT #3, USING E$;W(I);

NEXT: PRINT #3,

RETURN

'DAILY PRINTOUT
86

4880 NEXT :PRINT #3,
4890 ' (RESET ACCUMULATING VARIABLES)
4900 RSD=0: ETPD=0: EAD=0: TAD=0: FOR S=1 TO 3:TAD(S)=0:TPD(S)=0: NEXT
4910 RETURN
4920 '
4930 ' (VALUES TO PLOT)
4940 JND=JD-6: GOSUB 3860: WB=DAY: JND=JD: GOSUB 3860: WE=DAY
4950 PRINT #3, USING D$;DAY;
4960 IF TPD(1)=0 THEN PRINT #3, USING W$;TPD(1);:GOTO 4980
4970 PRINT #3, USING W$;TAD(1)/TPD(1);
4980 GOSUB 6570
4990 PRINT #3, USING W$;AWCT/TAWCT;
5000 PRINT #3, USING W$;W(4);
5010 PRINT #3, USING B$;P(4)/1000;
5020 PRINT #3, USING "##%%%%"; K(4);
5030 PRINT #3, USING E$;ETPS;
5040 PRINT #3, USING A$;TAS(1);
5050 PRINT #3, USING A$;EAS+TAS(1);
5060 PRINT #3, USING A$;EAS+TAS+DR ' TOTAL WATER LOSS
5070 RETURN
5080 '
5090 '**********************
5100 'WEEKLY PRINTOUT
5110 '**********************
5120 IF WK=1 THEN GOTO 5330
5130 IF PLOT=1 THEN GOSUB 5450: GOTO 5330
5140 PRINT #3,""
5150 PRINT #3," WEEK RS RAIN ETP ET EVAP FIR GRASS SHRUB A/P(FIR)"
5160 JND=JD-6: GOSUB 3860: WB=DAY: JND=JD: GOSUB 3860: WE=DAY
5170 PRINT #3, USING D$;WB;:PRINT #3, ","; PRINT #3, USING D$;WE;
5180 PRINT #3, USING R$;RSS/10^6;
5190 PRINT #3, USING A$;PRS;
5200 PRINT #3, USING A$;ETPS;
5210 PRINT #3, USING A$;EAS+TAS;
5220 PRINT #3, USING A$;EAS;
5230 FOR S=1 TO 3: PRINT #3, USING A$;TAS(S);:NEXT
5240 IF TPW(1)=0 THEN PRINT #3, USING W$;TPW(1);:GOTO 5260
5250 PRINT #3, USING W$;TAW(1)/TPW(1)
5260 ' (WATER CONTENT PROFILE)
5280 PRINT #3, " ";
5290 FOR I=1 TO 7
5300 PRINT #3, USING E$;W(I);
5310 NEXT: PRINT #3,
5320 ' (RESET ACCUMULATING VARIABLES)
5330 DC=0: RSW=0: PRW=0: ETPW=0: EAW=0: EPW=0: TAW=0: TPW=0
5340 FOR S=1 TO 3: TAW(S)=0: TPW(S)=0: NEXT
5350 RETURN
5360 ' 
5370 ' (WATER POTENTIAL PROFILE)
PRINT #3, "";
FOR I = 1 TO 7
PRINT #3, USING B$; P(I)/1000;
NEXT: PRINT #3, RETURN
'
'(VALUES TO PLOT)
PRINT #3, USING D$; WB; "-"; PRINT #3, USING D$; WE;
IF TPW(1) = 0 THEN PRINT #3, USING W$; TPW(1): GOTO 5500
PRINT #3, USING W$; TAW(1)/TPW(1);
GOSUB 6570
PRINT #3, USING W$; AWCT/TAWCT;
PRINT #3, USING W$; W(4);
PRINT #3, USING "###^###; K(4);
PRINT #3, USING E$; ETPS;
PRINT #3, USING A$; TAS(1);
PRINT #3, USING A$; EAS+TAS(1);
PRINT #3, USING A$; EAS+TAS
RETURN

PRINT #3, "": PRINT #3, "SEASON:"; RS ETP EA FIR
GRASS SHRUB A/P(FIR)"
PRINT #3, " ";
PRINT #3, USING E$; RSS/10^6;
PRINT #3, USING E$; ETPS;
PRINT #3, USING E$; EAS;
FOR S = 1 TO 3: PRINT #3, USING E$; TAS(S);: NEXT
IF TPS(1) = 0 THEN PRINT #3, USING E$; TPS(1): GOTO 5720
PRINT #3, USING E$; TAS(1)/TPS(1)
PRINT #3, "": PRINT #3, "MASS BALANCE: ET FLUX": PRINT #3, USING C$; CF;
PRINT #3, " DRAINAGE": PRINT #3, USING C$; DR;
PRINT #3, " SW BAL. ": PRINT #3, USING C$; CW
PRINT #3, "SOIL WATER BUDGET: + RAIN": PRINT #3, USING C$; PRS-ER;
PRINT #3, " ET,DRAIN ": PRINT #3, USING C$; CW+DR;
PRINT #3, " CHANGE IN SW ": PRINT #3, USING C$; SW-IW
RETURN

PRINT #3, "": PRINT #3, "GRAPHICS SUBROUTINE"
SCREEN 2: CLS
LOCATE 1, COLHEAD: PRINT "SL:"; 100*TAN(SL); "% AS:"; AZ*RAD;
LOCATE 2, COLHEAD: PRINT "SEEDLINGS:"; SEEDS; "/ACRE";
LOCATE 3, COLHEAD: PRINT "SLASH COVER:"; CO(0)*100; "%"
LOCATE 4, COLHEAD: PRINT "GRASS COVER:"; CO(2)*100; "%"
LOCATE 5, COLHEAD: PRINT "SHRUB COVER:"; CO(3)*100; "%"
LOCATE 5,COLHEAD :PRINT "SHELTER COVER:";BA;"M2/HA";

WATER POTENTIAL GRAPH
VPSI=20 :HPSI=60
LOCATE VPSI/200*25-2,HPSI/640*80 :PRINT
"SOIL WATER POTENTIAL,
BARS";
LOCATE VPSI/200*25-1,HPSI/640*80 :PRINT "DRY -30 -20 -10 SAT";
LINE (HPSI,VPSI)-(HPSI+200,VPSI)
LINE (HPSI,VPSI)-(HPSI,VPSI+80)
LOCATE 6,1 :PRINT "DEPTH" ; :LOCATE 7,1 :PRINT "IN cm"
FOR I=1 TO 4 :LOCATE (VPSI+1*I)/200*25,6 :PRINT USING "##";CD/4*I :NEXT
RAD + PPT VS TIME
VRAD-190 :HRAD-60 :YRAD1=VRAD :XRAD1=0
LOCATE (VRAD-40)/200*25,1 :PRINT "RAD" ; :LOCATE
(VRAD-40)/200*25+1,1 :PRINT "Mj/M2" ; 6050 LINE
(HRAD,VRAD)-(HRAD,VRAD-80)
LINE (HRAD,VRAD)-(HRAD+(J2-J1)*3,VRAD)
LOCATE (HRAD+(J2-J1)*3,VRAD)-(HRAD+(J2-J1)*3,VRAD-40)
LOCATE (VRAD-80)/200*25+1,HRAD/640*80-2 :PRINT "30";
LOCATE (VRAD-27)/200*25+1,HRAD/640*80-2 :PRINT "10";
LOCATE (VRAD-54)/200*25+1,HRAD/640*80-2 :PRINT "20";
LOCATE (VRAD-40)/200*25,(HRAD+3*(J2-J1))/640*80+2 :PRINT "2";
LOCATE (VRAD-20)/200*25,(HRAD+3*(J2-J1))/640*80+2 :PRINT "1";
PRINT "RAIN";
CUM WATER USE GRAPH
VCUM=190 :HCUM=420
LINE (HCUM,VCUM)-(HCUM,VCUM-80)
LOCATE (VCUM-40)/200*25-2,HCUM/640*80-7 :PRINT "CUM."
LOCATE (VCUM-40)/200*25-1,HCUM/640*80-7 :PRINT "WATER"
LOCATE (VCUM-40)/200*25,HCUM/640*80-7 :PRINT "USE"
LOCATE (VCUM-40)/200*25+1,HCUM/640*80-7 :PRINT "cm"
LOCATE (VCUM-80)/200*25,HCUM/640*80-2 :PRINT "15"
LOCATE (VCUM-40)/200*25,HCUM/640*80-2 :PRINT "8"
LOCATE 25,HCUM/640*80 :PRINT "AWC EVAP SEED GRASS SHRUB"
AWCT-TAWCT 'AWCT INITIAL
RETURN
DAILY GRAPHICS SUBROUTINE
XPLOT2=200+P(I)/1000/40*200+HPSI :IF XPLOT2<200+HPSI THEN XPLOT2=200+HPSI
YPLOT2=Z(I)/LB(M)*80+VPSI
FOR I=2 TO M :XPLOT1=XPLOT2 :YPLOT1=YPLOT2
XPLOT2=200+P(I)/1000/40*200+HPSI :IF XPLOT2>200+HPSI THEN
YPLOT2=Z(I)/LB(M)*80+VPSI
LINEx(YPLOT1,YPLOT1)-(XPLOT2,YPLOT2) :NEXT
YRAD2=YRAD1 :YRAD1=RSD/1000/1000/30*80+VRAD
YRAD2-YRAD1 :YRAD1=RSD*FBA/1000/1000/30*80+VRAD
6390 LINE (HRAD+XRAD1,YRAD2)-(HRAD+XRAD1+3,YRAD1)
6400 LINE (HRAD+XRAD1,YRAD)-(HRAD+XRAD1+3,YRAD-PRD/2*40),1,BF
6410 LOCATE 25,22 :PRINT USING D$;DAY;
6420 XRAD1=XRAD1+3 :RETURN
6430 
6440 ' WEEKLY GRAPHICS SUBROUTINE
6450 LINE (HPSI+1,VPSI+1)-(HPSI+200,VPSI+80),0,BF
6460 LINE (HCUM+1,VCUM-1)-(640,VCUM-120),0,BF 6470 HPLOT=10 :GOSUB 6570 :LINE (HCUM+HPLOT,VCUM)-
6480 LINE (HCUM+HPLOT,VCUM)-(HCUM+HPLOT+20,VCUM-AWCT*80/15),1,BF
6490 'LINE (HCUM+HPLOT,VCUM)-(HCUM+HPLOT+20,VCUM-80*EPS/15),1,B
6500 LINE (HCUM+HPLOT,VCUM)-(HCUM+HPLOT+20,VCUM-80*EAS/15),1,BF
6510 FOR I=1 TO 3 :HPLOT-HPLOT+40
6520 LINE (HCUM+HPLOT,VCUM)-(HCUM+HPLOT+20,VCUM-80*TPS(I)/15),1,B
6530 LINE (HCUM+HPLOT,VCUM)-(HCUM+HPLOT+20,VCUM-80*TAS(I)/15),1,BF
6540 NEXT I
6550 RETURN
6560 
6570 AWCT=0 :FOR I=1 TO M :AWCT-AWCT+(W(I)-WWP(I))*V(I) :NEXT :RETURN
6580 GOSUB 6570 :VAWC=VCUM-80*AWCT/15 :LINE
6590 (HCUM+10,VCUM)-(HCUM+30,VAWC),1,B :RETURN
### Appendix II. Program variables.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>Depth of A horizon.</td>
</tr>
<tr>
<td>ANGINCR</td>
<td>Solar angle increment.</td>
</tr>
<tr>
<td>AWCT</td>
<td>Available water content.</td>
</tr>
<tr>
<td>AX</td>
<td>Texture of A horizon.</td>
</tr>
<tr>
<td>AZ</td>
<td>Aspect of site.</td>
</tr>
<tr>
<td>B(I)</td>
<td>Matrix component in numerical method.</td>
</tr>
<tr>
<td>BL(I)</td>
<td>Inverse of BR(I).</td>
</tr>
<tr>
<td>BD</td>
<td>Cumulative depth of B horizon.</td>
</tr>
<tr>
<td>BR(I)</td>
<td>Regression constant for soil hydraulic functions.</td>
</tr>
<tr>
<td>BS</td>
<td>Batch switch.</td>
</tr>
<tr>
<td>BX</td>
<td>Texture of B horizon.</td>
</tr>
<tr>
<td>C(I)</td>
<td>Matrix component in numerical method.</td>
</tr>
<tr>
<td>Cl</td>
<td>Jensen-Haise coefficient.</td>
</tr>
<tr>
<td>CD</td>
<td>Cumulative depth of C horizon.</td>
</tr>
<tr>
<td>CF</td>
<td>Cumulative ET calculated flux.</td>
</tr>
<tr>
<td>CH</td>
<td>Jensen-Haise coefficient.</td>
</tr>
<tr>
<td>CL</td>
<td>Cloud coefficient.</td>
</tr>
<tr>
<td>CLIM</td>
<td>Climate data file.</td>
</tr>
<tr>
<td>CO(0)</td>
<td>Soil surface cover.</td>
</tr>
<tr>
<td>CO(1)</td>
<td>Seedling cover.</td>
</tr>
<tr>
<td>CO(2)</td>
<td>Grass cover.</td>
</tr>
<tr>
<td>CO(3)</td>
<td>Shrub cover.</td>
</tr>
<tr>
<td>CP(I)</td>
<td>Soil hydraulic capacitance.</td>
</tr>
<tr>
<td>CT</td>
<td>Jensen-Haise coefficient.</td>
</tr>
<tr>
<td>CW</td>
<td>Cumulative ET water balance loss.</td>
</tr>
<tr>
<td>CX</td>
<td>Texture of C horizon.</td>
</tr>
<tr>
<td>D(I)</td>
<td>Matrix component in numerical method.</td>
</tr>
<tr>
<td>D1</td>
<td>Begin season.</td>
</tr>
<tr>
<td>D2</td>
<td>End season.</td>
</tr>
<tr>
<td>DAY</td>
<td>Day of season.</td>
</tr>
<tr>
<td>DC</td>
<td>Day counter.</td>
</tr>
<tr>
<td>DECL</td>
<td>Solar declination.</td>
</tr>
<tr>
<td>DF</td>
<td>Daily ET calculated flux.</td>
</tr>
<tr>
<td>DP(S,I)</td>
<td>Root density function (species, depth).</td>
</tr>
<tr>
<td>DM</td>
<td>Day of month.</td>
</tr>
<tr>
<td>DR</td>
<td>Drainage.</td>
</tr>
<tr>
<td>DS</td>
<td>Daily printout switch.</td>
</tr>
<tr>
<td>DW</td>
<td>Daily ET water balance loss.</td>
</tr>
<tr>
<td>E3</td>
<td>Maximum soil water supply rate for evaporation.</td>
</tr>
<tr>
<td>EAL</td>
<td>Diurnal actual evaporation.</td>
</tr>
<tr>
<td>EAD</td>
<td>Daily actual evaporation.</td>
</tr>
<tr>
<td>EAW</td>
<td>Weekly actual evaporation.</td>
</tr>
<tr>
<td>EAS</td>
<td>Seasonal actual evaporation.</td>
</tr>
<tr>
<td>EPL</td>
<td>Diurnal potential evaporation.</td>
</tr>
<tr>
<td>EPD</td>
<td>Daily potential evaporation.</td>
</tr>
<tr>
<td>EPW</td>
<td>Weekly potential evaporation.</td>
</tr>
<tr>
<td>EPS</td>
<td>Seasonal actual evaporation.</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>ETPL</td>
<td>Diurnal potential evapotranspiration.</td>
</tr>
<tr>
<td>ETPD</td>
<td>Daily potential evapotranspiration.</td>
</tr>
<tr>
<td>ETPW</td>
<td>Weekly potential evapotranspiration.</td>
</tr>
<tr>
<td>ETPS</td>
<td>Seasonal potential evapotranspiration.</td>
</tr>
<tr>
<td>EL</td>
<td>Site elevation.</td>
</tr>
<tr>
<td>EM</td>
<td>Mass balance.</td>
</tr>
<tr>
<td>ER</td>
<td>Direct evaporation of rain from soil and leaf surfaces.</td>
</tr>
<tr>
<td>ES</td>
<td>Solar elevation angle.</td>
</tr>
<tr>
<td>F</td>
<td>Time weighting factor for numerical method.</td>
</tr>
<tr>
<td>FR</td>
<td>Time weighting factor for numerical method on rain days.</td>
</tr>
<tr>
<td>FX</td>
<td>Variable for summation of ET flux.</td>
</tr>
<tr>
<td>G</td>
<td>Function of F.</td>
</tr>
<tr>
<td>GS</td>
<td>Graph switch.</td>
</tr>
<tr>
<td>H8</td>
<td>Mean maximum air temperature for warmest month of year.</td>
</tr>
<tr>
<td>HR</td>
<td>Plant water potential.</td>
</tr>
<tr>
<td>HRM</td>
<td>Minimum plant water potential.</td>
</tr>
<tr>
<td>HW(S)</td>
<td>Minimum plant water potential characteristic (species).</td>
</tr>
<tr>
<td>I</td>
<td>Depth increment.</td>
</tr>
<tr>
<td>IO</td>
<td>Solar constant.</td>
</tr>
<tr>
<td>IL</td>
<td>Iteration counter.</td>
</tr>
<tr>
<td>IWCM</td>
<td>Initial water potential of bottom layer.</td>
</tr>
<tr>
<td>IX</td>
<td>Switch.</td>
</tr>
<tr>
<td>J</td>
<td>Diurnal counter.</td>
</tr>
<tr>
<td>J1</td>
<td>Begin season (day of year).</td>
</tr>
<tr>
<td>J2</td>
<td>End season (day of year).</td>
</tr>
<tr>
<td>JD</td>
<td>Day of year.</td>
</tr>
<tr>
<td>JF</td>
<td>Truncation, day of year.</td>
</tr>
<tr>
<td>K(I)</td>
<td>Soil layer routine counter.</td>
</tr>
<tr>
<td>K(I)</td>
<td>Hydraulic conductivity (depth).</td>
</tr>
<tr>
<td>KS(I)</td>
<td>Saturated hydraulic conductivity (depth).</td>
</tr>
<tr>
<td>KU</td>
<td>Unsaturated hydraulic conductivity (surface).</td>
</tr>
<tr>
<td>L2</td>
<td>Equivalent latitude.</td>
</tr>
<tr>
<td>L8</td>
<td>Mean minimum air temperature for warmest month of year.</td>
</tr>
<tr>
<td>LA</td>
<td>Latitude.</td>
</tr>
<tr>
<td>LB(I)</td>
<td>Lower soil boundary (depth).</td>
</tr>
<tr>
<td>LN</td>
<td>Longitude.</td>
</tr>
<tr>
<td>LP</td>
<td>Atmospheric density, elevation function.</td>
</tr>
<tr>
<td>LX</td>
<td>Limit, change in P(I) per iteration.</td>
</tr>
<tr>
<td>M</td>
<td>Bottom depth increment.</td>
</tr>
<tr>
<td>MD</td>
<td>Month and day.</td>
</tr>
<tr>
<td>MO</td>
<td>Month.</td>
</tr>
<tr>
<td>MT</td>
<td>Mean temperature of solar day.</td>
</tr>
<tr>
<td>N(I)</td>
<td>Function of BR(I).</td>
</tr>
<tr>
<td>N0</td>
<td>Solar noon.</td>
</tr>
<tr>
<td>N1(I)</td>
<td>Function of N(I).</td>
</tr>
</tbody>
</table>
NL  Number of diurnal loops.
P  Calculation of mean K.
P(I)  Soil water potential (depth).
PO  Atmospheric transmissivity.
P3  Estimate of PN(I) for E3.
PE(I)  Air entry soil water potential (depth).
PH(I)  Intermediate P(I) during iteration.
PN(I)  Soil water potential (depth), end of time increment.
PRD  Daily precipitation.
PRW  Weekly precipitation.
PRS  Seasonal precipitation.
PS  Print switch.
Q  Calculation of mean K.
RAD  Radians.
RC  Rise correction for uniform time step.
RD(S)  Root depth (species).
RFP  Rock fragment porosity.
RFV  Rock fragment volume.
RISE  Sunrise.
RP(S,I)  Root profile (species, depth).
RSR  Calculation of root density function.
RSL  Diurnal solar radiation.
RSD  Daily solar radiation.
RSW  Weekly solar radiation.
RSS  Seasonal solar radiation.
RX  Rain distribution.
RZ  Calculation of root density function.
S  Species.
SA  SW before recalculation.
SC  Sky cover.
SET  Sunset.
SL  Site slope.
SW  Soil water total.
SX  Variable for summation of SW.
T  Air temperature.
TAL  Diurnal actual transpiration.
TAD  Daily actual transpiration.
TAW  Weekly actual transpiration.
TAS  Seasonal actual transpiration.
TPL  Diurnal potential transpiration.
TPD  Daily potential transpiration.
TPW  Weekly potential transpiration.
TPS  Seasonal potential transpiration.
TAWC  Available water capacity.
TC  Total ground cover.
T(S,I)  Transpiration (species, depth).
TBD(I)  Transpiration (depth).
TH  Maximum air temperature.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIME</td>
<td>Time of day.</td>
</tr>
<tr>
<td>TIMINCR</td>
<td>Time increment for water flow subroutine.</td>
</tr>
<tr>
<td>TIMESTEP</td>
<td>Initial time increment constant.</td>
</tr>
<tr>
<td>TL</td>
<td>Minimum air temperature.</td>
</tr>
<tr>
<td>TX</td>
<td>Jensen-Haise coefficient.</td>
</tr>
<tr>
<td>U</td>
<td>Root water uptake routine.</td>
</tr>
<tr>
<td>UI(I)</td>
<td>Root water uptake routine.</td>
</tr>
<tr>
<td>US(S)</td>
<td>Root water uptake routine.</td>
</tr>
<tr>
<td>V(I)</td>
<td>Volume of soil layer (depth).</td>
</tr>
<tr>
<td>V1</td>
<td>Vapor pressure at L8.</td>
</tr>
<tr>
<td>V2</td>
<td>Vapor pressure at H8.</td>
</tr>
<tr>
<td>W(I)</td>
<td>Soil water content (depth).</td>
</tr>
<tr>
<td>WB</td>
<td>Week begin.</td>
</tr>
<tr>
<td>WE</td>
<td>Week end.</td>
</tr>
<tr>
<td>WFC</td>
<td>Water potential at field capacity.</td>
</tr>
<tr>
<td>WWP</td>
<td>Water potential at wilting point.</td>
</tr>
<tr>
<td>WS</td>
<td>Saturated water content.</td>
</tr>
<tr>
<td>XH(I)</td>
<td>Change in soil water potential per iteration.</td>
</tr>
<tr>
<td>XL</td>
<td>Number of night loops.</td>
</tr>
<tr>
<td>XX</td>
<td>Counter.</td>
</tr>
<tr>
<td>Z(I)</td>
<td>Depth of node for calculations (depth increment).</td>
</tr>
</tbody>
</table>