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Using the TIMS to Estimate Evapotranspiration from a Forest

by

Robert Teskey
Associate Professor
School of Forest Resources
University of Georgia
Athens, GA 30602

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Introduction

There were two primary goals of this project. The first was to characterize the evapotranspiration of two forested watersheds using direct measurement techniques. The second was to evaluate if remotely sensed surface temperatures could be used to estimate evapotranspiration from the same watersheds. The funding and the research efforts for these two portions of the project were divided between the University of Georgia and NASA. The first goal was the responsibility of Dr. Robert Teskey at the University of Georgia. The second was the responsibility of Dr. Jeffrey Luvall at the Science and Technology Laboratory of the Stennis Space Center. The two portions of the project were interrelated because the information obtained from the first part of the project was essential for the development of the models needed to reach the second goal. It also provided the "ground truth" or validation data set for the evapotranspiration estimates developed through the remote sensing approach. This report will describe the research results from the University of Georgia portion of the project funded under Grant NAGW-1034 to the University of Georgia Research Foundation.

Approach

The study was conducted at the USDA Forest Service Coweeta Hydrologic Laboratory in western North Carolina. This site was chosen because it contained gauged watersheds with accurate records of water use by hardwood and pine forests on a landscape (watershed) basis. This information was needed to verify the accuracy of the evapotranspiration estimates provided by direct measurements and remote sensing. The site was also conveniently located near the University of Georgia, an important consideration since repeated access to the site was essential for measurement purposes.

Two independent approaches for estimating the evapotranspiration (Et) from watersheds were used. The first estimate was derived using the Penman-Monteith Equation:

$$E_T = \frac{sA + c_p\, p_a\, D\, g_a}{L\,[s + Y(1 + g_a / g_c)]}$$

Where E_T is evapotranspiration, s is the rate of change of saturation vapor pressure with respect to air temperature, c_p is the specific heat of dry air of density p_a D is the vapor pressure deficit, L is the latent heat of vaporization of water, Y is the psychrometric constant, g_a is the boundary layer conductance and g_c is the canopy conductance.

This model requires the direct measurement of the microclimate of the site as well as biological measurements, i.e., stomatal conductance to water vapor and the leaf area of the stand. The primary limitation of this approach is that the measurement of stomatal conductance is time consuming, and in large trees, access to the foliage is difficult so the sample imust be limited to a small number of trees. In this study, the sample was limited to the trees which could be measured from a single tower in each stand. Because the measurements were restricted to a single site within the watershed, how representative the sample will be must be considered. To address this issue we collaborated with USDA Forest Service research scientists on the staff at the Coweeta Hydrologic Laboratory to share data and compare the results obtained with the Penman-Monteith approach with direct measurements of the water yield from these watersheds obtained from gauged streams.

Results:

Stomatal conductance

Measurements were made in alternating weeks in the two watersheds using a LI-1600 porometer. Samples were taken at three canopy heights on all species. This was very simple in the white pine stand since this was a uniform plantation. Only white pine existed in the overstory, and the understory was very sparse, and made up only 3% of the total leaf area in the stand. The white pine stand was 38 years old, with a fully developed canopy. Total height of the trees was approximately 30 meters. Measurements were made on eight white pine (Pinus strobus) trees in three canopy layers (top, middle and bottom). In this stand sampling was made every other week throughout the year, except when snow prevented access to the stand. Since under these conditions there would be negligible Et, this loss of these measurements was not considered important.

In the hardwood watershed the species diversity was much greater. A total of seven species were sampled. The species included white oak (Quercus alba), scarlet oak (Q. coccinea), red maple (Acer rubrum), black gum (Nyssa sylvatica), American beech (Fagus grandifolia), rhododendron (Rhododendron maximum) and flowering dogwood (Cornus florida). The first four species were in the overstory, and the last three were in the understory. Stomatal conductance was measured in the same way in this stand as in the pine stand, with the exception that the sample size changed with season. All of the species were sampled from the spring leaf out period beginning in early May until leaf drop in late September. Only rhododendron is evergreen, so it was the only species sampled on this site during the winter.

The results of these measurements are shown in Figures 1 and 2. In both stands there was a difference in stomatal conductance with height in the canopy. The top of the canopy consistently had the highest conductance values. This appeared to result from the high light levels at the top, and a relative lack of temperature, vapor pressure deficit or soil moisture stresses. There was a large difference in conductance between the stands as well. Stomatal conductance was much higher in the hardwood stand than the pine stand.

Fig. 1 Stomatal Conductance by Canopy Layer for the White Pine Stand, June 28

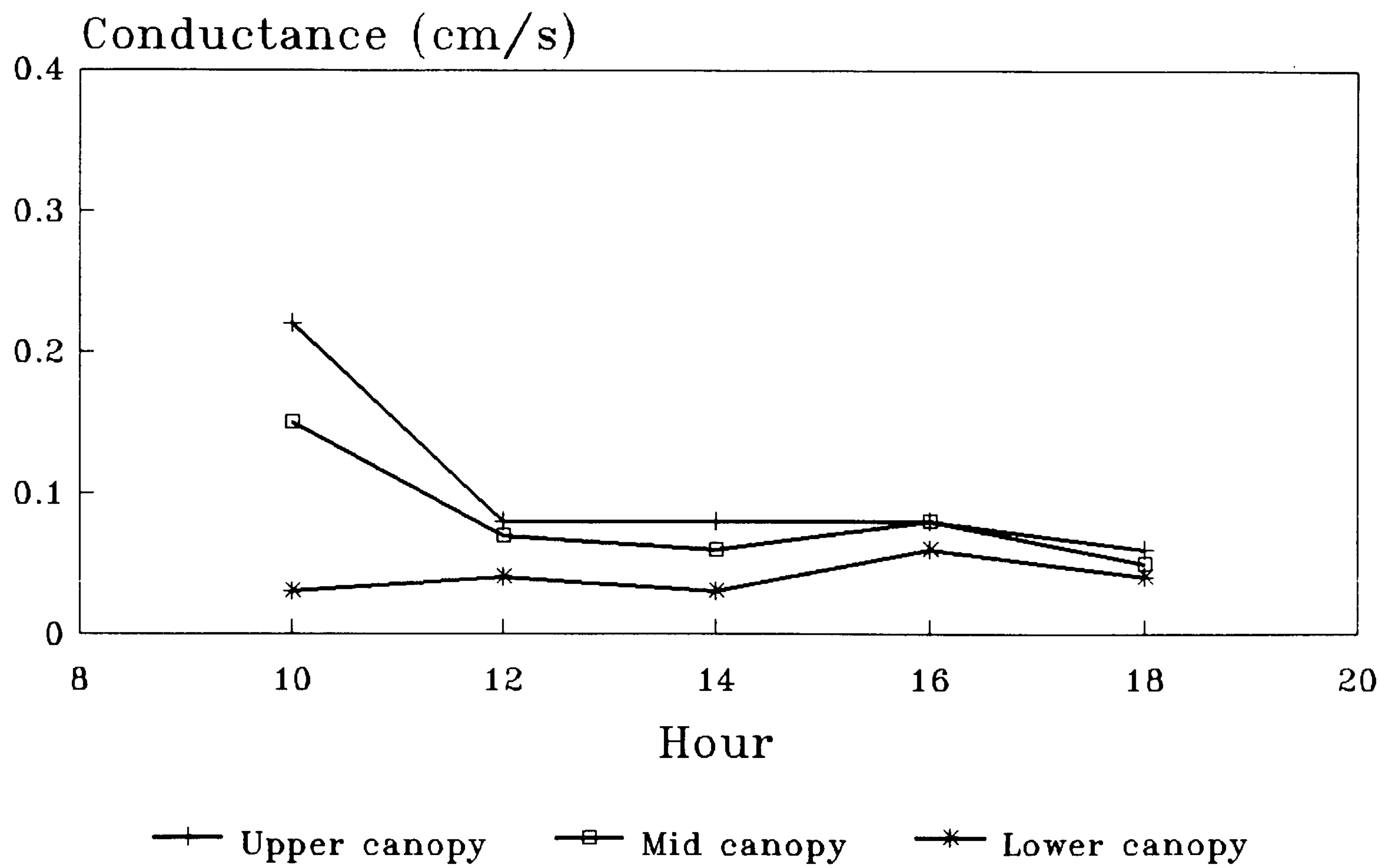
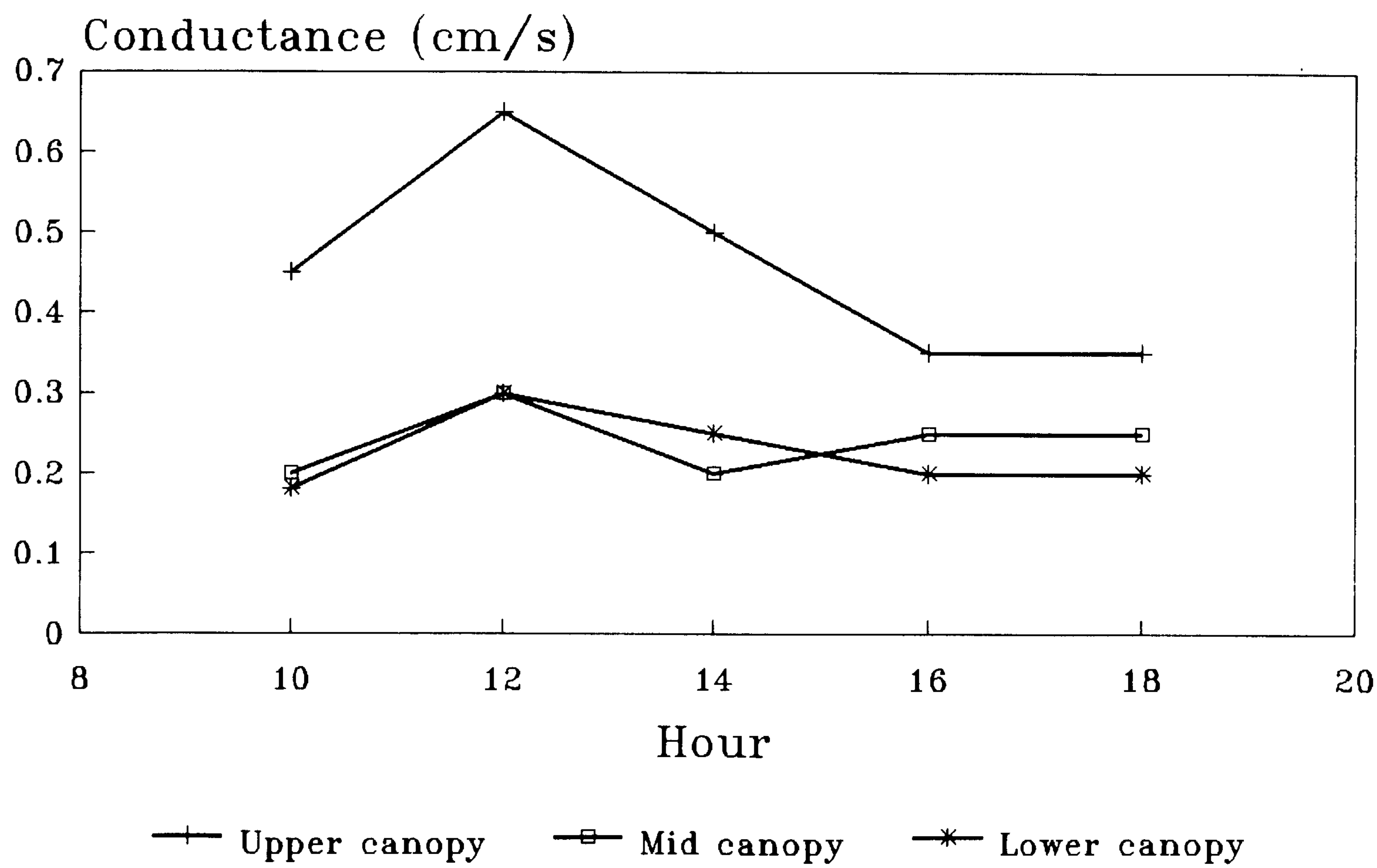


Fig. 2 Stomatal Conductance by Canopy Layer for the Hardwood Stand, June 28



These data were used to develop a model of stomatal conductance based on the environmental conditions at the time of measurement. The initial variables which were used in the model included: photosynthetically active radiation, net radiation, global radiation, air temperature, leaf temperature, relative humidity, vapor pressure deficit, wind speed, and leaf water potential. These environmental variables were used in a regression to predict stomatal conductance during periods when measurements were not available. The regression equations for the two watersheds are shown below:

Table 1. Linear Regression Equations for Stomatal Conductance as a Funtion of Environmental Influences.

White pine (all year):

Stomatal conductance = -0.67+0.098(CT)-0.023(AT)-0.037(AHD)+0.20(WS)-0.002(CT^2)+0.000001(NR^2)-0.012(WSxAHD)+0.0014(ATxAHD)

$R^2 = 0.67$

Hardwood:

A. growing season

Stomatal conductance = -1.28-0.036(AT)-0.0008(GR)+0.34(LGR)+0.036(CT)

$R^2 = 0.46$

B. dormant period (rhododendron only)

Stomatal conductance = -3.14+0.004(NR)-0.38(CT)+7.77(AHD^{-1})+0.46(AT)

$R^2 = 0.98$

Variables: AT = air temperature, CT = canopy temperature, WS = wind speed, AHD = absolute humidity deficit, GR = global radiation, LGR = log global radiation, NR = net radiation.

This portion of the project was very time consuming, but essential since estimates of stomatal conductance are an important component of the Penman-Monteith equation. We felt that it would be desirable to have prediction equations which had better fit, i.e. higher R^2 values, but after many months of attempting this, these were the best models we could develop. The models are not biased or skewed, and all variables are significant. The lack of a better fit of the data may be because the hourly weather records were not sensitive enough to pick up variation within the hour when the actual measurements were made.

For example, if a cloud passed over during a measurement it would significantly lower the stomatal conductance, but if the sun came out again during the hour, this reduction might not be apparent in the weather averaged weather record. In addition, it is now apparent that stomatal conductance is controlled by internal as well as external factors. These include the rate of net photosynthesis, which alters the internal carbon dioxide concentration, which in turn modifies the stomatal aperture. In addition, the rate of transpiration through the stomatal gaurd cells has been shown to modify conductance.

Canopy Leaf Area

In order to estimate canopy conductance to water vapor, stomatal conductance values must be multiplied by the quantity of foliage that the measurements represent. The canopy phenology and quantity of foliage was monitored during the year in both stands. In the white pine stand the leaf area was quite high, reflecting the excellent growing conditions of the site. Leaf area index changed during the year since this species retains foliage for 1.5 years. During the winter (Day 1, i.e., Jan. 1 until Day 120) the foliage was at a minimum (LAI = 8.4). During the period of new foliage development the LAI increase: (121 to 135, LAI = 9.4), (136 to 166, LAI = 11.5). The summer LAI was at maximum (166 to 260, LAI = 13.2). From 261 to 274 the leaf area index declined to 11.8, representing the fall leaf drop period. After that period a bit more foliage senescenced, finally producing the yearly minimum leaf area of 8.4.

In the hardwood stand the winter leaf area index only consisted of rhododendron foliage, which represented an LAI of 0.5. After day 121 foliage began to emerge (121-130 LAI = 2.0). Foliage development continued from Day 131-145 (LAI = 3.5) and the maximum leaf area (LAI = 5.5) existed from Day 146 to 260. After this the leaf drop occurred, decreasing LAI to 3.5 (261 to 275) and further from 276 to 289 (LAI = 2.5) with the winter LAI (0.5) present from 290 to 365.

Estimates of Evapotranspiration

Using the weather data, and estimated canopy conductances, the evapotranspiration from both the pine and hardwood watersheds was estimated using the Penman-Monteith equation. The results are summarized in Figures 3 and 4, along with the monthly precipitation and the difference between the precipitation input and the measured stream outflow from the stands. An examination of these figures reveals that there is a strong seasonality to Et. This is caused by a combination of factors, including the increase in leaf area in the growing season, and an increase in evaporative demand by the air during the summer. It is evident that the monthly precipitation and Et are almost inversely related, i.e., Et is highest in the summer, when precipitation is low, and Et is low in winter when precipitation is high. The high Et in the summer is reasonable, even though it exceeds the input for those months, because of soil water storage. The amount of soil water storage in each month is a function of the difference between precipitation, Et and streamflow. Precipitation should equal Et and streamflow (over a long time period) if it is assumed that soil moisture storage is constant. For the white pine watershed, yearly precipitation was 1275 mm, Et was estimated to be 1382 mm and streamflow was 255 mm. The difference between precipitation and streamflow was 1020 mm. The difference was 362 mm. This indicates that the Penman-Monteith equation was overestimating Et by 35% for the year. For the hardwood watershed, precipitation was 1275 mm, the streamflow was 338 mm, and Et was estimated to be 1128 mm. The difference between precipitation and streamflow was 937 mm. A comparison of that value with Et indicated that Et was overestimated by 20%.

The exact sources of the overestimates cannot be determined. However, it is likely that the primary reason for the difference is that the hydrologic approach has integrated across the entire watershed, while the Et estimates were developed from measurements of only a limited portion of the stand. It is possible that the Penman-Monteith equation has accurately predicted Et for the restricted sampling area within the watershed, but this sampling procedure, which unfortunately is typical of many ecophysiological studies in forests, appears to be inadequate for accurately estimating landscape level processes. Without an independent estimate of the water balance of the stand this error would not have been possible to determine, and would have lead to a serious overestimation of the total water use by these forests by this calculated approach. Manuscripts concerning the results of this study are in preparation.

Fig. 3 Comparison of Et and Hydrology for the White Pine Watershed

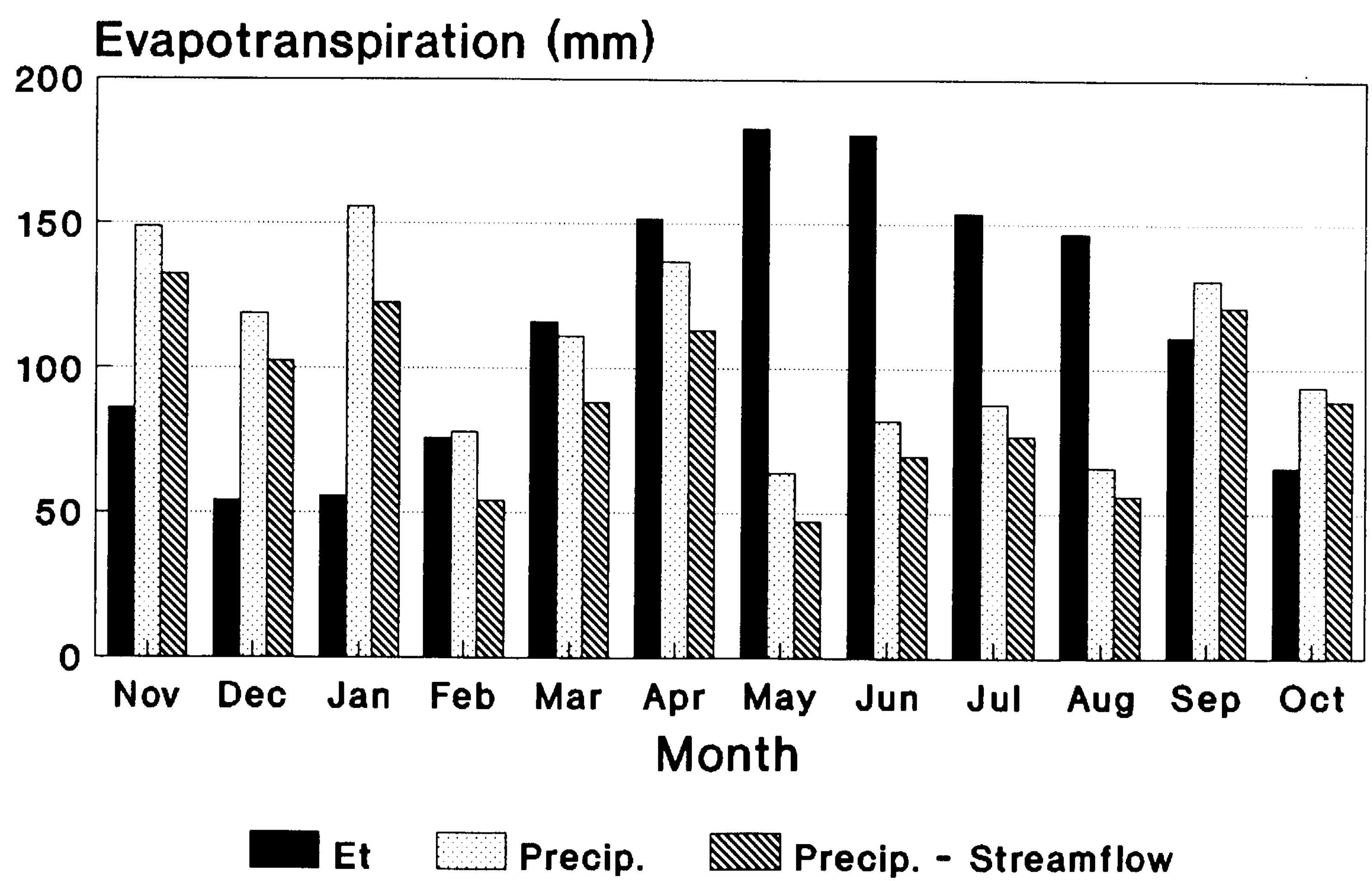


Fig. 4 Comparison of Et and Hydrology for the Hardwood Watershed