PINE TREE EVAPOTRANSPIRATION

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ABSTRACT

Evapotranspiration data of a young slash pine tree (Pinus elliottii) is presented. The information was obtained with a weighing lysimeter placed in the poorly-drained soil of a flatwoods site. The installation had a sensitivity of about 0.5 mm water.

Average seasonal evapotranspiration was 2.4 mm/day for the autumn months, 1.2 mm/day for the winter months, and 5.7 mm/day for the spring months. Equipment failures due to high humidity and lightning damage prevented reliable measurement of evapotranspiration for the summer.

Potential evaporation was calculated with the Penman equation using data from a nearby weather station. Total potential evaporation was 1440 mm for the year of measurement.

The seasonal ratios of measured evapotranspiration to calculated potential evaporation were 0.92 for the autumn months, 0.44 for the winter months, and 0.89 for the spring months.

Measurements will be continued for several years until root restriction begins to have an effect.

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CHAPTER I
INTRODUCTION

Forests are the dominant vegetation type in Florida covering about 15.7 million acres (6.4 million ha) (45% of the total land area) of which about 175,000 acres (70,000 ha) are replanted annually (Bechtold and Sheffield, 1980; U.S.D.A., 1977). Annual income during 1979 was estimated at 132.5 million dollars including sales from farm forests (Greene et al. 1980). Vegetation cover and its stage of development are major determinants of water fluxes in the hydrologic cycle. Forest regeneration starts on nearly bare soil, where evaporation dominates water loss, and progresses through herbaceous development to full site occupation by the forest trees which expand water loss through intensive evapotranspiration.

Water yields from forest lands under a given precipitation regime vary with the stage of forest development (Hibbert , 1967; Anderson et al., 1976). Early successional stages of uplands in North Carolina may initially yield up to 40% more runoff than the mature stage (Swank and Helvey, 1970). Similar studies in central Florida flatwoods suggested 100 to 250% increases in runoff after forest vegetation removal (Swindel et al., 1982). Such water yield changes are controlled mainly by rates of evapotranspiration as modified by changes in vegetation cover (leaf area index) and interception, rooting depth, surface roughness, annual insolation and albedo (Douglass and Swank, 1975; Robins, 1965).

Annual insolation varies little over north-central Florida because aspect influences are insignificant. Therefore, manipulation of the distribution and extent of each forest successional stage over time and space represents an important tool for controlling soil moisture storage, aquifer recharge, and runoff from most of Florida's landscape. Water supply and water quality are rapidly becoming crucial issues for water policies in Florida (Lynne and Kiker, 1976; Maloney 1980; Hutchinson, 1981).

The objective of this study was to evaluate the relationship of the Penman equation of potential evaporation to actual evapotranspiration from a developing flatwoods pine plantation. Daily estimates of atmospheric demand from weather station information were compared with daily evapotranspiration data from a nearby weighing lysimeter installed in a young pine plantation. This report covers the first three years of construction, calibration and evapotranspiration data of the installation. Monitoring will be continued for another decade until root restriction and crown closure are expected to significantly affect the lysimeter tree.

CHAPTER II
LITERATURE REVIEW

Forest Water Management

Forest water management in Florida traditionally has been focused on drainage of excess water from wet areas for better equipment access and tree growth (Young and Brendemuehl, 1973; Klawitter and Young, 1965). Water management control by shallow ditches (0.6 m deep) did not affect water table levels, but 1.5-m-deep ditches improved drainage to the point of droughty conditions for slightly higher elevations in the flatwoods landscape (Kaufman et al. 1977). A seasonally fluctuating water table was less beneficial for tree growth than a constant-level water table (White and Pritchett, 1970).

Little attention has been given to non-structural water management control by manipulation of evapotranspiration. Forest evapotranspiration represents the major pathway (60-90%) of precipitation disposal in Florida. Manipulation of evapotranspiration can be achieved by selecting appropriate tree species with respect to crown structure and vigor of growth (Krygier 1971; Verry, 1976; Van Lill et al., 1980). Vegetation with deeper and more extensive root and canopy systems tends to use more water (Pritchett, 1980; Duncan and Terry, 1982). Also, it has been shown that coniferous tree canopies increase water use mainly due to more rain interception and evaporation as compared to deciduous broadleaf trees (Swank and Douglass, 1974; Maxwell, 1976). The dense needle-like foliage of Australian pine (Casuarina glauca) of south Florida may be expected to significantly increase rain interception.

Major management control of areal evapotranspiration, however, is by judicious harvest patterning (Douglass, 1965). Vegetation removal reduces evapotranspiration in some proportion of the amount of leaf area removed. Consequently soil moisture increases often to the point of saturation bringing the water table to the surface and generating runoff (Williams and Libscomb, 1981). This process begins in the wetlands adjacent to streams and expands the runoff source area uphill with continual rainfall inputs (Hewlett and Hibbert, 1967). Douglass and Swank (1975) estimated for Appalachian highlands the annual water yield increase (ΔQ inch/yr) from percent of basal area cut (x_1) and solar radiation (x_2 microlangleys) by: $\Delta Q = 0.0024\ (x_1/x_2)^{1.446}$. For north-central Florida the calculation amounts to a 30 cm yield increase after

clearcutting. Clearcut harvesting followed by windrowing for site preparation of a pine flatwoods site in north-central Florida increased water yield by 12 cm (Riekerk et al., 1980). Minimum site preparation by drum chopping quickly regenerated considerable weed and sprout vegetation resulting in an increase of only 5 cm runoff/year. Hibbert (1967) in a worldwide literature review reported average increases of 25 cm (range 3 to 45 cm) water yield from clearcut upland forests. Experimental manipulation of evapotranspiration by species conversion and vegetation removal generated a range in runoff changes from minus 20 cm to plus 40 cm, respectively (Stone et al. 1978).

As an example, areal evapotranspiration and water yield from a large pine flatwoods watershed may be regulated to maintain a sustained increase of water yields assuming a 25-year harvesting rotation and a 100% increase of runoff due to commonly used clearcut harvesting and regeneration practices. A 25-year rotation schedule causes 4 percent of such a large watershed to be harvested each year. Doubling the yield from this clearcut area results in an annual yield increase of 4 percent from the total watershed. Triple the runoff from the clearcut area would result in an 8 percent annual yield increase from the total watershed (Riekerk, 1982).

Recent interest in tree farming for fuelwood with fast-growing exotic species may drastically alter these water yield fluctuations. Rapidly growing dense stands of Melaleuca quinquenervia in south Florida are thought to transpire substantially more water than the more open native vegetation (Woodall, 1980). Similarly, high-density fuelwood plantations could considerably increase transpiration as well as rain interception, reducing watershed yields significantly below those of native forest or wet savanna vegetation (Hibbert, 1969; Ursic, 1974). Forest growth at a high planting density soon occupies the total growing site, necessitating a much shorter harvesting rotation (Wells and Crutchfield, 1974). Therefore, doubling of runoff from 20% of the area each year by a 5-year harvesting rotation would result in a 20% increase of annual water yield from the total fuelwood-farm watershed. Rapid coppice sprouting however would reduce this effect.

Forest Water Use Information

Some crude evapotranspiration information may be derived from annual precipitation and runoff data, neglecting differences in storage between years, and assuming groundwater loss to be only a few percent of the precipitation input (Lee, 1970). Using these assumptions Klein et al. (1975) estimated a 1220 mm/yr evapotranspiration rate from the Big Cypress Swamp in south Florida. This rate represented 90% of the precipitation input. Speir et al. (1969) reported undisturbed runoff

from a forest and range watershed of Taylor Creek in South Florida as 27% of the 129 cm/yr precipitation input. Subsequently, more detailed accounting for aquifer recharge and changes in storage yielded an estimate of 86 cm evapotranspiration per year for this area (Knisel et al., 1982). Faulkner (1975) calculated evapotranspiration as 66% of 135 cm/yr rainfall using flow-net analysis of geohydrologic data from uplands in north-central Florida. Riekerk et al. (1978) reported 39% runoff from a poorly-drained flatwoods forest in north-central Florida after 153 cm precipitation in a wet year. Similar data for drier years (126 cm/yr precipitation) yielded about 10% runoff (Riekerk, 1981). Campbell (1979) reported runoff from a flatwoods forest in north central Florida as 5 and 10 percent with 105 and 88 cm/yr precipitation during dry years. Turner et al. (1977) from a forested-agricultural watershed in north Florida measured an average of 12.3% runoff with an average of 127 cm/yr precipitation. Such data suggest that a significant portion of incoming precipitation is disposed of by evapotranspiration as compared to runoff and deep seepage.

These calculations are based on measurements from experiments on research watersheds. A wider application requires a state-wide data base for representative physiographic provinces and forest vegetation types. Direct measurements of actual evapotranspiration from forest vegetation at different stages of successional development could considerably refine forest water management guidelines.

Dohrenwend (1977) calculated with the Holdridge method (Holdridge, 1967) annual potential and "actual" evaporation rates for Florida from biotemperature data (Figure 1). The calculated value for Gainesville in north-central Florida underestimated within 6 percent the corresponding value measured by Bartholic and Buchanan (1976). Agreement of calculated potential evaporation values with lake evaporation data was good for southern Florida but underestimated measurements for north Florida. Burns (1978) measured annual evapotranspiration from Fakahatchee Swamp at 1024 mm which approximates the 1000 mm value calculated by Dohrenwend for the area. Parker et al. (1955) measured a range of 890 to 1525 mm annual evapotranspiration for a variety of vegetation covers near West Palm Beach. Potential evaporation for that area is about 1250 mm/year and evapotranspiration as calculated by Dohrenwend is about 1000 mm/yr. Preliminary information from tension lysimeters in north Florida's sand hills suggested a water use rate of more than 90% of 120 cm precipitation during a relatively dry year at the initial stages of pine forest succession (Riekerk et al. 1981).

Methods of Water Use Measurement

Measurements of forest evapotranspiration as reported above contain large errors and are poorly replicated in time and space. Predictions

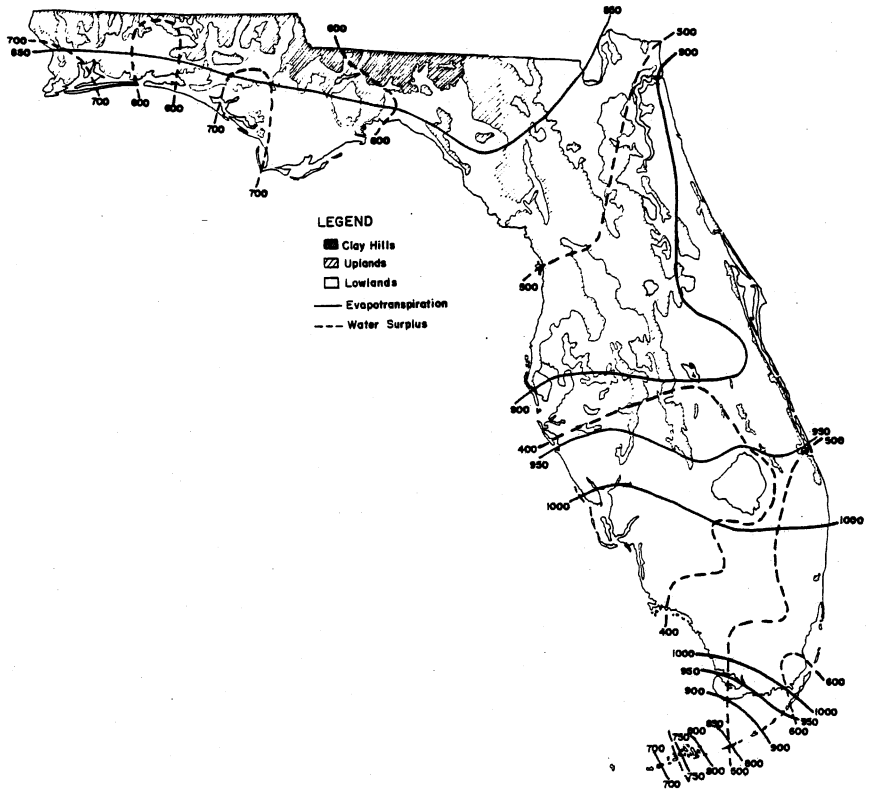

Figure 1. Physiographic provinces and annual evapotranspiration (mm) regimes (Dohrenwend, 1977).

of evapotranspiration at any location in Florida for a given successional stage of a forest type are difficult to make. Utilization of climatological data, or more recently aircraft imagery (Jackson et al., 1981), in empirical or theoretical equations (Thornthwaite, 1948; Penman, 1948; Monteith, 1965) may provide areal estimates of evapotranspiration such as published by Dohrenwend (1977). Checking these calculated values against actual field measurements for the duration of a forest rotation is still required.

Field estimates of evapotranspiration have been made from water balances of experimental watersheds over the entire development of a forest (Swank and Helvey, 1970; Rodda, 1976). These units were also large enough to calibrate satellite imagery (IFAS, 1980). Time resolution of such water balances is in the order of days. Calibration for watershed leakage may take a decade. Measurement errors of less than 15% are considered fair (Lee, 1978).

Measurements of instantaneous vapor fluxes at a measuring point can be made for short time series with an anemometer and sensitive temperature, humidity and net radiation sensors (Stanhill, 1969; Hicks et al., 1975), but rapid degradation of complex electronic instruments and sensors is yet a serious drawback.

Transpiration of individual branches or even small trees enclosed in transparent chambers may be measured from vapor analyses of input-output fluxes of the ventilation air stream (Lee, 1978; Kaufman, 1981). Temperature control to approximate exterior field conditions is the largest error component of this method. By definition the method excludes evaporation of rain normally intercepted by the foliage.

Water use also may be estimated from frequent soil moisture measurements to assess changes in water content. This technique works well in deep soils of dry climates where drainage is minimal, or for a short time interval by excluding rainfall with a soil cover (Metz and Douglass, 1959).

Daily changes in watertable levels may be used to estimate evapotranspiration (White, 1932). Assuming early-morning rises to represent only recharge, this term can be subtracted from the daytime drawdown to estimate the water use component. Woodall (1980) used this method for a Melaleuca stand in south Florida and found a good correlation with potential evaporation and daily insolation. This simple method is limited to shallow watertables in or near the rooting zone such as occur in Florida's flatwoods. Daily barometric pressure changes may confound the observations and need to be accounted for (Turk, 1975). Increased drainage during low atmospheric pressure was also observed from a saturated subsoil of a San Dimas lysimeter under pine (Patric, 1974), and from a sloping forest soil in North Carolina (Hewlett and Hibbert, 1963).

Accurate daily water balance measurements can be made from smaller forested areas with sealed boundaries such as lysimeters (Van Bavel, 1961, and lysimetric plots (Law, 1957). Boundary restrictions and the usually disturbed soil profile are the major drawbacks of these methods. However, lysimeter studies of water balances appear to be a practical compromise between long-term accuracy, time resolution and cost to evaluate evapotranspiration during stand development. Walled lysimetric plots require an impermeable substrate (aquiclude) such as compacted basal till of glaciated soils (Law, 1957) or a dense clay layer under the rooting zone (Riekerk et al. 1981). Such plots have undisturbed soils and can be large enough to alleviate root restriction, but require calibration or assumptions regarding leakage.

Monolith lysimeters are large containers flush with the surface and backfilled with soil in an approximation of the original horizons. Drainage of earlier units was only by gravity, causing a saturated subsoil, a condition that was absent in the surrounding area (Patric, 1974). Later units had forced drainage through ceramic tubes to simulate subsoil suction. The problem of root restriction for large trees remained unresolved except for the very large lysimeters built and planted with pines near Castricum, Holland (Van Wyk, 1967).

The weighing lysimeter is a large container buried in the soil but placed on a weighing mechanism to follow changes in water content continually (Fritschen et al., 1977). For practical purposes a daily resolution of 0.1 mm sensitivity is sufficient for most studies of water relations in trees. Fritschen et al. (1973) built a steel weighing lysimeter around the root ball (3.7 mm diam x 1.2 m depth) of a 28 m Douglas-fir tree. Later lysimeters were filled with the rootballs of small trees transplanted with a large crane (Schiess, 1977). Sensitivity of these units was about 0.1 mm water.

Lysimeter water balances may not be very representative for forest stand evapotranspiration because of the above noted limitations, but can be used successfully to evaluate plant water relations and to calibrate other more extensive (meteorological) methods (Lee, 1978; Van Bavel, 1961). For example, Mustonen and McGuinness(1967) used data from the grass-covered Coshocton, Ohio, lysimeters to establish correlations with data from watersheds under different levels of forest management.

Numerous empirical and theoretical equations have been proposed to describe evapotranspiration using weather data (Gray, 1973). Several of these estimate "potential evapotranspiration" for a given set of conditions as a reference. Seasonal crop correction factors derived from comparisons with actual evapotranspiration measurements have been published (Van Bavel, 1966). The term "potential evapotranspiration" is misleading because the transpiration component is not only determined by atmospheric

conditions (Lee, 1980). Some investigators incorporated soil moisture and plant stomata variables to achieve a closer correlation (Monteith, 1965; Rutter, 1967). A better descriptive term for the predictions from pure meteorological equations is "potential evaporation."

The Penman equation (Penman, 1948) has been used in this report because of the sound theoretical foundation, the daily resolution, and the availability of standard weather data.

The original Penman equation is as follows:

$$E = \frac{\Delta \cdot H + \& \cdot E_a}{\Delta + \&} \text{ mm/day}$$

where E = potential evaporation or atmospheric demand
Δ = slope saturated vapor pressure (mm Hg/F)
& = psychrometric constant = 0.27 mm Hg/ F.

and

$$H = R_s (1 - r) - R_b$$

where

H = heat budget (mm/day)
R_s = incoming shortwave radiation (cal/cm^2/day)
R_b = outgoing longwave radiation (cal/cm^2/day)
r = albedo (percent)

and

$$E_a = 0.35 (e_s - e_a) (1 + 0.24V)$$

where

E_a = evaporation at vapor deficit $e_s - e_a$ (mm/day)
e_s = saturated vapor pressure at Ta (mm Hg)
e_a = actual vapor pressure at Ta (mm Hg)
Ta = air temperature (F)
V = wind speed (mph)

CHAPTER III
PROCEDURES

Site Description

The study site is located within the research area of the Cooperative Research in Forest Fertilization (CRIFF) program at the Austin Cary Forest about 20 km northeast of the University of Florida (Figure 2). The general area is representative of the extensive flatwoods forest type in the Gulf-Atlantic lower coastal plain and Florida. The sandy soils are poorly drained and developed under slash pine (Pinus elliottii, Engelm.) and longleaf pine (Pinus palustris, Mill.) forest. The climate is characterized by about 1450 mm/yr rainfall (Dohrenwend, 1978). Winter storms are associated with passing cold fronts while summer rains derive primarily from convective storms. Average maximum air temperatures during January and July are 20.5° C and 32.7° C, respectively. Average minimum air temperatures are 7.0° C and 21.6° C, respectively. Evapotranspiration is about 900 mm/yr (Bartholic and Buchanan, 1976).

The research area was cleared and planted to 1000 trees/ha of slash pine during 1977 (Burger, 1979). A central weather station was established that records air temperature and humidity, rainfall, water table level, wind speed and direction, and total and net solar radiation. These variables include the parameters necessary for calculation of daily potential evaporation according to the Penman method (see Appendix).

The soil surrounding the weighing lysimeter is a siliceous sandy hyperthermic ultic haplohumod (Electra series) typical of the poorly drained flatwoods in north-central Florida. The ash-colored surface soil (pH = 4.8) is about 53 cm deep with a bulk density of 1.7 g/cm^3, 0.7% organic matter, 0.7 meq/100 g CEC, 143 ppm total nitrogen, 20 ppm total phosphorus, and 60 ppm extractable calcium (CRIFF, 1978). The underlying spodic horizon is darkly colored by humic-ferric precipitates and is about 36 cm thick with a bulk density of 1.9 g/cm^3. Chemical properties of this zone include 1.4% organic matter, 2.0 meq/100 g CEC, 219 ppm total nitrogen, 37 ppm total phosphorus, and 25 ppm extractable calcium. The light colored sandy parent material below grades into clay at 140 cm depth.

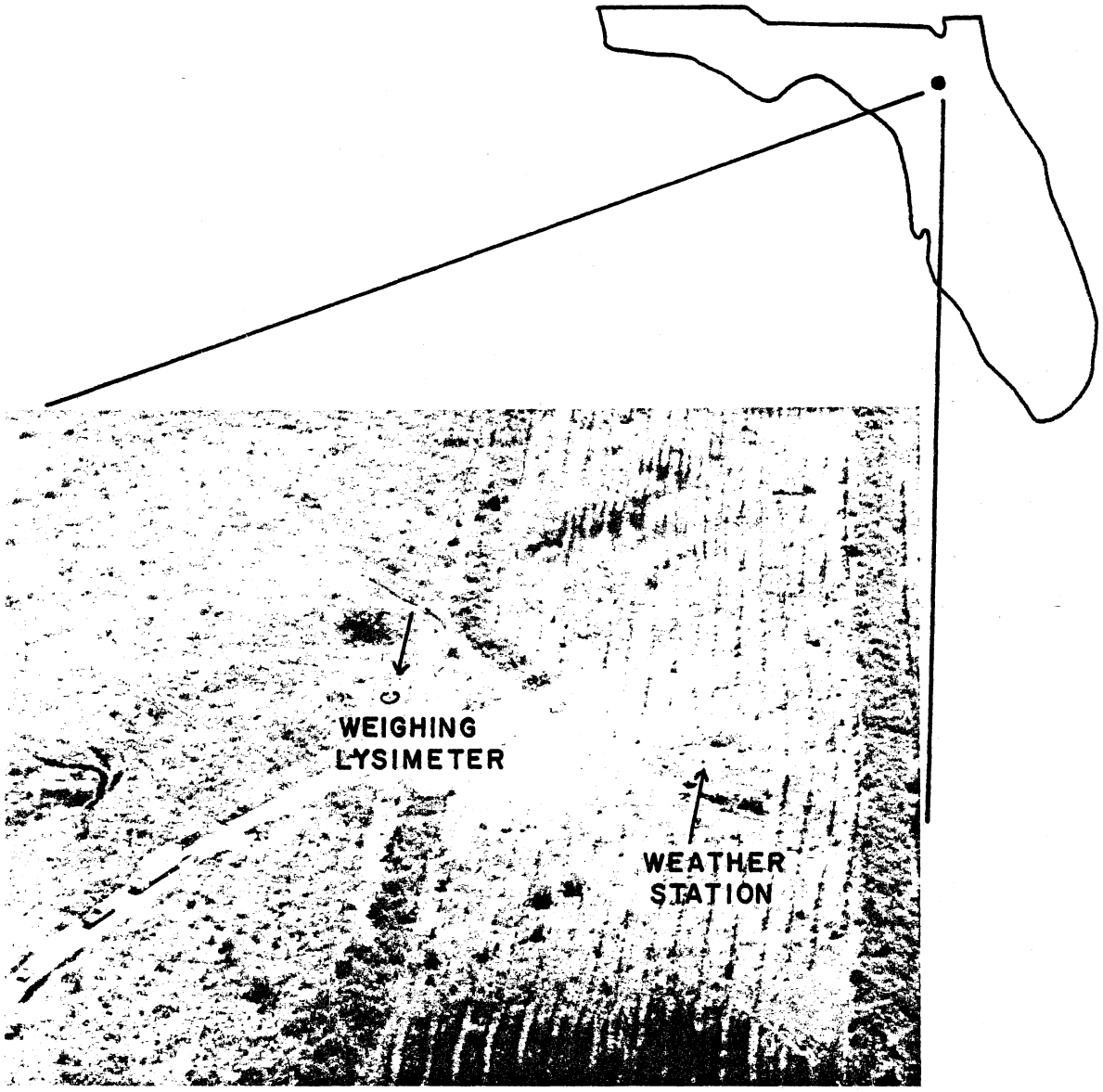

Figure 2. Location of the weighing lysimeter and adjacent weather station in the pine plantation.

Lysimeter Installation

A nested double-tank lysimeter was anchored flush with the soil surface (Figure 3) about 60 m east of the existing weather station. Each fiberglass tank had two 5-cm-thick reinforcing rings in the 0.6 cm thick wall to prevent circle deformation. The bottom was 0.5 cm thick fiberglass with reinforcements as explained under RESULTS. The outside tank (3.2 m diam x 1.4 m deep) provided a level and rigid base and a dry operating space in the poorly drained soil. Forced drainage from the inside tank (3.0 m x 1.2 m deep) was from twenty ceramic filter candles (25 cm x 5 cm diam) buried at the bottom. Pumping started when the interior water level exceeded the soil surface.

After lysimeter installation, soil settlement and system testing, pine tree seedlings were planted in and around the lysimeter to homogenize the plantation area at large. In this fashion the experiment became nested in a typical landscape and subject to the meteorological conditions of a developing pine plantation. Weight changes of the inside tank (resolution about 0.5 mm water) were monitored by a sensitive differential pressure tranducer and recorded both on a millivolt chart recorder and an electronic datalogger.

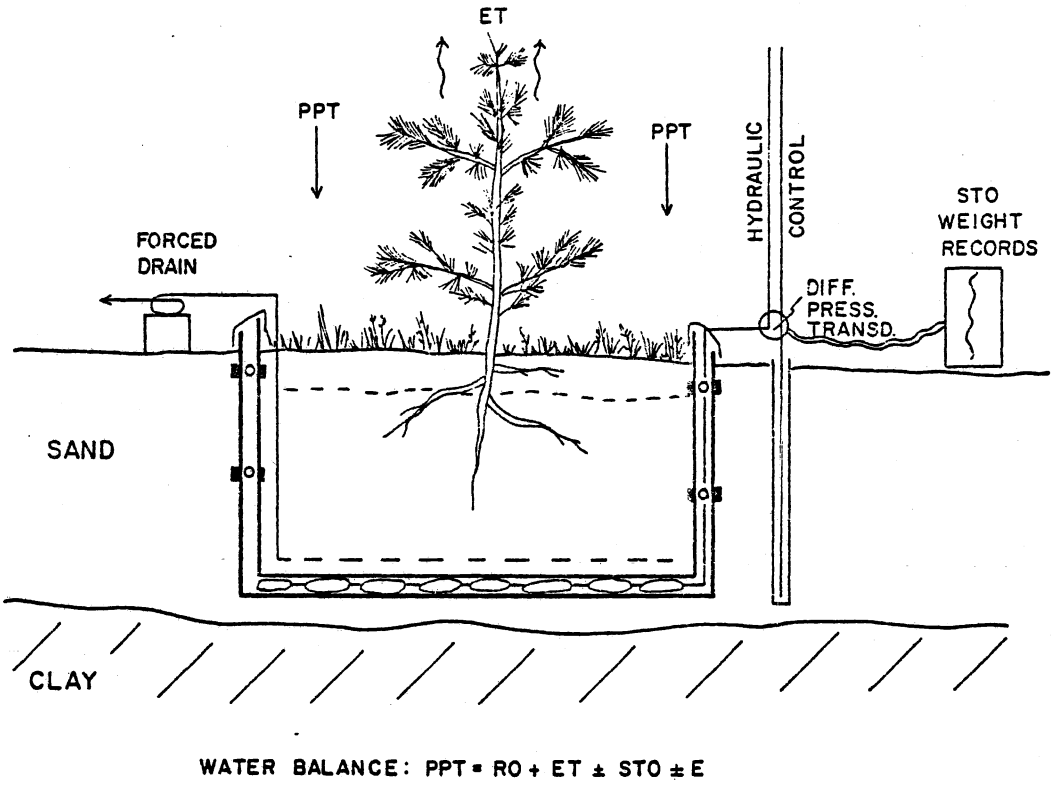

Figure 3. Diagram of hydraulically weighing lysimeter.

CHAPTER IV
RESULTS

Installation of Lysimeter

The installation of the weighing lysimeter in the poorly-drained soil of the area caused several problems. The external tank was buried and anchored through fiberglass extensions at the base during relatively dry conditions in the spring of 1979. Flotation pressure from the rising watertable broke the anchorage after the first rains. A second try during the summer also failed as funding limitations prevented the use of multiple-well pumping to keep the working area dry. During the dry fall season the tank was successfully anchored by the rim to 3 m deep x 10 cm diameter *in situ* grouted pilings.

Ten lapstrake butyl-rubber hydraulic tubes (15 m long x 5 cm diam) were filled with de-aired water and tested for pinhole leaks and then coiled on the bottom (Figure 4). Tire valves vulcanized to one end of each tube were connected by thickwall plastic tubing to the adjacent manometer standpipe. Multiple hydraulic tubes are easier to manage, and if one fails the remaining tubes still remain functional. Also manometer sensitivity can be changed by disconnecting individual tubes. Subsequently, the inside tank (213 kg) was centered on the hydraulic tubes and filled with water for preliminary testing of the system (Figure 5). The addition of 7400 liters of water brought the manometer from 96 cm to 297 cm above the bottom of the outside tank. Sensitivity was 0.4 mm water as read to the nearest mm on the manometer (coefficient = 2.2). After this test the water was pumped out of the inside tank and the bottom covered with 5 cm of coarse silica filter sand containing the 20 ceramic drainage tubes (Figure 6). Soil was backfilled to approximate the original horizonation and allowed to settle for some time in saturated condition. Fixed weight additions for calibration showed sensitivity to be 0.5 mm water. Increased hydraulic pressure by the heavier soil was brought down to the 3.0 m manometer level by bleeding excess water out of the hydraulic system, causing the rubber tubes to become more compressed. The reduction in sensitivity was probably due to the greater weight of soil and the resulting larger contact area between the rubber tubes and the bottom of the inner tank. A slash pine tree seedling was planted in the center of the lysimeter as part of the surrounding plantation during the winter of 1980 (Figure 7).

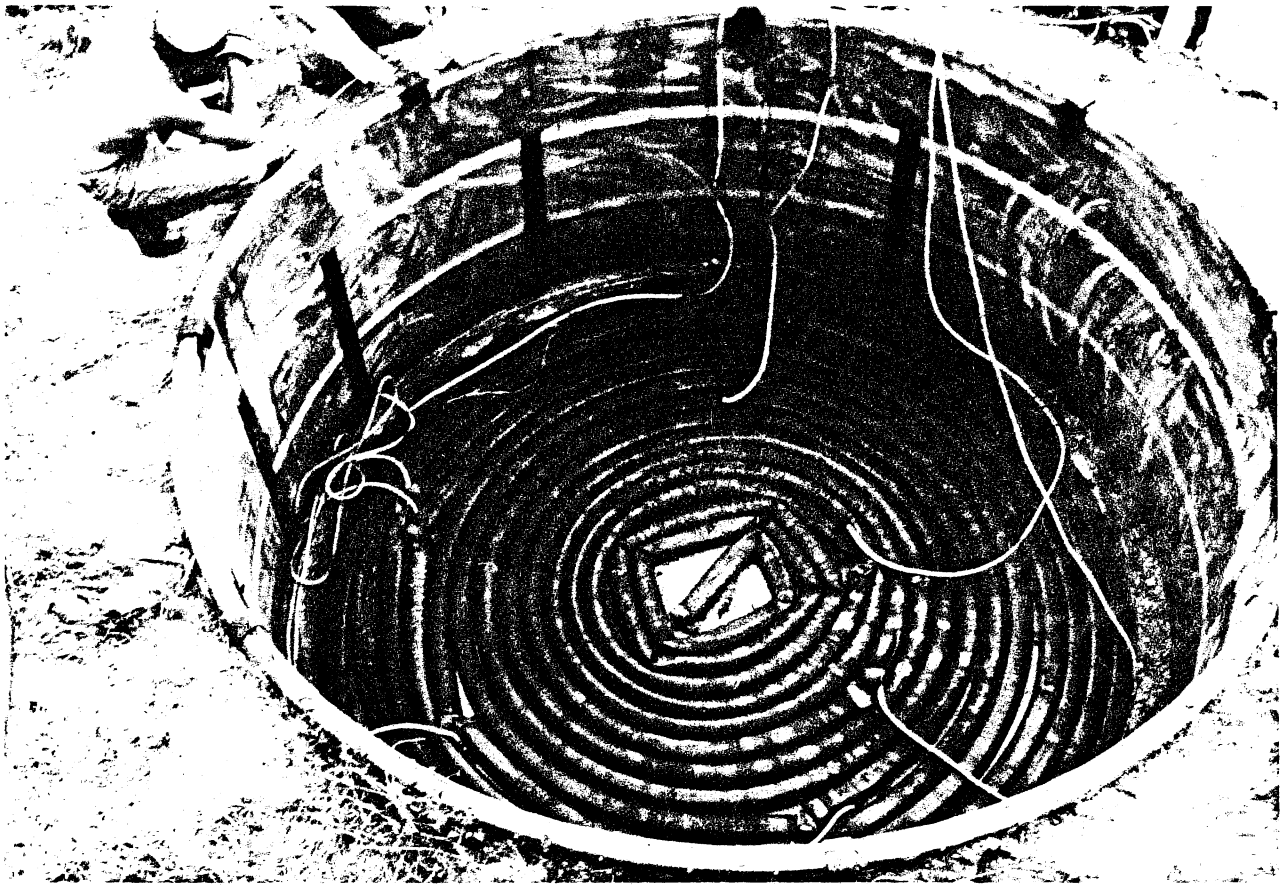

Figure 4. Hydraulic pressure tubes for weighing lysimeter.

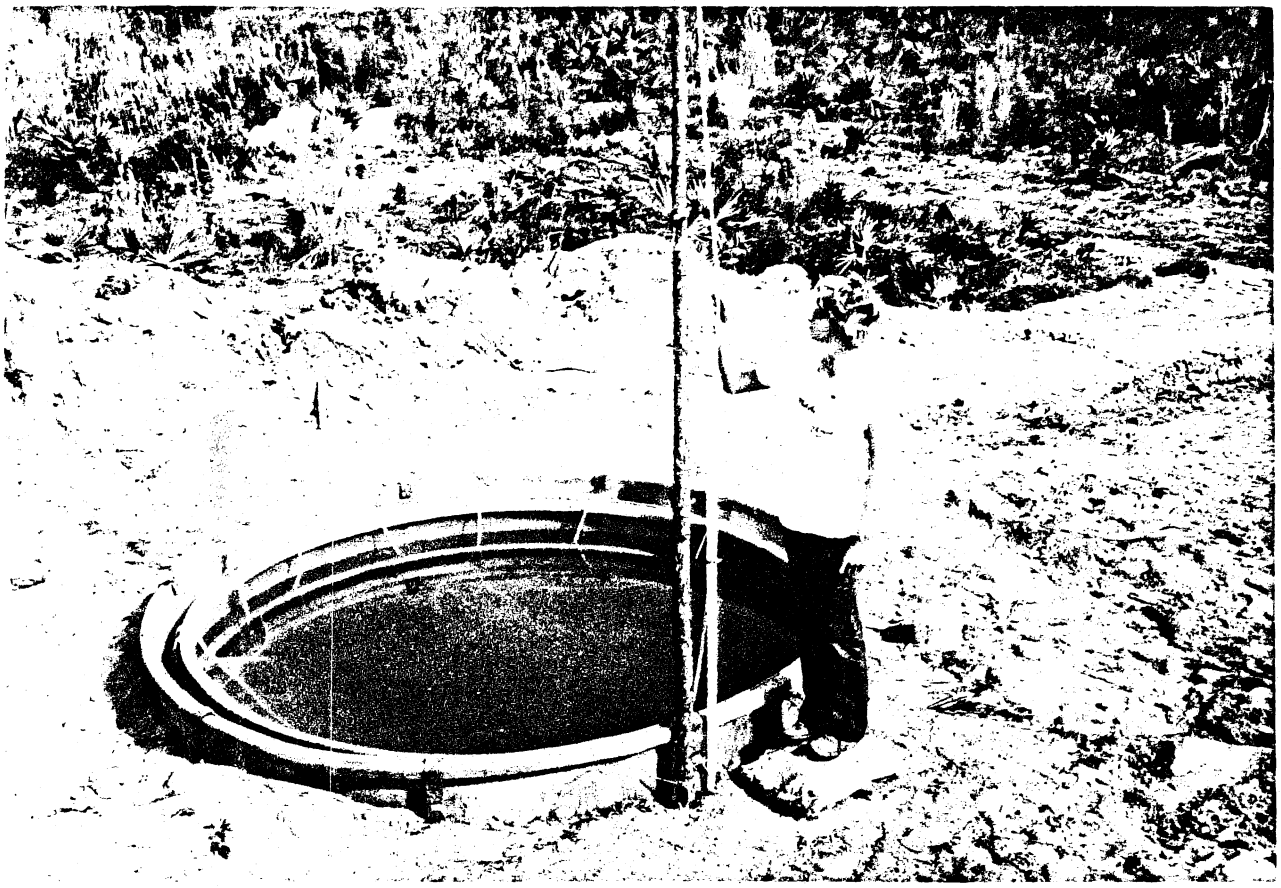

Figure 5. Preliminary testing of water-filled weighing lysimeter.

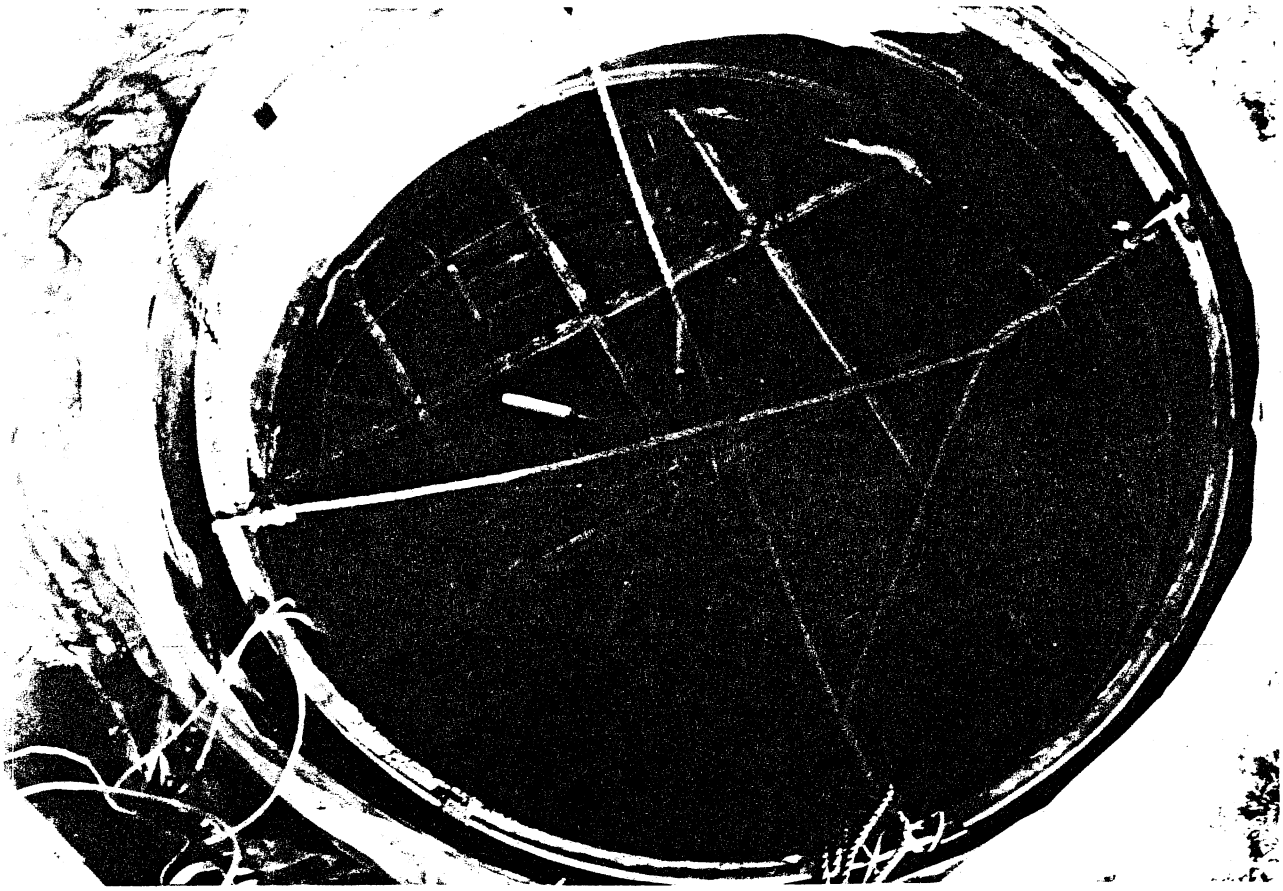

Figure 6. Ceramic drainage tubes at the bottom of the inside tank.

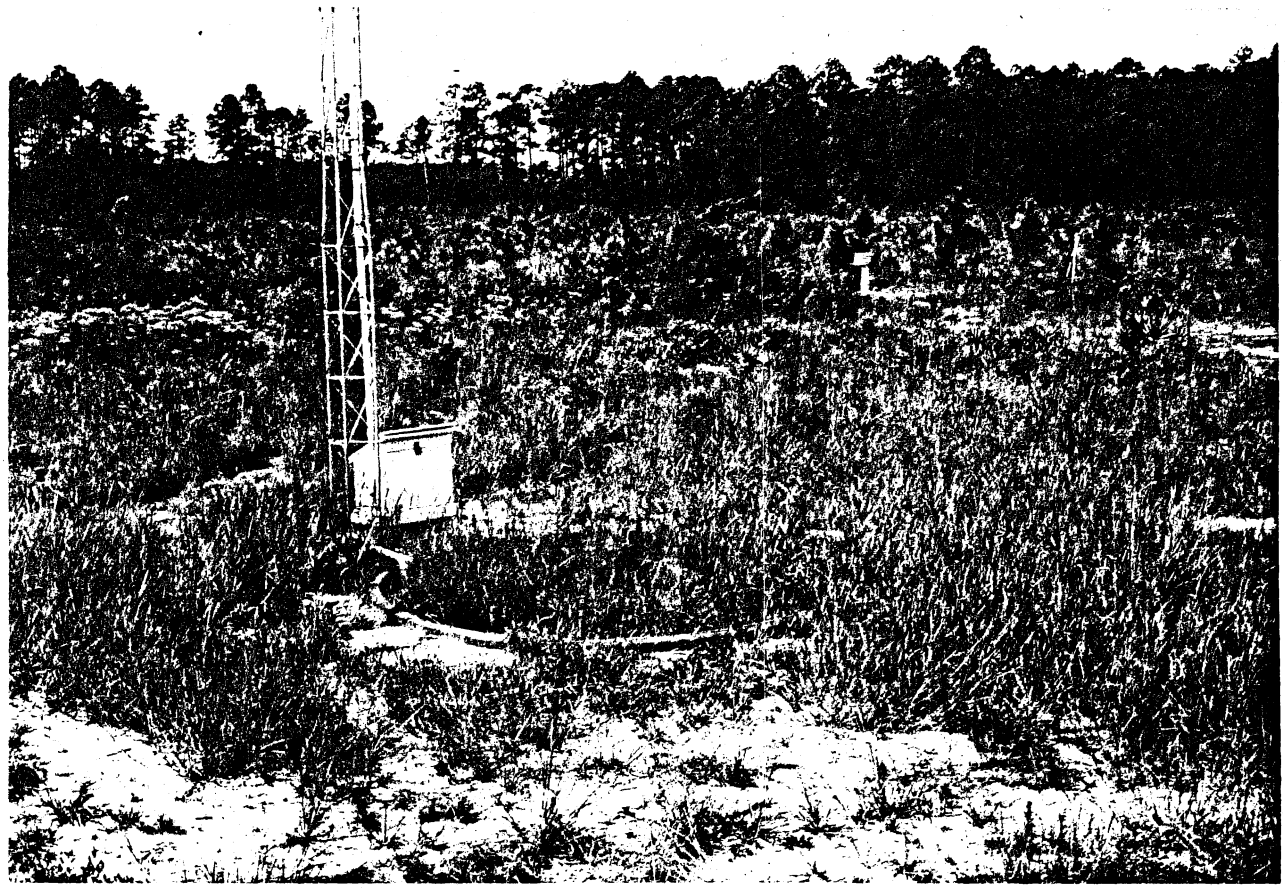

Figure 7. Weighing lysimeter after installation in 1980.

A differential pressure transducer (SETRA* Model 228, 24 VDC) was delivered and installed during the spring. The manometer line was connected to one port and a static reference line to the opposite port. The reference line was to compensate for pressure changes due to barometric pressure, and due to changes in water density at different air temperatures. The transducer initially had a linear sensitivity of 7 mV/mm water for a range of $\pm$ 50 cm differential water pressure. The electrical output was recorded first only on an Esterline 10 mV/mm chart recorder advancing at 2 cm/hr. Response time to fixed weight additions was immediate but stabilization required 2-4 hours. These early chart recordings were very difficult to interpret because of erratic and contradictory patterns. Figure 8 summarizes all manometer recordings uncorrected for re-calibration and manometer coefficients.

An electronic data logger (Campbell Scientific* Model CR-21) with 1 mV sensitivity also was delivered, tested, and installed in the weather station adjacent to the lysimeter during the fall of 1980. Datalogger memory storage was about 650 data points, but has been expanded to 10,000 data points with an on-line cassette recorder. Weather station sensors and the lysimeter transducer were connected for recordings of hourly summaries. Cassette tapes were read into the main frame computer by an RS 232 interface (Campbell Scientific* Model A 235).

During the wet summer months considerable confusion showed up in the chart recordings. The recordings also decreased in sensitivity due to a gradual unbalancing of the inner tank until it finally rested against the outside tank. A lightning storm severely damaged the pressure transducer and datalogger.

Analysis of the earlier records revealed a strong influence of outside watertable changes on the manometer readings. Only when the watertable dropped below the lysimeter installation did the recordings show some regularity. It was surmised that the bottom of the outside tank was flexing in response to forces from the watertable as well as from the hydraulic rubber tubes.

During the following dry autumn the lysimeter was dissassembled and a 10 cm thick slab of reinforced concrete was constructed in the bottom of the outside tank. The bottom of the inside tank was reinforced with fiberglassed wood braces (Figure 6). Hydraulic rubber tubes were replaced and the inside tank was centered again and backfilled with soil which now was more mixed than before. Sixteen steel skate wheels bearing against steel strips in the annular space were used to maintain balance.

*Use of brand names does not imply endorsement.

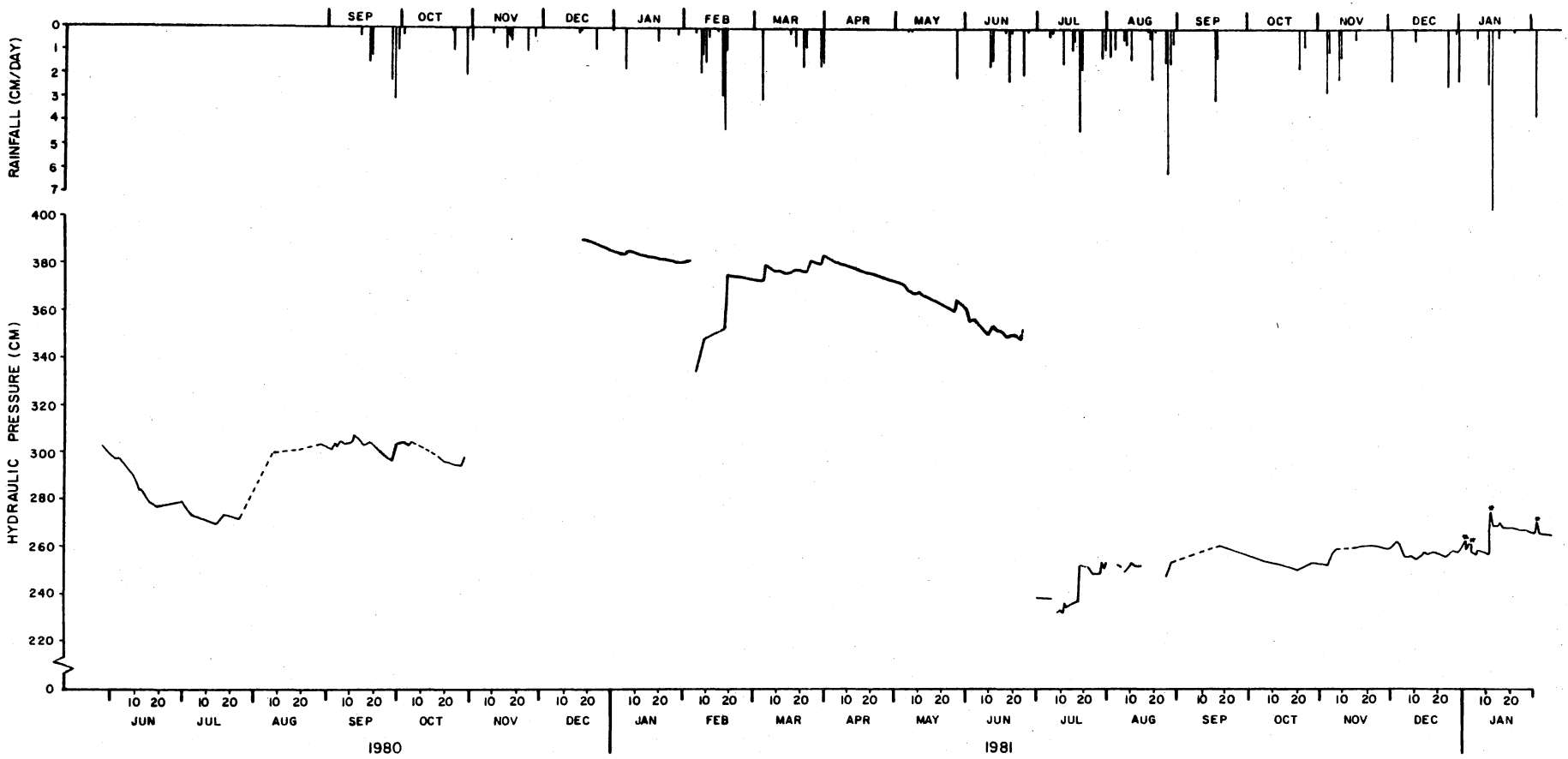

Figure 8. Record of manometer recordings from the weighing lysimeter. *Denotes runoff drainage.

The surrounding young pine plantation had been damaged by the heavy backhoe used for lysimeter repair and by soil storage piles. Replacement trees from the 1977 plantation adjacent to the weather station were transplanted during the spring, including a 2 m tree centered in the lysimeter (Figure 9). Leaf area of this tree was estimated during November 1981 at 5.8 m^2 resulting in a pine leaf area index (LAI) of 0.85 m^2/m^2 for the lysimeter area.

Hydraulic pressure in the manometer rose to 4.0 m by rainfall during the fall settlement period (Figure 8). Calibration showed that the sensitivity remained at 0.5 mm. A severe cold spell during the winter froze the manometer line and the resulting over pressure damaged the transducer. A break in the hydraulic line dropped the pressure, but winter rains brought the level back up. A calibrated lowering of the manometer level by 1.25 m on June 26 reduced the sensitivity to 0.7 mm (coefficient = 1.4).

As a result of the bottom rigidity and free-standing balance of the lysimeter general trends associated with periods of drought and rainfall became apparent in the chart recordings. However, contradictory daily fluctuations were still present and were found to be correlated with temperature changes. Such temperature effects have been reported by others for hydraulic weighing lysimeters (Dylla and Cox, 1973; Schiess, 1977). Apparently the reference line was not representative enough for the temperature conditions of the manometer system. The reference was connected to a larger waterfilled plastic tube located at the bottom of the annular space of the lysimeter. Temperature changes at the 1.3 m soil depth are insignificant and temperature essentially remains constant at 25 °C in this soil (Bastos and Smith, 1979). The larger volume of more temperature-stable water improved the thermal stability somewhat.

High humidity and a lightning storm early in the summer of 1981 again damaged the pressure transducer and datalogger. Periodic recordings of the manometer and watertable level presented general impressions of the changes in water content while instruments were being repaired. Datalogger sensitivity was diminished to 4 mV/mm water after repair. During December 1981 the reference was removed altogether and the manometer plus connecting hydraulic lines protected by a temperature controlled insulated chamber. The differential pressure transducer was moved to within 50 cm of the manometer level with one port open to the atmosphere. This arrangement stabilized the recordings and retained the linear sensitivity range of the pressure transducer.

Evapotranspiration Data

A data set of daily observations has been summarized in Figure 10. This information includes air temperature (TEMP), precipitation (PPT),

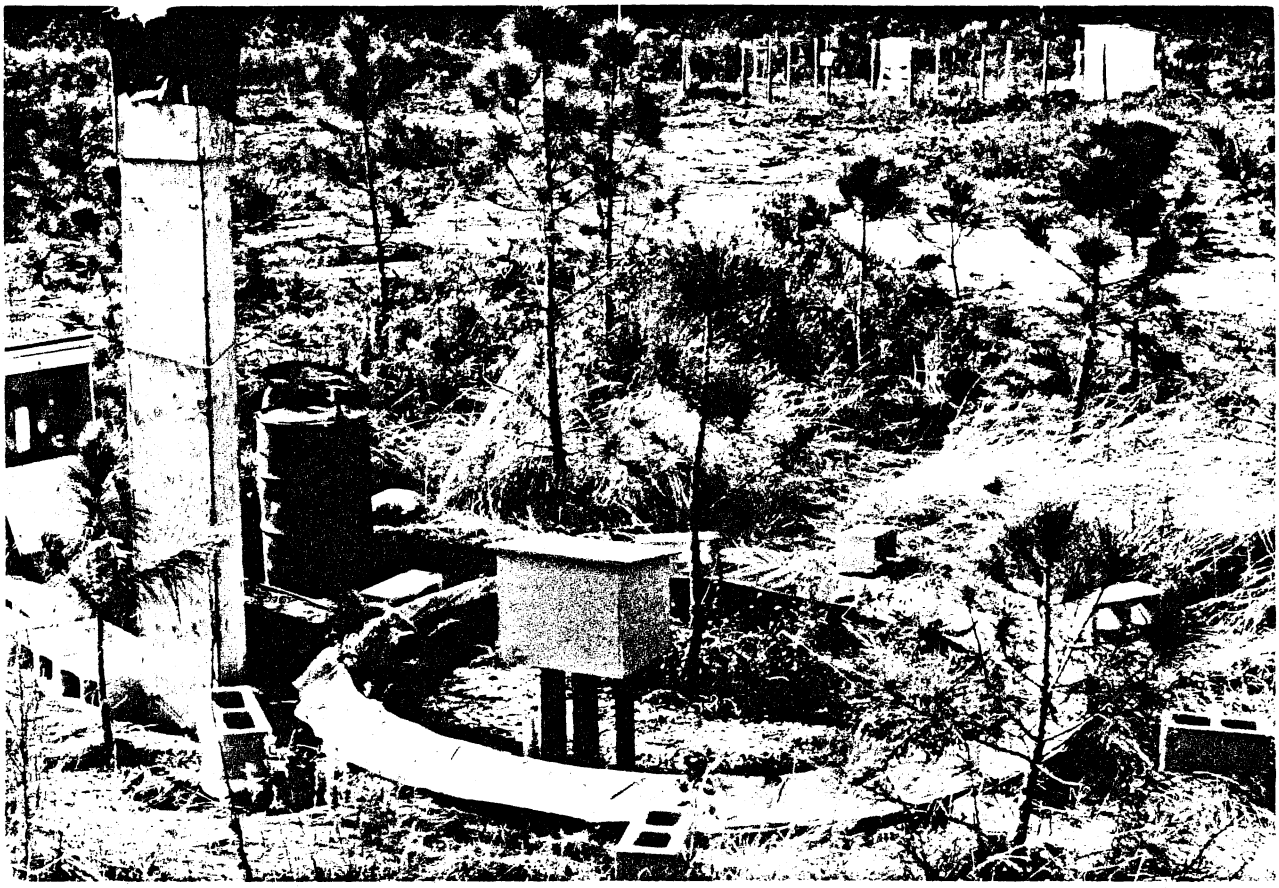

Figure 9. Weighing lysimeter installation during the second growing season with the standard weather station in the background.

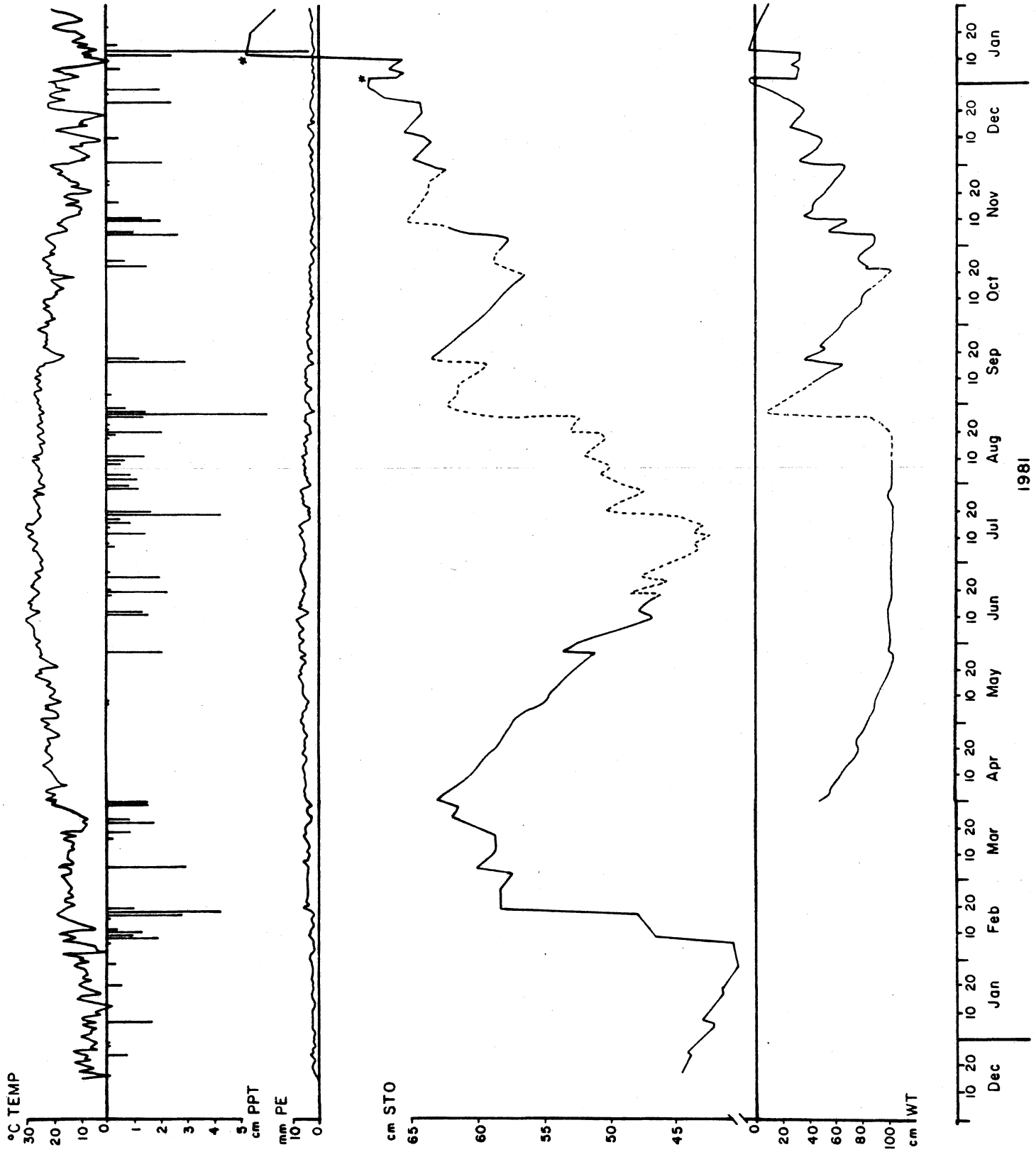

Figure 10. Weighing lysimeter and associated climatic data. Temp = air temperature, PPT = precipitation, PE = potential evaporation, STO = storage, and WT = water table.

calculated potential evaporation (PE), relative water content (STO), and interior watertable level (WT). The lysimeter water content data (STO) has been corrected for calibration shifts and associated changes in the manometer coefficient. Water content values estimated from rainfall inputs (dashed lines) are supported by the occasional observations as documented in Figure 8. The tentative nature of these estimated patterns unfortunately precludes reliable conclusions for the summer period.

It should be noted that the interior watertable level reached the tank bottom at the 1.02 m depth. The estimated values in Figure 10 were reconstructed from rainfall inputs and a specific yield value of 10%. The storm event of November 10 has been deduced from the watertable record.

The information of figure 10 has been obtained during an exceptionally dry year. Total precipitation for 1981 was only 88 cm which is 37% below normal. As a consequence no forced-drainage "runoff" was generated from the lysimeter tank. This simplified the water balance calculations considerably. Daily rates of evapotranspiration have been calculated from the slope of changes in water content during dry periods (Table 1).

Seasonal averages were weighted by the lengths of periods and came to 2.4 mm/day for the autumn months (October, November, December), 1.2 mm/day for the winter months (January, February, March), and 5.7 mm/day for the spring months (April, May, June). The seasonal potential evaporation was calculated by the Penman method and came to 2.7, 5.8, 4.9, and 2.6 mm/day for the winter, spring, summer, and autumn seasons of 1981, respectively. Total annual potential evaporation was 1440 mm which was considerably more than the longterm average of 1100 mm/yr as calculated by Dohrenwend (1978) for the area.

The ratio of evapotranspiration to potential evaporation represents a "crop factor". Penman (1963) published agricultural crop factors of 0.8 for May-August, 0.6 for November-February, and 0.7 for the transition months of March-April and September-October. The average seasonal crop factors obtained by this study were 0.92 for autumn, 0.44 for winter, and 0.89 for spring.

Table 1. Comparisons of evapotranspiration (ET) and potential evaporation (PE) for selected periods from December 17, 1980 to January 31, 1982.

Period	ET mm/day	PE mm/day	ET/PE ratio
Dec 17 - Dec 23	1.0	1.2	0.83
Dec 25 - Jan 5	2.0	1.3	1.54
Jan 7 - Jan 27	1.2	1.7	0.71
Feb 27 - Mar 4	1.3	3.9	0.33
Mar 5 - Mar 12	1.7	3.7	0.46
Mar 24 - Mar 28	1.5	3.9	0.38
Apr 1 - May 1	1.9	5.1	0.37
May 2 - May 26	2.6	5.8	0.45
May 27 - Jun 9	5.7	7.0	0.81
Jun 12 - Jun 18	2.7	6.1	0.44
Sep 18 - Oct 20	2.2	3.7	0.60
Oct 28 - Nov 4	1.3	2.3	0.58
Dec 3 - Dec 11	2.0	2.0	1.00
Dec 15 - Dec 22	1.9	1.8	1.00
Jan 18 - Jan 31	1.3	1.8	0.73

CHAPTER V
DISCUSSION

Lysimeter Performance

The above saga of trials and tribulations represents considerable frustration often to the point of project dismissal. However, the most serious problems were overcome, resulting in some useful information. The summertime failures especially made short thrift of the expectations at the start of the project. Part of this was due to the application of existing technology to untried (poorly-drained) soil conditions, and part was due to the time delays associated with limited resources. Such growing pains are commonly experienced with these installations (Fritschen, pers. comm. 1972).

Notwithstanding these problems this large weighing lysimeter is yet the only successful unit of high sensitivity in north-central Florida. Furthermore, the lysimeter is unique world-wide in that it measures water-use by a tree in a poorly-drained soil. All other lysimeters contain well-drained soils and associated plants.

The information derived from this installation was used to establish seasonal "crop factors" of water-use by a developing flatwoods pine plantation. These factors are being verified with data from ongoing watershed studies of similar plantations in the area. Also, the controlling processes of water relations are being elucidated in conjunction with different measurement methods of evaporation, transpiration, stomatal resistance, and soil moisture.

An alternative simpler method for evapotranspiration measurements is to build a deep single-tank lysimeter for monitoring a confined water table to assess daily changes in water content. Unsaturated soil conditions during the brief dry season could be assessed periodically with a neutron probe. The tank would prevent deep seepage and would simplify the daily water balance to precipitation, runoff and evapotranspiration. As an example, large excavations from surface mining operations could be lined with heavy-gauge plastic before refilling with spoil and reclamation with forest vegetation.

Pine Tree Evapotranspiration

The collected data provided for some information on evapotranspiration by the pine tree planted in the weighing lysimeter. As noted earlier any extrapolation to the surrounding large-scale plantation has to be viewed with caution.

The total potential evaporation of 1440 mm/yr was about 30% more than the longterm average as reported by Dohrenwend (1978). This over estimate may in part have been generated by the exceptionally high solar radiation input because the dry year of study had a reduced cloud cover according to data from a nearby airport.

The ET/PE ratios of 0.89 and 0.92 for the spring and autumn, respectively, of 1981, suggest a good prediction of evapotranspiration for these two seasons. However, the low ratio of 0.44 for the winter season reflects a significant over estimate by the Penman equation. This metereological method relies primarily on the solar radiation budget. The relatively high radiation input of the winter period in effect did not seem to significantly increase the vapor pressure deficit of frontal air masses flowing into north-central Florida.

The data of Figure 10 and Table 1 show that early winter time evapotranspiration of 1.2 mm/day slowly increased to nearly 2 mm/day with increasing air temperatures during March and April. Accelerated evapotranspiration rates of about 2.6 mm/day during May reflected the fully activated processes of tree physiology.

During the same period the rate of water table subsidence decreased slightly after passing the 80 cm depth mark. The rootball of the transplanted tree was about 60 cm deep. The capillary fringe above the water table in these sandy soils is about 20 cm high. These observations combined suggested that after the water table subsided below the reach of the majority of tree roots more of the transpired water was derived from the unsaturated rooting zone.

Evapotranspiration rates during the following period of May 27 to June 9 averaged 5.7 mm/day which was close to that of potential evaporation. Air temperatures had reached and exceeded 25° C and a drought breaking rainstorm recharged the moisture supply in the rooting zone (Figure 10). A similar rate of 5.5 mm/day was also obtained from preliminary measurements during the spring of 1980 (Figure 8).

A significant reduction in the rate of evapotranspiration down to 2.7 mm/day was measured during the middle of June. A similar reduction down to 2.8 mm/day was obtained for the first two weeks of July, 1980 (Figure 8). This reduction occurred after the above noted decrease of moisture supply from the receding water table. Apparently moisture became drastically limited when the water table in the lysimeter disappeared altogether. The interference of the lysimeter bottom with further soil water table interactions may have depressed the measured evapotranspiration more so than that of the surrounding plantation.

Nevertheless a real reduction in evapotranspiration occurred during this dry period which could significantly affect other tree physiological processes. Rosenzweig (1968) reported a good correlation between primary productivity at the rate of 2 t/ha for each 10 cm of additional evapotranspiration. Other observations of this nature for slash pine in poorly-drained flatwoods (White and Pritchett, 1970) also brought into question the common assumption that moisture supply is ample throughout the year.

At this time it is not known whether or not the following summertime rains kept the surface soil moist enough to provide for a nonlimiting supply of water to the roots. The water table level did not reappear until a large storm recharged the lysimeter during late August (Figure 10).

Perusal of the lysimeter observations for the dry period in the fall of 1981 (Figure 10) showed a rate of 2.2 mm/day. This was equal to the average evapotranspiration rate of the early spring months under similar temperature conditions. Some data from early fall of 1980 (Figure 8) approximated a rate of 3.0 mm/day and for early winter about 1.5 mm/day in comparison.

Watertable reduction during the dry spring season amounts to 17 mm/day for the month of April, and 8 mm/day for May when the general level had substantially subsided. The averaged rate for April-May was about 13 mm/day. The average watertable reduction over a similar range of depths during September-October was 19 mm/day. Comparison of these data with the corresponding evapotranspiration withdrawals gives ratios of 0.11, 0.31, and 0.12 mm evaporated water per mm watertable drop for April, May, and September-October, respectively. The general rates of lysimeter weight increase and watertable rise during October-November 1981 show a ratio of about 0.1. The above ratios suggests that the specific yield of the soil in the lysimeter is about 10%. The higher value during May probably reflects a relative increase in uptake of water from the unsaturated rooting zone.

CHAPTER VI
CONCLUSIONS

Installation and maintenance of a large weighing lysimeter and its instrumentation proved to be troublesome in the poorly-drained flatwoods soil, especially during the lightning-prone humid summer months. Recordings by sensitive automated equipment have to be supplemented with periodic manual manometer readings. Similarly, state-of-the-art electronic weather sensors and datalogger have to be backed up by less elegant but more reliable hygrothermographs and by periodic wind and cumulative precipitation measurements.

The available data show that cool season evapotranspiration was about 2 mm/day while that for late spring was about 6 mm/day when soil moisture became replenished by drought breaking rains. Prediction of the above seasonal rates of evapotranspiration by the Penman method was good for the autumn and spring seasons.

Water use during the spring drought lowered the watertable below the rooting zone. Soil water drawn by roots from the unsaturated zone rapidly became limiting for slash pine transpiration until summer rains raised the water table again.

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APPENDIX

CONTINUOUS SYSTEM MODELING PROGRAM
VERSION 1.3

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Title-Calculation of pet and potential rainfall deficit

Initial
/     Dimension RSI (365), TEMP (365), DEWP (365), WIND (365), RAIN (365)
/     Dimension DAY (365)
      FIXED I
 INCON Inc = 0.0
 CONST PYSCH = 0.27
 CONST ALB = 0.88
 CONST BOLTZ = 1.9978E-9
 FUNCTION VAPCUR = (-20.0, 0.776), (-15.0, 1.436), (-10.0, 2.149), ...
  (-5.0, 3.163), (0.0, 4.579), (5.0, 6.543), (10.0, 9.209), (15.0, 12.788), ...
  (20.0, 17.535), (25.0, 23.756), (30.0, 31.824), ...
  (35.0, 42.175), (40.0, 55.324)
 FUNCTION SI = (0.0, 510.0), (30.0, 580.0), (60.0, 710.0), (90.0, 840.), ...
  (120.0, 925.0), (150.0, 990.0), (180.0, 1005.0), (210.0, 950.0), ...
  (240.0, 885.0), (270.0, 760.0), (300.0, 630.0), (330.0, 520), (365.0, 500.0)
 NOSORT
    READ (5, 1000) (DAY (I), RSI (I), TEMP (I), DEWP (I), ...
    WIND (I), RAIN (I), I = (1,365)
1000 FORMAT (F3.0, F6.0, F6.1, F6.1, F5.1, F6.2)
DYNAMIC
NOSORT
    I = TIME + 1.0
    DATE = DAY (I)
    DEWPC = (DEWP (I) -32.))*0.5555
    TEMPD = (TEMP (I) -32.0)*0.5555
    TEMPA = TEMPD + 0.2
    TEMPB = TEMPD - 0.2
    ABST = TEMPD + 273.0
    ETA = NLFGEN (VAPCUR, TEMPD)
    EST = NLFGEN (VAPCUR, DEWPC)
    SLPVAP = (NLFGEN (VAPCUR, TEMPA) - NLFGEN (VAPCUR, TEMPB)) /0.72
    NAPDEF = 0.35*(ETA - EST)*(1.0 + 0.24*WIND(I))
    NN = ((RSI (I)?NLFGEN(SI,DATE)) -0.18)/0.55
    SHRTWV = RSI(I) * ALB /58.0
    LONGWV = BOLTZ*ABST**4.0*(0.56 - 0.092*EST**0.5)*(0.1 + 0.9*NN)
    H = SHRTWV - LONGWV
    PET = ((SLPVAP/PYSCH)*H + VAPDEF)/((SLPVAP/PYSCH) + 1.0)
TERMINAL
METHOD RECT
PRTPLT PET (DATE, VAPDEF, H)
PRTPLT TEMPD (DATE)
TIMER DELT = 1.0, FINTIM = 214.0, OUTDEL = 1.0
END
```