COMPARISON OF CALCULATED AND MEASURED EVAPOTRANSPIRATION OF POTATOES AND TOMATOES FOR SHORT PERIODS OF TIME

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

Cortland Ennis Young, Jr.

1960

This is to certify that the

thesis entitled

Comparison of Calculated and Measured Evapotranspiration of Potatoes and Tomatoes for Short Periods of Time.

presented by

Cortland Ennis Young, Jr.

has been accepted towards fulfillment of the requirements for

M.S. degree in Agricultural Engineering

E H Kidder
Major professor

Date May 20, 1960

O-169

COMPARISON OF CALCULATED AND MEASURED EVAPOTRANSPIRATION OF POTATOES AND TOMATOES FOR SHORT PERIODS OF TIME

By

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A THESIS

Submitted to the College of Agriculture of
Michigan State University of Agriculture and
Applied Science in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

Department of Agricultural Engineering

1960

Approved by [signature]

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Professor E. H. Kidder of the Agricultural Engineering Department for his helpful suggestions and guidance as major professor during the course of this study.

Appreciation is also expressed to Dr. A. E. Erickson of the Soil Science Department for his interest and constructive suggestions.

The author's wife, Judy, deserves much credit for her patience and encouragement through the entire study, and helpful suggestions while reviewing the manuscript.

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INTRODUCTION

Vegetables grown in Michigan will undergo periods of drought during the growing season. Farmers, realizing this fact, have purchased irrigation equipment to use during drought periods.

For maximum crop production it is important to irrigate at the correct time and with adequate amounts of water. Proper use of evapotranspiration data can aid in determining the correct time to irrigate.

Evapotranspiration for any plant-soil system is dependent on climatic conditions, soil moisture conditions, and type and stage of plant growth. Extensive work has been done to determine the effect each variable, and their interactions, has on evapotranspiration. As a result of these studies, several methods of estimating evapotranspiration have been developed, which are usually based on climatic variables. These estimates have been compared with measured evapotranspiration in many locations, in order to determine their validity under differing climatic conditions.

In an experiment at Michigan State University, the evapotranspiration rate of two crops, potatoes in 1958 and tomatoes in 1959, was determined by the use of

Bouyoucous moisture blocks. This thesis compares this measured evapotranspiration to evapotranspiration estimates computed by the methods of Blaney-Criddle, Thornthwaite, Penman, and van Bavel. Evaporation pan data is also compared to the measured evapotranspiration.

These comparisons cover periods of five days in order to determine the validity of each estimate during measured maximum and minimum evapotranspiration periods. In comparisons covering more than five days, maximum and minimum evapotranspiration periods are minimized and thus make conclusions inaccurate. Special emphasis is placed on determining the relationship between evaporation pan data and measured evapotranspiration.

REVIEW OF LITERATURE

There are two ways of determining evapotranspiration values: (1) estimates of evapotranspiration based on climatic conditions, soil moisture conditions, and physiology of plants; (2) direct measurement of the soil moisture condition and the change in soil moisture. Accurate evapotranspiration values have a practical significance for horticulturalists, soil scientists, agronomists, engineers, and ultimately for the farmers interested in irrigation and drainage.

Methods of Estimating Evapotranspiration

The three basic methods of estimating evapotranspiration, either directly or indirectly, can be grouped into the following broad categories: (8)

(1) Empirical methods, in which existing climatological data are fitted into certain arbitrary factors.

(2) Theoretical methods based on the removal of vapor that must take place in the evaporation process.

(3) Theoretical methods based on the balance of energies available and used in the evaporation process.

In this section, each of the above methods will be discussed.

Blaney-Criddle Equation

Blaney and Criddle (3) developed one of the first workable empirical equations for determining evapotranspiration. Their equation is expressed as:

$$U = \frac{tpk}{100}$$

k = monthly crop coefficient
p = per cent of annual daytime hours occurring that month
U = monthly evapotranspiration in inches
t = average monthly temperature in ° F.

They based their equation on the fact that evapotranspiration rates change proportionately with temperature changes. Recognition is given to radiation influence by the inclusion of day length.

Seasonal crop factors have been evaluated for many crops. Monthly crop factors have been determined for a few crops. These monthly crop factors show the fluctuation of water usage during a growing season.

Phelon (13) proposed that the k values vary proportionally as the temperature varies over a growing season. His work on alfalfa showed that the water use requirement varied considerably during the course of a season.

Thornthwaite's Equation

An empirical approach has been developed by Thornthwaite (20). His equation, like Blaney-Criddle's, placed maximum climatic emphasis on temperature and was expressed as:

$$E = (c)\ (t)^a$$

E = monthly potential evapotranspiration in cm.
t = mean monthly temperature
c&a = constants for a given year

$$a = 0.000000675\ (I)^3 - 0.0000771\ (I)^2 + 0.01792\ (I) + 0.49239$$

$$I = \Sigma\, i \text{ (monthly heat indexes)}$$

$$i = \left(\frac{t}{5}\right)^{1.514}$$

$$c = \frac{1}{I}$$

The equation for evapotranspiration then resolves itself to:

$$E = 1.6\ \left(\frac{10t}{I}\right)^a$$

The computation of evapotranspiration has been made relatively easy with a nomograph constructed from this equation.

Thornthwaite did not attempt to distinguish between crops. The equation was designed for use primarily in central and eastern United States. However, it has been tested against values from evapotranspirometers all over the world. Agreement has been good in areas of similar climate, but wide discrepancies have developed in some areas (9).

Dalton's Equation

Dalton (8) was one of the first to work on the rate of evaporation from a water surface. His theory has been the basis for most of the later work in this field. He derived an equation, based on the effect of vapor pressure and wind movement, for estimating evaporation from a water surface. His equation is expressed as:

$$E = (e_s - e_d)\ f\ (u)$$

E = evaporation in a unit time
e_s = vapor pressure at the evaporating surface
e_d = vapor pressure at some height above the water surface
$f\ (u)$ = a function of the horizontal wind velocity

Rohwer (18) evaluated constants for the equation to give:

$$E = 0.04\ (e_s - e_d)\ (1 + 0.17U_2)$$

U_2 = wind speed at two meters in miles per hour

Since Rohwer's equation represents water loss over a water surface, evapotranspiration cannot be obtained directly from the equation.

Thornthwaite-Holzman Equation

Thornthwaite and Holzman (19) pioneered work in the theory of vapor diffusion as applied to evaporation. They developed an equation of the form:

$$E = \frac{p\ K^2\ (q_1 - q_2)\ (U_2 - U_1)}{(\ln Z_2/Z_1)}$$

E = Rate of evaporation
q_1 & q_2 = specific humidity
U_1 & U_2 = mean wind velocities
Z_1 & Z_2 = two different heights
K = Karman's constant

The difficulty in applying this equation lies in the necessity of making exact measurements of specific humidity and wind speed at the two different heights. The lack of available equipment and data reduces the practical application and testing of this technique.

Pasquill (11) has developed a modification of the above equation:

$$E = BU_2 \; (e_1 - e_2)$$

$$B = \frac{K^2M \; (1 - U_2/U_1)}{RT \; (\ln Z_2/Z_1)^2}$$

M = molecular weight of water
R = gas constant
T = absolute temperature
e_1 & e_2 = vapor pressures
U_1 & U_2 = wind speed
Z_1 & Z_2 = heights 1 & 2

This equation is limited in use to a site of a fixed roughness. B will vary as the roughness of an area changes.

<u>Other Equations</u>

Mankkunk, Turc, Haude, and Uhlig (15) have developed equations that estimate evapotranspiration. They are theoretical and make use of climatic conditions as the variables for determining evapotranspiration. They have been tested in specific locations in Europe.

<u>Penman's Equation</u>

Penman (12) has made use of the theories of both energy balance and diffusion of vapor in arriving at his method of determining evapotranspiration. His estimate represents evaporation from a water surface and is classified as potential evapotranspiration.

Two basic steps are involved in solving his equation; first, the evaluation of net radiation energy and second, determining how this energy is divided in heating the air and evaporation. He assumed that: (1) the gain in heat by the soil is relatively small over a short period of time, and (2) advective heating is negligible.

Penman's most recent equation is expressed as:

$$E = \frac{\Delta H + \gamma E_a}{\Delta + \gamma / SD}$$

E = potential evapotranspiration in mm per day
Δ = slope of saturated vapor pressure curve
γ = 0.27
H = net radiation
E_a = auxiliary quantity (measure of the diffusion of vapor)
S = factor denoting influence of diffusion resistance
D = factor denoting influence of length of day

$$H = R_a (1-r) (.18 + .55\ n/N) + \sigma T_a^4 (.56 + .092\sqrt{e_d}) (.1 + .9\ n/N)$$

R_a = mean monthly extraterrestrial radiation in mm per day
r = radiation reflection coefficient
n/N = ratio of actual to possible hours of sunshine
σ = Stefan Boltzman constant 2.01×10^{-9} mm per day
T_a = absolute air temperature in deg Kelvin
e_d = actual vapor pressure of the air in mm of mercury

$E_a = 0.35\ (e_a - e_d)\ (1 + 0.0098U_2)$ mm per day

e_a = saturation vapor pressure at mean air temperature

U_2 = wind speed at two meters

$S = L_a / (L_a + 0.16)$

$L_a = 0.65\ (1 + 0.0098U_2)$ effective diffusion length of air

$D = N/24 + 1/\pi \quad \sin N\pi/24$

N = hours from sunrise to sunset

Penman suggests that a factor of 0.80 will modify the potential evapotranspiration to actual evapotranspiration for England. This factor will vary from area to area. An extensive effort has not been made to find other factors. van Bavel (23) suggests a factor of 0.75 for the southeastern United States.

Penman has not incorporated a crop factor into his equation. He has suggested that a crop factor would increase the accuracy of the equation.

The assumption of no advective heat losses will cause serious discrepancies in Texas and other plains areas. The estimates are made on the basis of two dimensional analysis and plants have a third dimension.

The Penman equation has been checked and found accurate in many parts of the world. The difficulty of computation and of measuring climatic conditions has limited its use.

van Bavel's Method

The approach by van Bavel (23) is based on the theory of energy balance as expressed by Penman's equation. A nomograph, based upon the measurement of radiation and air temperature, has been prepared to simplify computation.

van Bavel's procedure is based on the theory of a conservation process going on in nature. Evapotranspiration intensity is bounded by limits of 0 and 0.35 inches of water per day. Evapotranspiration is principally dependent upon incident radiative energy. Radiation is determined by latitude, time of year, and cloud-cover. The first two variables are easily predicted. Cloud-cover is unpredictable but can be measured. Temperature is significant to this process since warm air can retain more water than cold air. Windspeed and relative humidity are of minor significance for evapotranspiration from large homogenous areas.

Two practical methods of arriving at daily evapotranspiration estimates have been devised. A choice of which to use depends upon the precision desired. Both methods are based on the Penman equation and have given reasonable predictions for the eastern part of the United States. These methods are illustrated in Appendix IV.

Evaporation Pan Method

The question of whether evaporation from a water surface is in proportion with evapotranspiration from plants in the surrounding area, has provoked numerous experiments in the past decade.

Harrold (6) compared evaporation pan values against measured evapotranspiration from monolith lysimeters and found an encouraging relationship. Pruitt (14), Bouwer (4), and others have also obtained promising results.

The theory behind the validity of evaporation pan values as estimates of measured evapotranspiration is that an evaporation pan in the same habitat as a growing crop will experience the same effect from climatic conditions as the plant. (6) Any change or equalizing effects from climatic factors will affect pan evaporation and crop evapotranspiration proportionally, if not equally.

In order to achieve a good relationship, the soil on which the crop is produced should always be kept at a high level of available moisture. Thus lack of soil moisture will not be a limiting factor in evapotranspiration.

Even though the soil is kept at a high moisture level, the total evapotranspiration for a set period of time will not usually be as high as the evaporation pan loss. Plants cease transpiration almost completely at night, while the evaporation pan continues to lose water. It is important that the difference between the two be fairly constant. This difference can be compensated for by multiplying evaporation pan values by a factor to obtain values at or near the rate of measured evapotranspiration.

Methods of Determining Evapotranspiration

Two methods for measuring the evapotranspiration rate of a plant-soil system are: (1) a direct measure of the soil moisture condition, and (2) a measure of the change in weight, due to moisture loss, of a plant-soil system.

Methods proposed to measure the soil moisture condition directly include gravemetric (2), tension (2), electrical (2), and neutron scattering measurements (17).

Lysimeters have been used to determine the change in weight of a plant-soil system. Harrold (7), Thornthwaite (9), Visser (15), and Tanner (16) have developed different types of lysimeters to measure evapotranspiration.

Practical Uses of Evapotranspiration Data

van Bavel (24) points out that at the present time evapotranspiration data can be used in conjunction with past and current weather records for practical applications such as: determining drought and flood probabilities, and irrigation requirements of crops.

The practical applications listed are based upon the soil moisture condition of an area at a given time. To know this condition, several variables must be measured or estimated. The time and amount of effective rainfall must be known as it increases soil moisture. Evapotranspiration and percolation rates must be obtainable as they represent moisture loss from the root zone of the soil.

van Bavel (21), Allred and Chen (1), and Moranic (10) have used evapotranspiration estimates in conjunction with past rainfall data to predict drought probabilities. van Bavel (24) points out that evapotranspiration estimates can be used in conjunction with past rainfall data to predict flood probabilities.

The foremost use of evapotranspiration data in recent years has been for determining time for irrigation. The common procedure has been to test the reliability of various methods of estimating measured evapotranspiration. The best evapotranspiration estimating method is used to determine the time for irrigation.

Harrold (6) found that data obtained from a BPI - evaporation pan could be correlated to measured evapotranspiration. He compared measured evapotranspiration with estimates computed by the methods of van Bavel, Thornthwaite, and Blaney-Criddle (5). The results were encouraging, both from the standpoint of relative accuracy of present methods, and the possibility of developing adjustments where desirable and practical.

Pruitt and Jensen (14) compared evaporation pan data, Thornthwaite values, and Blaney-Criddle values to measured evapotranspiration. During periods of good crop cover, tank-evaporation rates gave a much closer estimate of actual evapotranspiration rates than either the Blaney-Criddle or Thornthwaite procedures.

van Bavel and Wilson (22) compared Thornthwaite estimates with measured evapotranspiration. The Thornthwaite values were accumulated to estimate time for irrigation. They found that these accumulated estimates predicted a time to irrigate that was very close to the actual time when irrigation should have occurred according to measured soil conditions.

Bouwer (4) has made use of the relationship between evaporation pan data and measured evapotranspiration in developing an integrating rainfall-evaporation recorder, which is a modification of a standard evaporation pan. This device could make possible fully automatic irrigation with solid sprinkler irrigation systems.

PROCEDURE

Bouyoucous moisture blocks were used to obtain soil moisture data from a controlled irrigation experiment conducted at the Michigan State University horticultural farm. This data was used to compute actual evapotranspiration for the plant-soil system in the experiment. Measured evapotranspiration was compared to evapotranspiration estimates computed by the methods of Blaney-Criddle, Thornthwaite, van Bavel, and Penman. The comparisons were made of five-day averages to determine the correlation during short periods of time. The maximum and minimum water use periods and the cycling of evapotranspiration values showed up very clearly in this length of time when plotted as comparison curves.

Experiment Procedure

The problem of determining the minimum available moisture level at which crops should be irrigated in order to produce the best yields was the basis for the experiment, of which this study was an outgrowth.

In order to establish an experiment which would give an answer to this problem, certain variables had to be controlled.

(1) A uniform soil type was selected for the plots.

(2) Tile drains were used to keep the water table below the reach of plant roots.

(3) Roofs with an automatic control system were constructed on rails so that when rain began, the roofs would come out and cover the plots.

(4) Cultivation and fertilization were identical on all plots.

(5) All plots were planted at the same time, with the same variety of plants, and with standard spacing throughout.

(6) All plots had the same number of guard rows.

(7) All plots were irrigated and harvested by the same procedure.

The general plan of the experiment site is shown in Figure 1. The portable irrigation apparatus was operated at the same application rate on all plots.

Bouyoucous gypsum moisture blocks were used to measure soil moisture. Four blocks were installed at 0, 1, 3, 6, 9, 12, 15 and 18 inch depths in each plot.

Daily readings were taken on all moisture blocks with a Bouyoucous moisture meter, to measure per cent of available moisture. The moisture content of the soil in each plot was expressed as the average of the available moisture readings from the blocks located in the three to eighteen inch depth in the soil. It was assumed that the crop extracted its water from the surface eighteen inches.

In 1958, with potatoes as the crop, plots B-2 and D-1 were kept above 70 per cent of available water. Plots B-1 and C-2 were kept above 40 per cent for the first part of the season and above 70 per cent for the remaining part. Plots A-1 and D-2 were kept above 40 per cent. Plots A-2 and C-1 were kept above 10 per cent, and check plots A-3, B-3, C-3, and D-3 received natural rainfall. The percentages represent the minimum level of available moisture in the root zone to which the plots were allowed to fall. When the soil moisture level reached this minimum value they were irrigated to bring the soil back to field capacity.

In 1959, with tomatoes as the crop, plots B-1 and D-1 were kept above 70 per cent of available water. Plots A-1 and D-2 were kept above 70 per cent for the first part of the season and above 40 per cent for the remaining part. Plots B-2 and C-2 were kept above 40 per cent. Plots A-2 and C-1 were kept above 20 per cent. Plots A-3 and C-3 were natural rainfall check plots.

The eight tomato plants in the middle of each plot were harvested each week. The potatoes were harvested after a blight killed the vines in late August, 1958. An analysis of variance test was conducted on the crop yields data.

A weather sub-station was located at the experiment site, where temperature, humidity, rainfall, wind, and evaporation pan data were obtained. These data were used in subsequent calculations of evapotranspiration.

In order to obtain net radiation values to use in conjunction with Penman's equation, a net radiometer was operated on the plots during a period from September 1 - 28, 1959.

Calculation Procedure

It was necessary to average the measured evapotranspiration data for five to eight day periods due to the apparent non-uniformity in moisture block readings after an irrigation. It took from three to four days before the soil moisture readings in a plot would begin dropping after an irrigation. A five to eight day average was needed to give a realistic picture. In order to obtain consistent results, moisture data taken between irrigations was averaged for periods of five to eight days.

The magnitude of evapotranspiration losses between plots, for the same period of time, was not always the same. At times values for certain plots seemed unreasonable. Instead of disregarding periods of questionable data, a daily average was made of the six plots kept above the 40 per cent available moisture level. This method of averaging was equivalent to averaging all the blocks for a five to eight day period.

Another reason for all plots being averaged together was that, due to the staggered irrigations on the plots, values for the six plots represented rates nearer potential evapotranspiration. The average available moisture level was well above fifty per cent during the whole growing season. An example of the procedure used in obtaining the measured evapotranspiration rates is illustrated in Appendix V.

Blaney-Criddle's Method

The Blaney-Criddle equation was designed to estimate evapotranspiration on a monthly or seasonal basis. Therefore, only seasonal crop factors (K) and a few monthly crop factors (k) have been developed for various crops.

With no available way of determining k factors for short periods of time, the seasonal factor of 0.65 for potatoes and 0.70 for tomatoes was used. Each factor in the equation was converted to a daily basis, as is illustrated in a sample calculation, Appendix IV.

Thornthwaite's Method

Potential evapotranspiration as computed by Thornthwaite's method uses the following equation.

$$e = 1.6\ (10t/I)^{a}$$

In order to simplify working with this equation, Thornthwaite developed tables and a nomograph. The computation was reasonably easy with mean air temperatures and the latitude of the location known. The equation gave unadjusted rates of potential evapotranspiration. It became necessary to reduce or increase the unadjusted rates by a factor that varied with the day and with latitude.

The first step in calculating evapotranspiration was to obtain the heat index, I. Thornthwaite's table 1 (9) provided monthly values of i corresponding to monthly mean temperatures. Summation of the twelve monthly values gave the index I.

The value of I was used to construct the nomograph, Figure 21. Since there is a linear relationship between the logarithm of temperature and the logarithm of unadjusted potential evapotranspiration, straight lines on the nomograph define the relationship. All lines pass through the point of convergence at $t = 26.5°$ C and potential evapotranspiration = 13.5 cm. The slope of the line is determined by the heat index (I). Values of evapotranspiration were then found for any temperature.

These values of potential evapotranspiration were adjusted for latitude and day length. Tables (9) provided correction factors by which the unadjusted potential evapotranspiration of each day was multiplied. A sample calculation is found in Appendix IV.

van Bavel's (simplified) Method

This method of estimating evapotranspiration was very simple. All the information that was needed to make an estimate was van Bavel's table, Appendix III, and the per cent of possible sunshine that reached the earth each day.

The United States Weather Bureau at Capitol City Airport, Lansing, Michigan, makes a daily reading of the per cent of possible sunshine that reaches the earth. These values were used in conjunction with the table to arrive at daily estimates. This method is illustrated in Appendix IV.

van Bavel's (detailed) Method

The detailed van Bavel method yielded evapotranspiration values readily with the aid of a nomograph, Figure 22. It was necessary to know the per cent of possible sunshine for a given day and the mean daily air temperature. Also, the amount of radiation intensity that will reach our atmosphere at a given latitude on a certain day was needed, Table 2 (23). This method is illustrated in Appendix IV.

Penman's Method

Calculation by Penman's equation was made much easier by using the net radiation readings taken on the plots of growing plants. It was necessary to have mean daily air temperatures, mean daily dew point temperatures (obtained from the United States Weather Bureau), wind speed (measured at the experiment site), and number of hours from sunrise to sunset (obtained from the United States Weather Bureau). A sample calculation appears in Appendix VI.

Evaporation Pan

Evaporation pan readings were taken daily at 5:00 p.m. from a United States Weather Bureau Class A Pan. A standard weather bureau eight inch rain gauge was located near the pan to provide data for days when rainfall made it necessary to adjust evaporation pan values.

Comparison Procedure

The measured evapotranspiration data was accurate for average periods of from five to eight days. A standard period of comparison of five days was chosen.

Comparisons for 1958 and 1959, for the average periods of time indicated, consisted of measured evapotranspiration compared to evaporation pan three, five, and seven day averages, van Bavel five day averages, both simplified and detailed, Blaney-Criddle five day averages, and Thornthwaite five day averages. Comparison was also made between van Bavel (detailed) three day averages and evaporation pan three day averages. For a period during 1959 comparisons were made between measured, evaporation pan, van Bavel (detailed), and Penman evapotranspiration values.

These comparisons appear as curves in Figures 2-20. Plotted points represent an average of the daily values within the stated period of comparison. Exact values of maximum differences between curves has been tabulated in Tables 1 and 2.

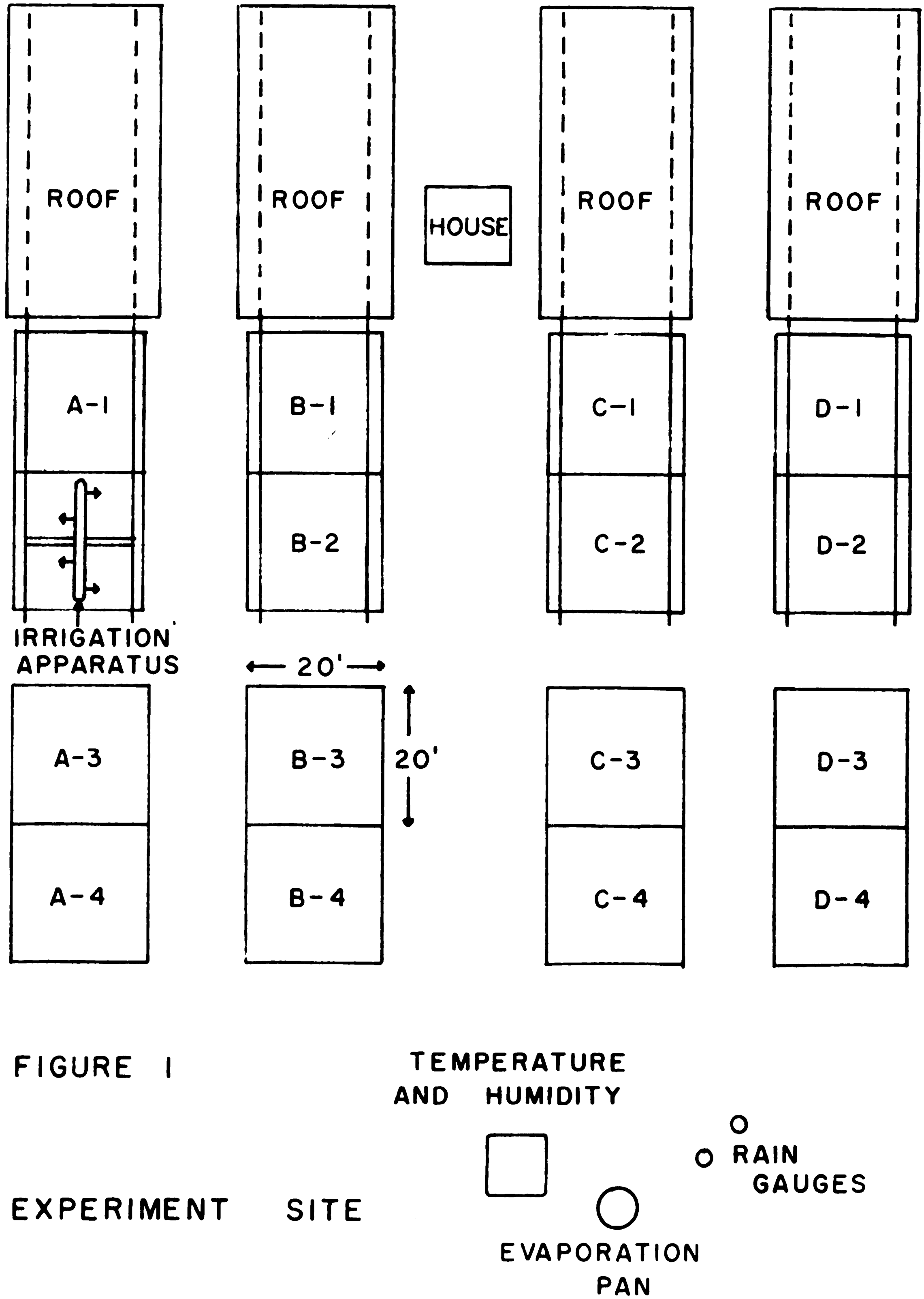

FIGURE I

EXPERIMENT SITE

DISCUSSION OF RESULTS

Comparisons were made between measured and computed evapotranspiration in order to determine which computation method would give the best estimate of evapotranspiration. These comparisons covered short periods of time during the growing season so that maximum and minimum water use periods would be apparent.

A summary table for each year, Tables 1 and 2, shows the results taken from the comparison curves of computed and measured evapotranspiration. Data of particular interest are measured and computed seasonal totals, and largest total over and under estimations.

Evaporation Pan Values Compared to Measured Evapotranspiration

As shown in Figures 2 and 3, in periods leading up to July 8, 1958, and July 1, 1959, the evapotranspiration was well below evaporation pan values. The reason for this great difference was that the plants in an early stage of growth were transpiring at a rate less than that of a mature plant. The other methods of estimating evapotranspiration were not compared to measured evapotranspiration during this period because their estimates are based on mature transpiring plants.

Around August 18, 1958, a blight killed the potato vines in the plot area. The blight resulted from extremely moist atmospheric conditions existing while the crops were covered. Figure 2 illustrates the immediate reduction in crop transpiration and the resulting differences in the two curves.

A 1:1 ratio existed between the curves from September 9 - 16, 1959. This could have been an accident or an indication of the actual relationship during the latter part of the growing season for tomatoes. A frost occurring on September 16, 1959, killed 50 per cent of the plants. The transpiration rate was greatly reduced and the evapotranspiration curve remained low when the evaporation pan rate increased, Figure 3.

To be of value in comparison with measured evapotranspiration, the evaporation pan curves, Figures 4-9, for each year had to be adjusted by a factor. A possible reason for the difference between measured evapotranspiration and evaporation pan data is that plants almost completely cease transpiration at night while the evaporation pan can lose water at any time that there is a moisture deficit in the air.

The evaporation pan correction factors were obtained by dividing the total evapotranspiration for a certain period of time by the evaporation pan values for the same period. Factors were determined for periods of approximately a month. Only one factor was determined for 1958 because there was relatively the same magnitude of difference between the two curves through the entire period, Figure 5. During 1959, the relative difference between the two curves changed around August 5. The factor for 1958 was 0.707. The factors were 0.72 and 0.80 respectively for the first and last half of 1959.

Adjusted evaporation pan values gave very good estimations of measured evapotranspiration losses for both years, Figures 4-9. This was true regardless of whether the pan average that was chosen for comparison was three, five, or seven days. The largest single overestimation was 0.28 inches during a six day period in 1958. The largest single underestimation was 0.24 inches covering a nine day period in 1959. These resulted from a comparison of three day pan averages to measured evapotranspiration.

The close agreement can be explained by the hypothesis that evaporation from water and evapotranspiration from a plant-soil system should react similarly to various climatic changes. This similar reaction should result in approximately the same cycling for each set of data.

The same cycling can best be observed from the comparisons of five and seven day evaporation pan data and measured evapotranspiration, Figures 5, 6, 8, 9. The three day evaporation pan averages curve fluctuated quite irregularly back and forth across the measured evapotranspiration curve, but this was because the measured values were computed in five to eight day increments, Figures 4 and 7.

The two curves were often out of phase. As has been pointed out, even though this did happen, the periods of over or under estimation were not significant. The plant-soil system probably reacted more slowly to climatic change than did evaporation from a water surface. The moisture blocks would have been the last part of the whole system to feel the effect of any changes.

Care must be taken in using evaporation pan data as a source of estimating actual evapotranspiration loss from a plant-soil system. The accuracy is greatly dependent on using the correct factor to adjust the evaporation pan values. Within two year periods the factors varied depending on (1) the type of crop, (2) the stage of development of crop, and (3) the portion of the growing season concerned.

Blaney-Criddle Estimates Compared to Measured Evapotranspiration

Blaney-Criddle total seasonal estimates ran somewhat below total measured evapotranspiration for both 1958 (0.50 inches), and 1959 (0.75 inches), Figures 10 and 11. For 1958 the underestimation was fairly constant and consistent for the whole season. For 1959, the majority, (0.53 inches), of the underestimation occurred in the period of maximum water usage, July 1 - July 17. For the remainder of the season the agreement was good.

The accuracy of computed values obtained by the Blaney-Criddle equation in 1958 was dependent on the crop factor used. An increase of the crop factor from 0.65 to 0.72 would have brought the two curves into their best agreement. Since temperature is the climatic variable that determines evapotranspiration in the Blaney-Criddle equation, the good agreement during 1958 seems to give support to their hypothesis that evapotranspiration is directly proportional to temperature.

In 1959, an adjustment in the crop factor was not needed over the whole season, but just during periods of maximum water usage. Since high water use periods cannot be predicted, an additional crop adjustment factor cannot be used. A combination of temperature and other climatic conditions caused the period of high water usage from July 1 - July 17, 1959. Therefore, Blaney-Criddle's equation, based only on temperature, is unreliable during these periods.

Thornthwaite's Estimates Compared to Measured Evapotranspiration

For both years, the total of the values found by using Thornthwaite's method of estimating evapotranspiration was within 0.10 inches of measured totals, Figures 12 and 13. For 1958, due to the good agreement, the maximum over or under estimation did not exceed 0.15 inches for any period. In 1959, an extreme period of underestimation (0.80 inches) occurred from July 1 - July 15, and an extreme period of overestimation (0.67 inches) occurred from August 5 - September 1.

In spite of the good agreement during 1958, there was a definite phase shift between the two curves. According to Thornthwaite's hypothesis, potential evapotranspiration is dependent on temperature at a given time. Therefore, the values computed by his method showed an immediate response to temperature changes. The moisture conditions measured by the blocks reflected a slower response to temperature changes, due to the buffering effect of the soil and the physiological adaptations of the plants to meet climatic changes.

In 1959 this method proved unreliable for estimating evapotranspiration during a period of high water use, and also during a different period of extremely high temperatures. The underestimation during July 1 - July 17, was probably due to the failure of the equation, based primarily on temperature, to estimate properly extended periods of high evapotranspiration rates resulting from all climatic variables. The period of overestimation, August 5 - September 1, was probably due to Thornthwaite's hypothesis that the logarithm of evapotranspiration increases with the logarithm of temperature. Because of this, evapotranspiration estimates are too high during extended periods of high temperature; August, 1959, was the fourth warmest August on record.

van Bavel (detailed) Estimates Compared to Measured Evapotranspiration

van Bavel's (detailed) method provided values too low for both 1958 and 1959, Figures 16 and 17. The magnitude of difference between the two curves was fairly consistent for each year. A factor times the van Bavel values would produce a reasonable estimate. A factor of 1.32 for 1959 and 1.19 for 1958 would produce the best results for estimation purposes.

The large emphasis van Bavel places on the effect of daily amounts of radiation was the probable reason for the consistently low values. He proposes that on days with low effective radiation due to cloud cover, the evapotranspiration values will also be low -- regardless of the temperature. During the summer, there are enough days with reduced radiation in this area to make computed evapotranspiration estimates consistently lower than measured evapotranspiration. It can be seen from the comparison curves that values computed using van Bavel's equation will always be low for this area. Adjusting the nomograph would better relate the effects of radiation.

van Bavel (simplified) Estimates Compared to Measured Evapotranspiration

The van Bavel (simplified) method of estimating evapotranspiration provided high values for both 1958 and 1959, Figures 14 and 15. In July, 1958, the estimates were considerably above the measured evapotranspiration for that period and made up the majority of the 1.09 inches of overestimation for the season. In August, 1958, the two curves were in close agreement. In 1959 the method provided good results as an estimate of measured evapotranspiration even though there were some periods of overestimation, which reached a maximum of 0.43 inches for one extended period.

It is difficult to explain why the van Bavel simplified estimated values approximated measured evapotranspiration so well for July, 1959, and so poorly for July, 1958. The estimated values are based on the effect of temperature and radiation, but during July of both years these values were approximately the same. July, 1959, had higher wind movement than July, 1958; and this could have accounted for the difference by producing higher evapotranspiration rates in 1959.

van Bavel (detailed) Estimates Compared to Evaporation Pan Values

A comparison of evaporation pan values and van Bavel (detailed) values is shown in Figures 18 and 19. van Bavel places maximum emphasis on radiation and temperature changes but practically no emphasis on wind speed and vapor pressure. If the losses from an evaporation pan fluctuate due to the same variables and in the same proportion as the van Bavel estimates, the plotted data should show a relationship. A three day average was chosen so that any maximum and minimum periods would be readily apparent.

The two curves fluctuated together with the same cycling frequency and with no phase shift for 1958. The agreement was not as good in 1959. The two curves still generally followed each other. For both years the magnitude between peaks and valleys was greater for the evaporation pan than for the van Bavel curve.

The results are encouraging for assuming that radiation and temperature changes provide the greatest influence for fluctuations in evaporation from a pan. Other climatic factors may change the magnitude, but do not appreciably alter the established trend set by radiation and temperature. Both evaporation pan data and van Bavel (detailed) values, when adjusted, have proven to be good estimates of measured evapotranspiration.

Comparison of Penman, van Bavel (detailed), Evaporation Pan, and Measured Evapotranspiration Values

These four different values were compared because all but the van Bavel values were affected by temperature, radiation, wind speed, and vapor pressure. The van Bavel values were affected only by temperature and radiation. All values would be expected to react similarly to the same climatic changes.

The Penman and measured curves ran extremely close together until the frost killed the plants on September 16, 1959, Figure 20. Evaporation pan and Penman curves were together between September 8 and 25. The van Bavel (detailed) curve ran proportionally below the other curves for the entire period.

The results of comparing Penman values to measured evapotranspiration indicated that actual evapotranspiration was affected by a combination of temperature, radiation, wind speed, and vapor pressure. The Penman values provided a better two week estimate of measured evapotranspiration than the other methods used for both seasons. After the frost hit the tomatoes, the low values for the measured evapotranspiration curve, as compared to the Penman curve, indicated the reduced transpiration by the crop.

A correction factor was not needed for the Penman values computed during September, 1959. This was probably because measured net radiation readings were used to compute Penman values; also the plant-soil system was near to its potential evapotranspiration and equal to pan evaporation during this period.

Net radiation readings were taken for only one month, thereby limiting the amount of computed Penman values for comparison with measured evapotranspiration. It would be impractical to predict the Penman -- measured evapotranspiration relationship for an entire season.

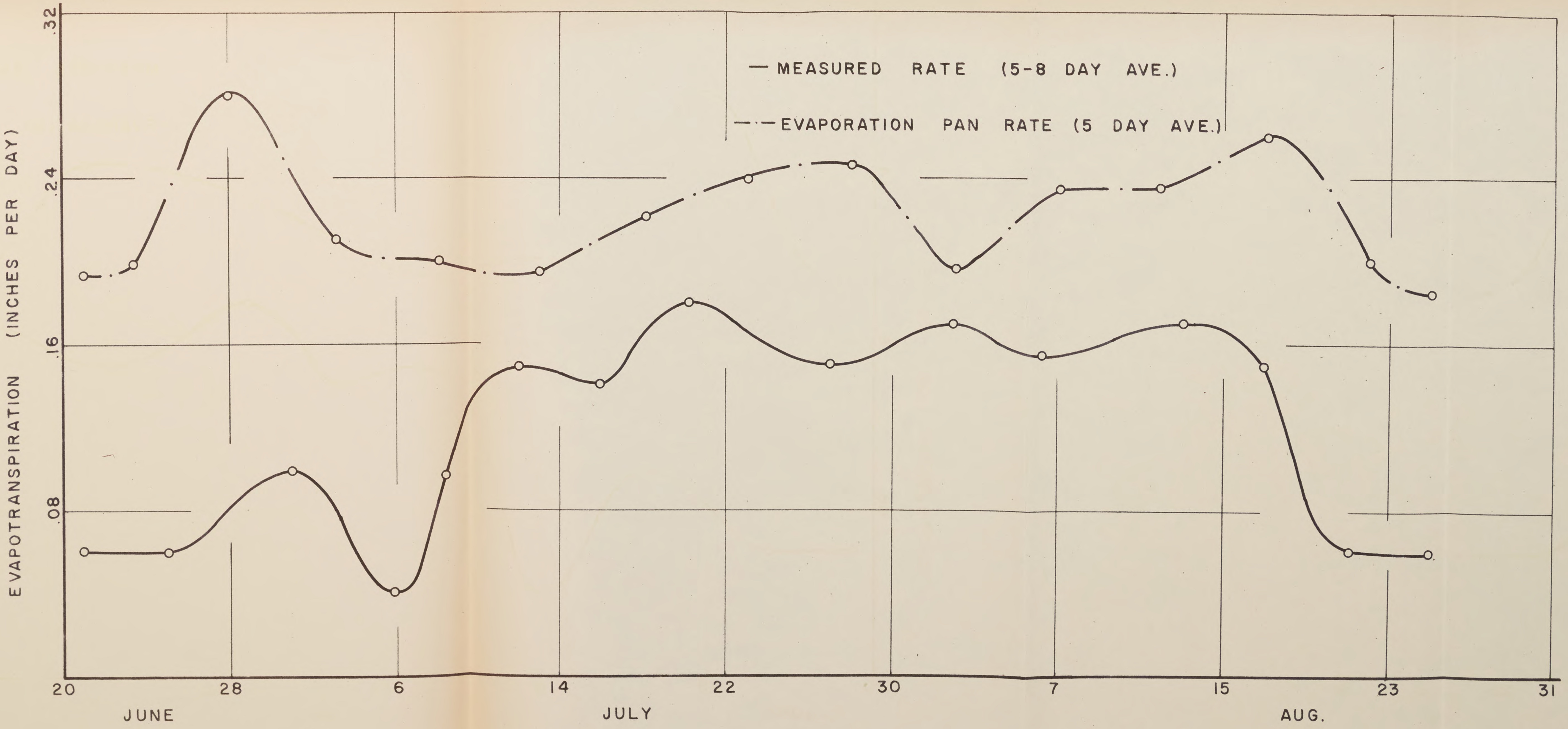

FIGURE 2 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND EVAPORATION PAN DATA FOR POTATOES 1958

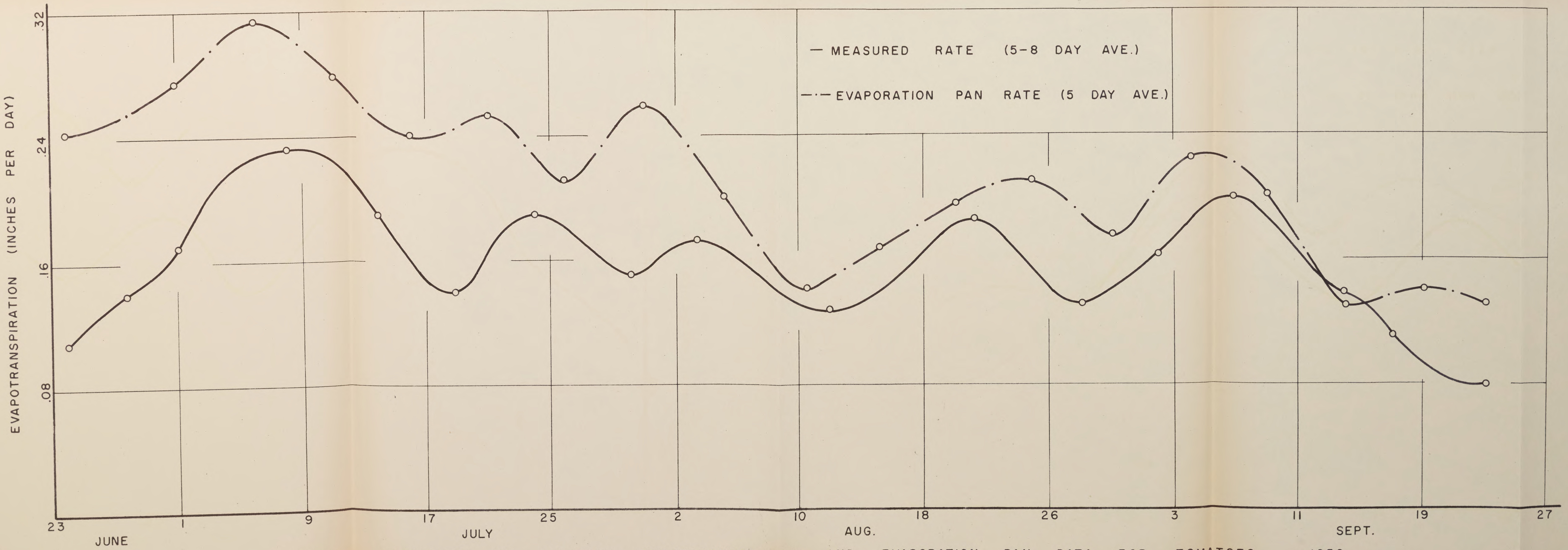

FIGURE 3 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND EVAPORATION PAN DATA FOR TOMATOES 1959

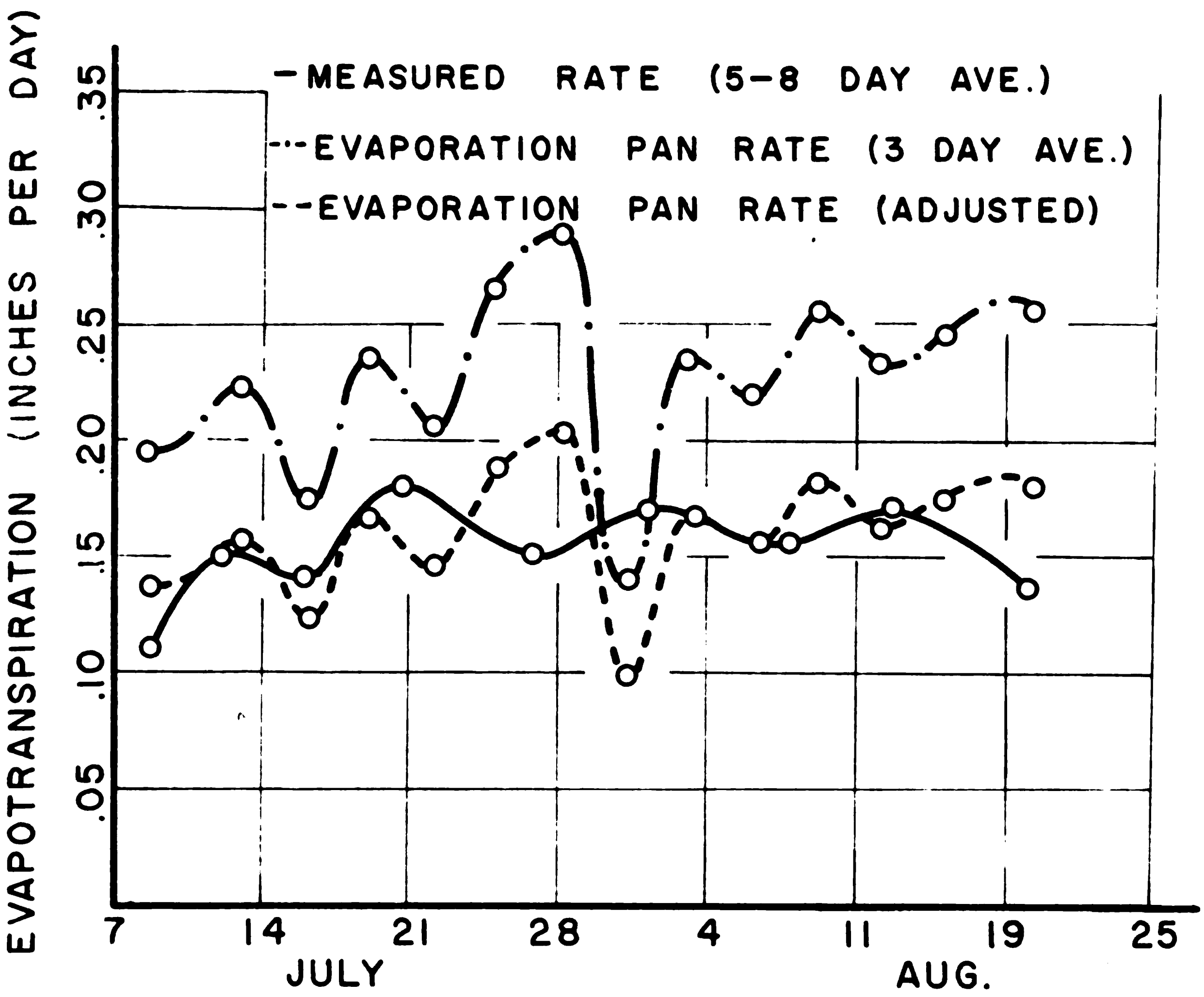

FIGURE 4 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND EVAPORATION PAN DATA FOR POTATOES 1958

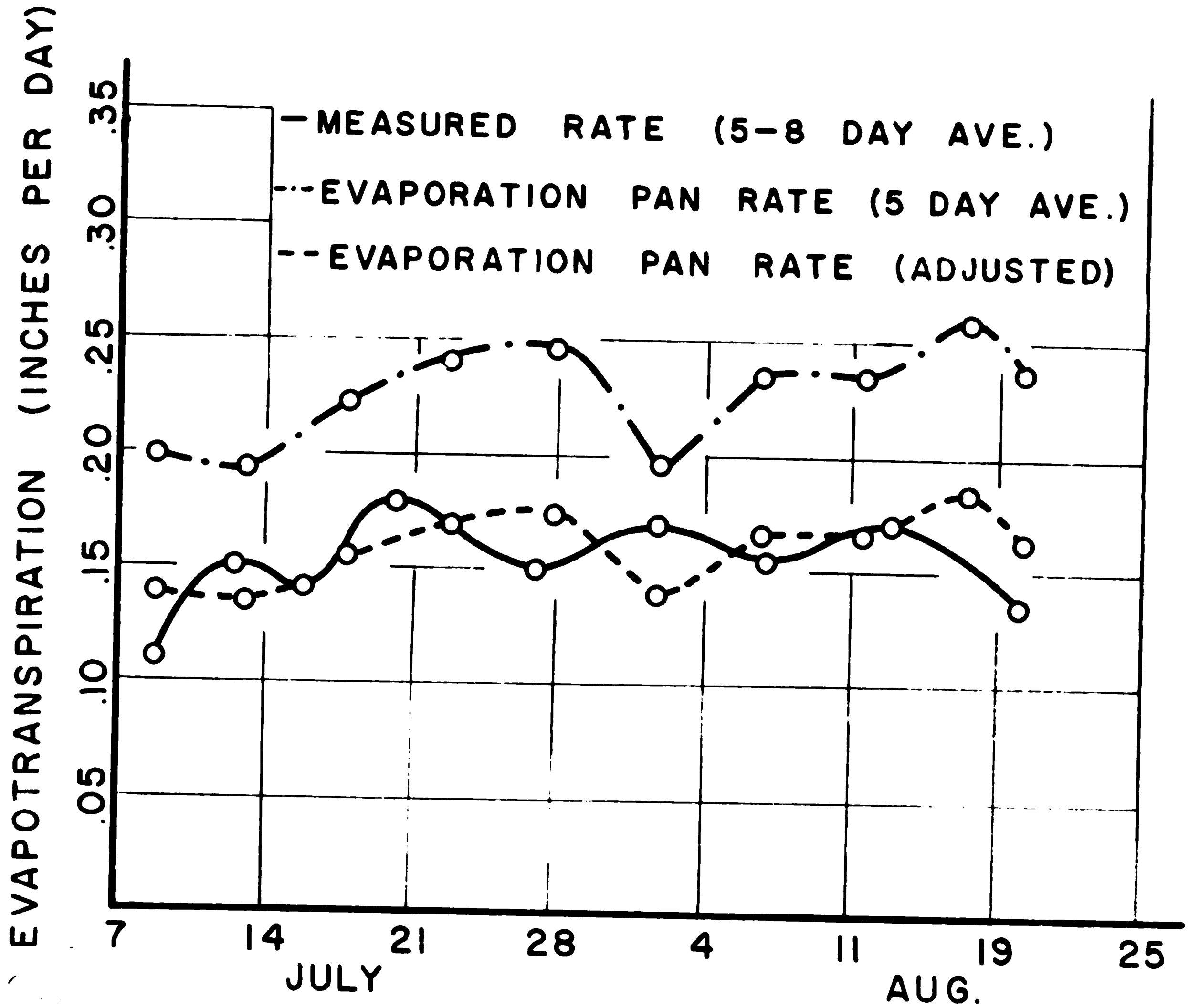

FIGURE 5 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND EVAPORATION PAN DATA FOR POTATOES 1958

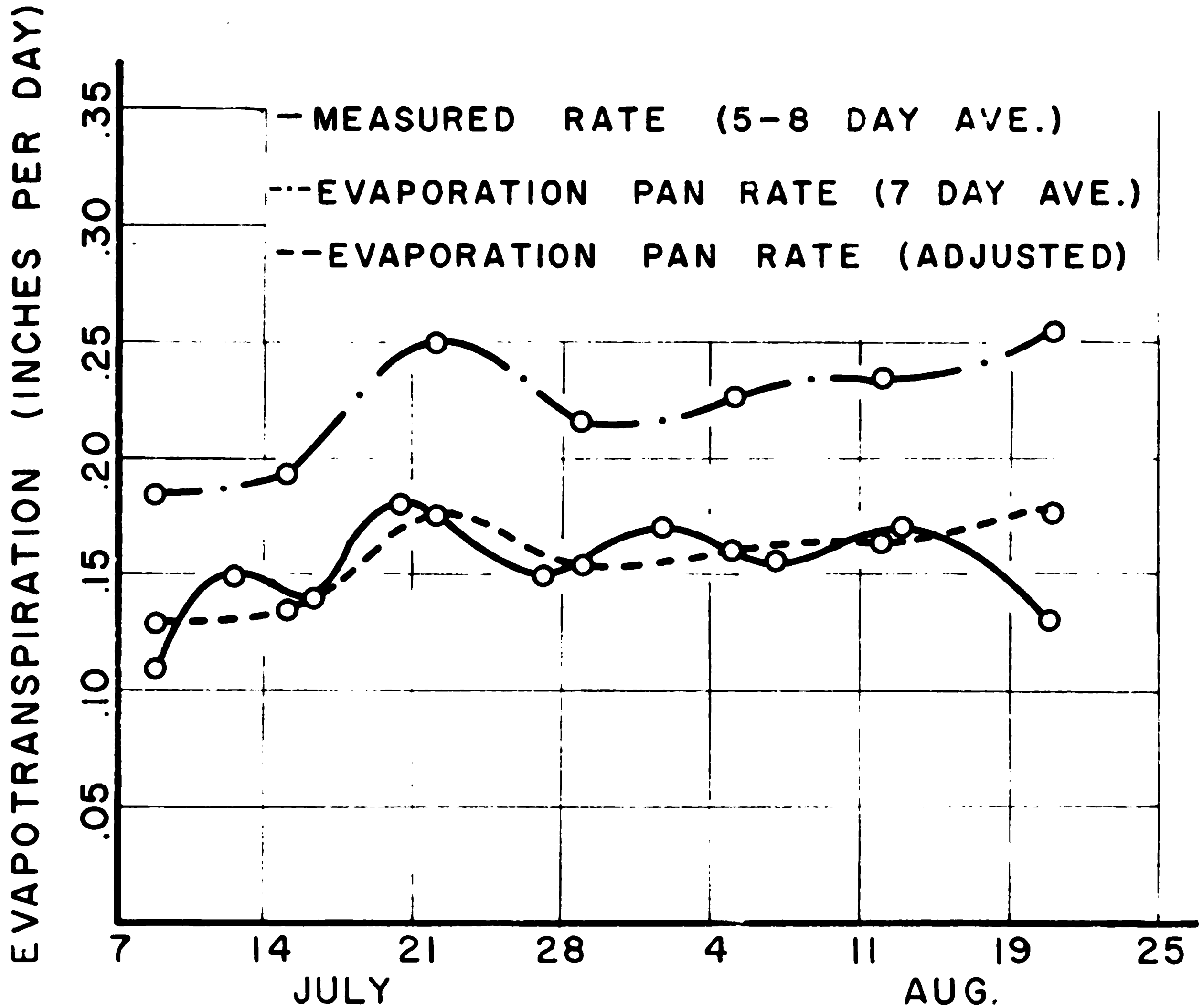

FIGURE 6 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND EVAPORATION PAN DATA FOR POTATOES 1958

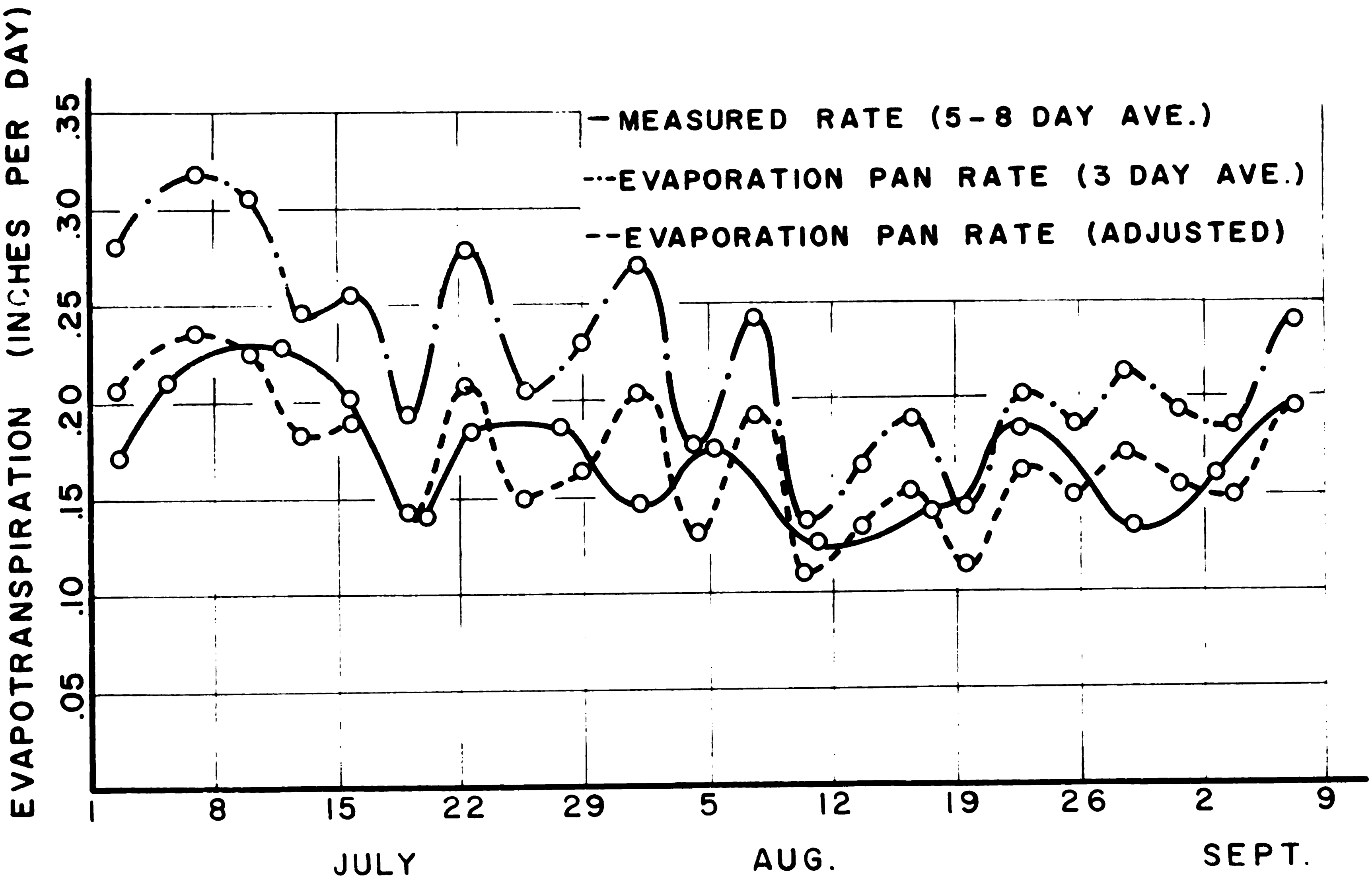

FIGURE 7 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND EVAPORATION PAN DATA FOR TOMATOES 1959

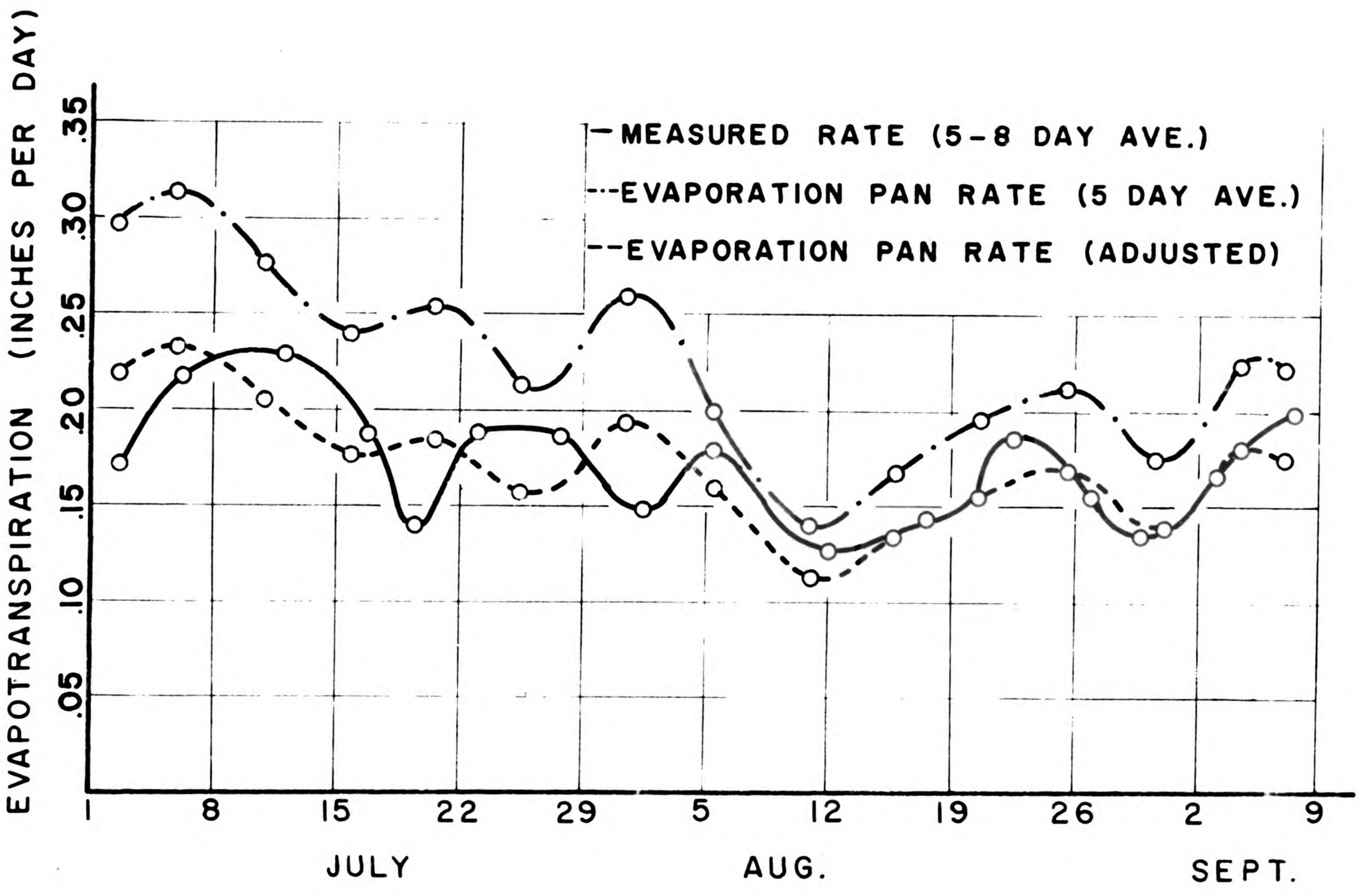

FIGURE 8 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND EVAPORATION PAN DATA FOR TOMATOES 1959

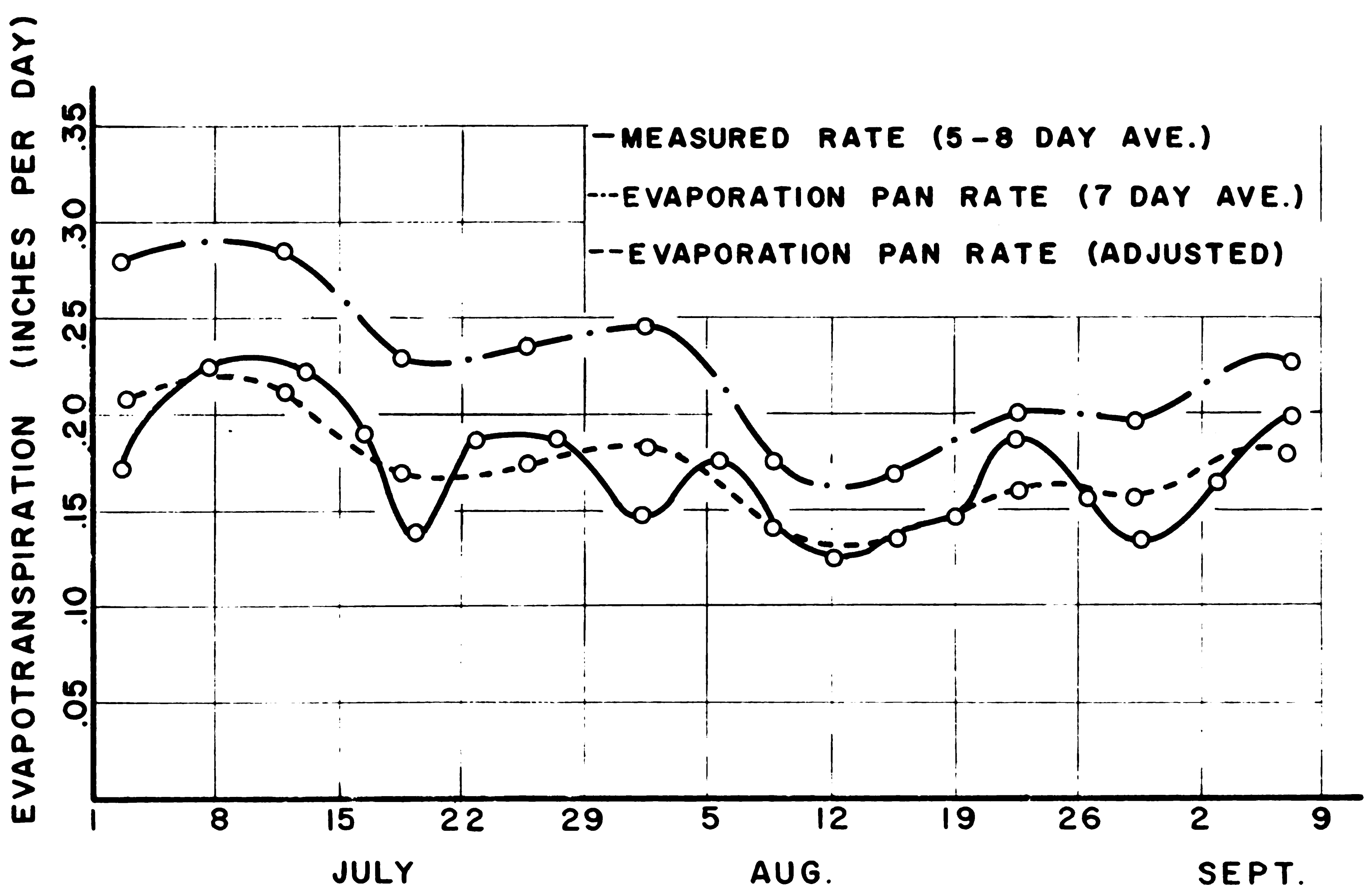

FIGURE 9 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND EVAPORATION PAN DATA FOR TOMATOES 1959

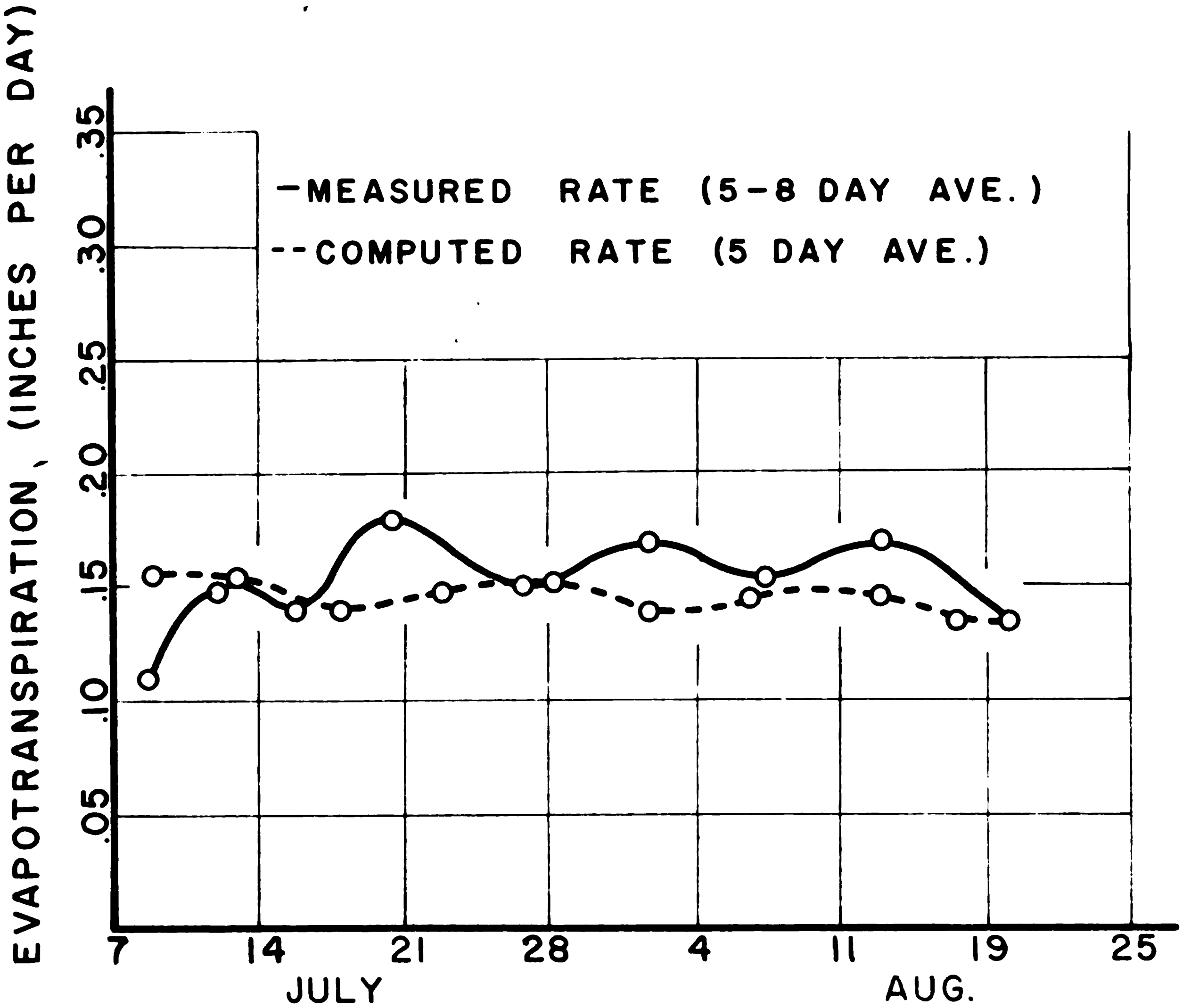

FIGURE 10 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND BLANEY—CRIDDLE VALUES FOR POTATOES 1958

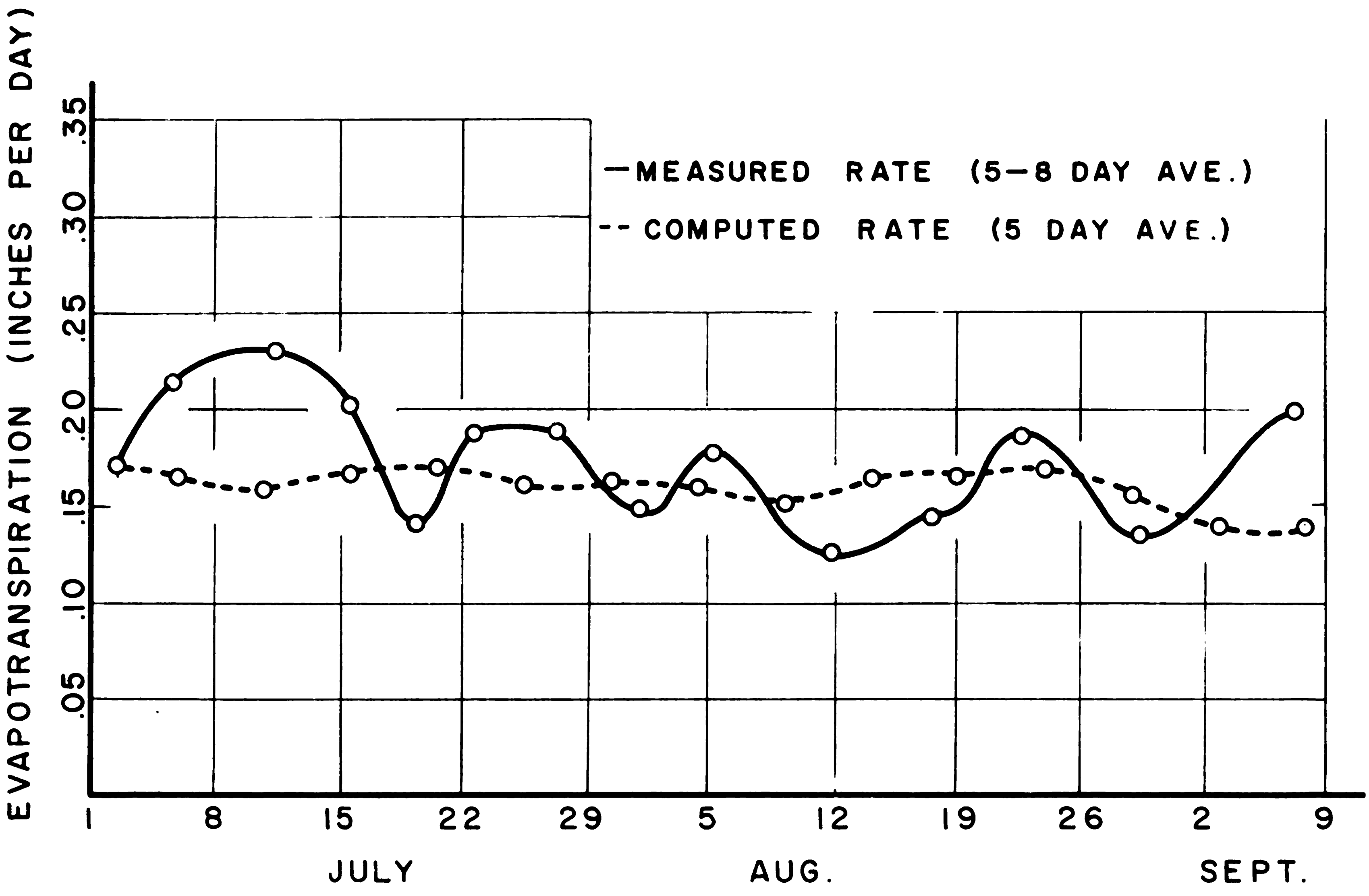

FIGURE 11 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND BLANEY—CRIDDLE VALUES FOR TOMATOES 1959

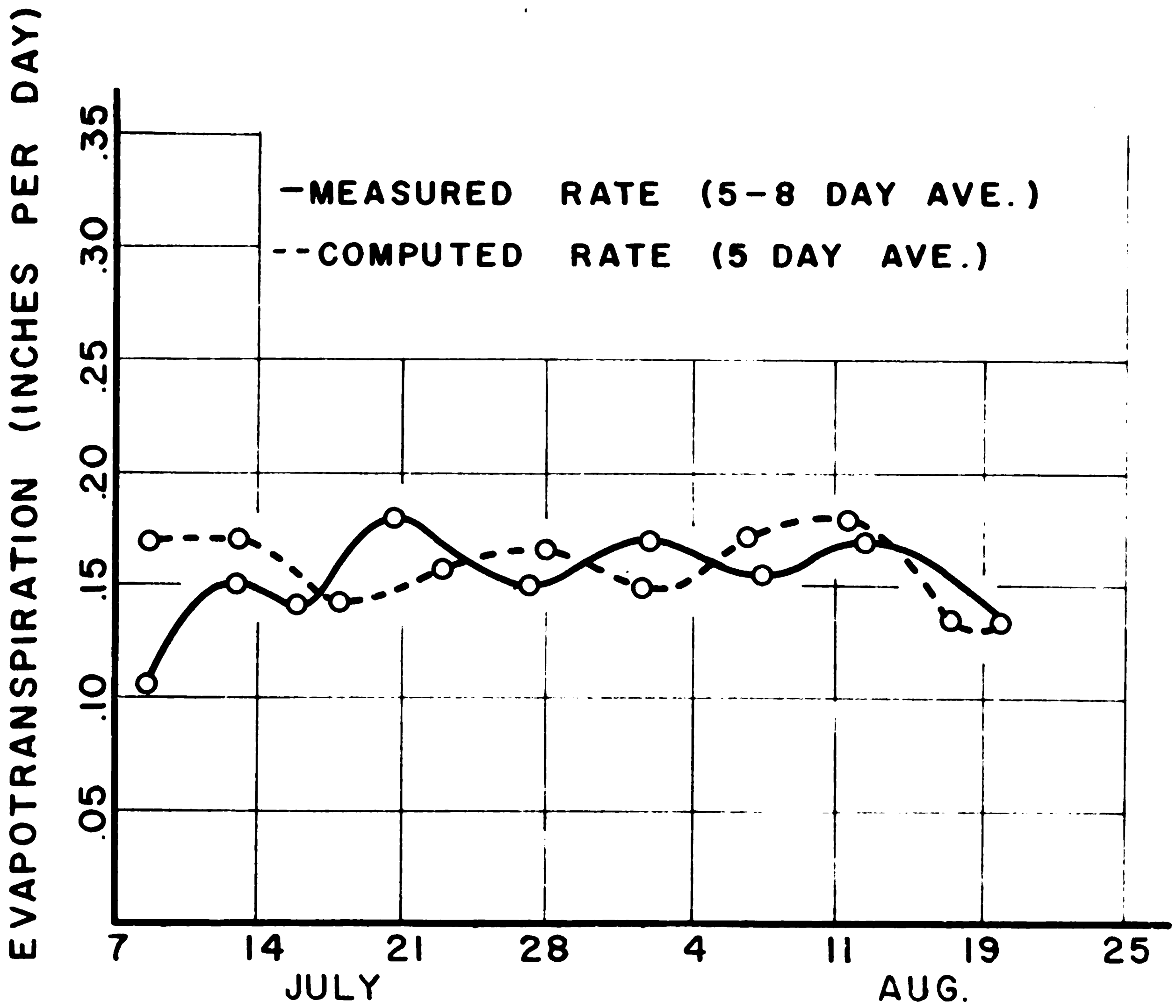

FIGURE 12 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND THORNTH—WAITE VALUES FOR POTATOES 1958

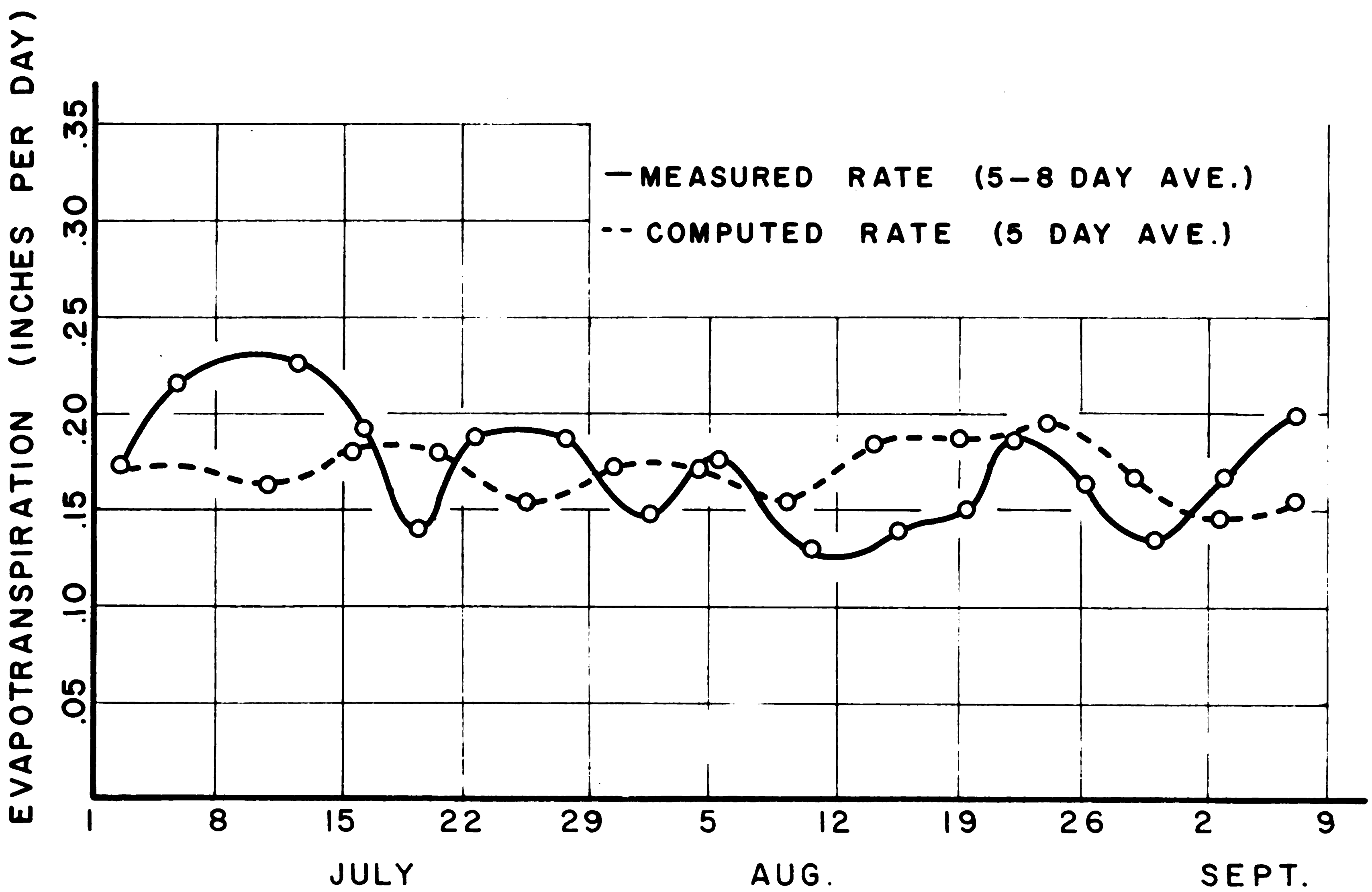

FIGURE 13 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND THORNTHWAITE VALUES FOR TOMATOES 1959

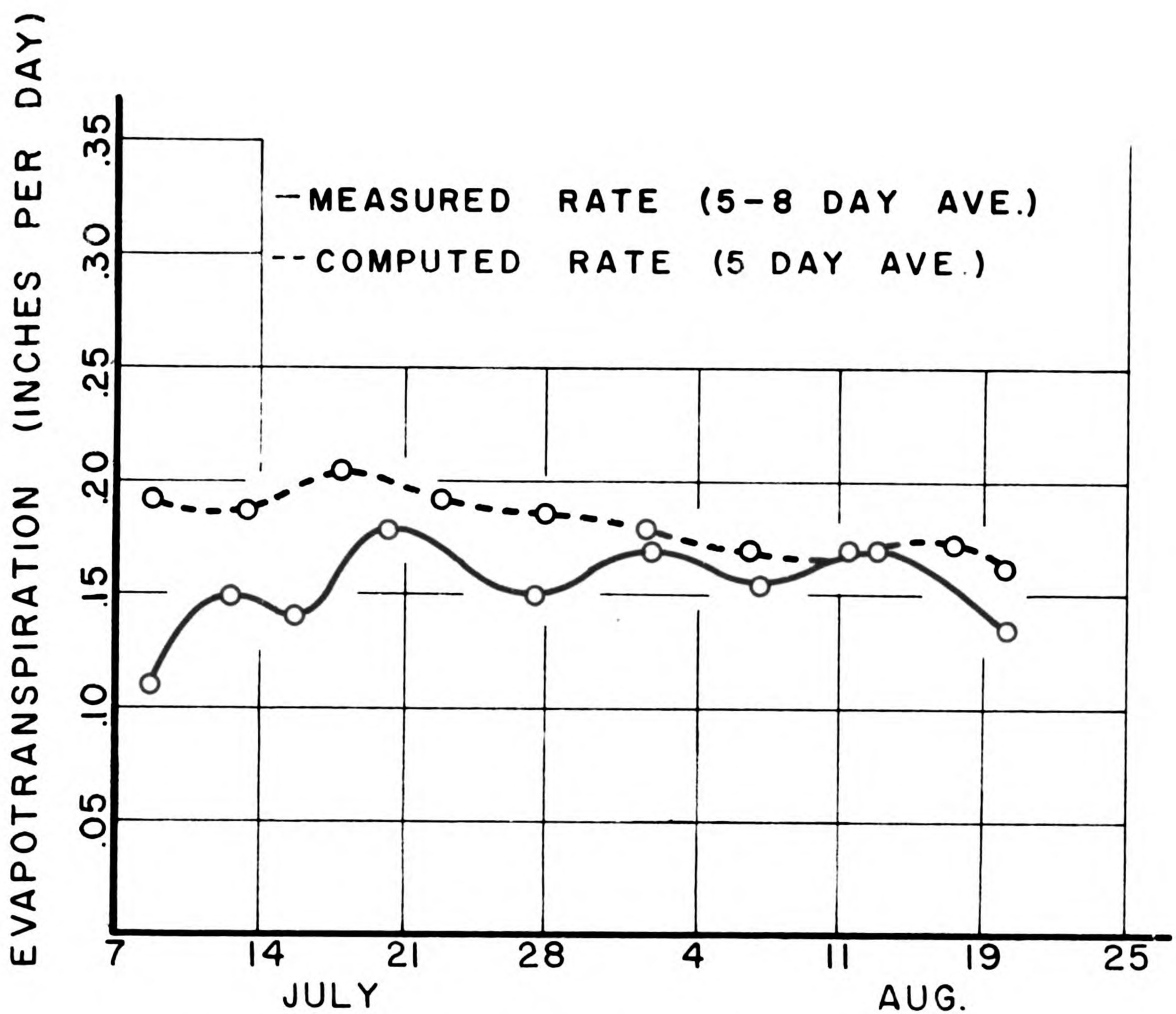

FIGURE 14 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND VAN BAVEL (SIMPLIFIED) VALUES FOR POTATOES 1958

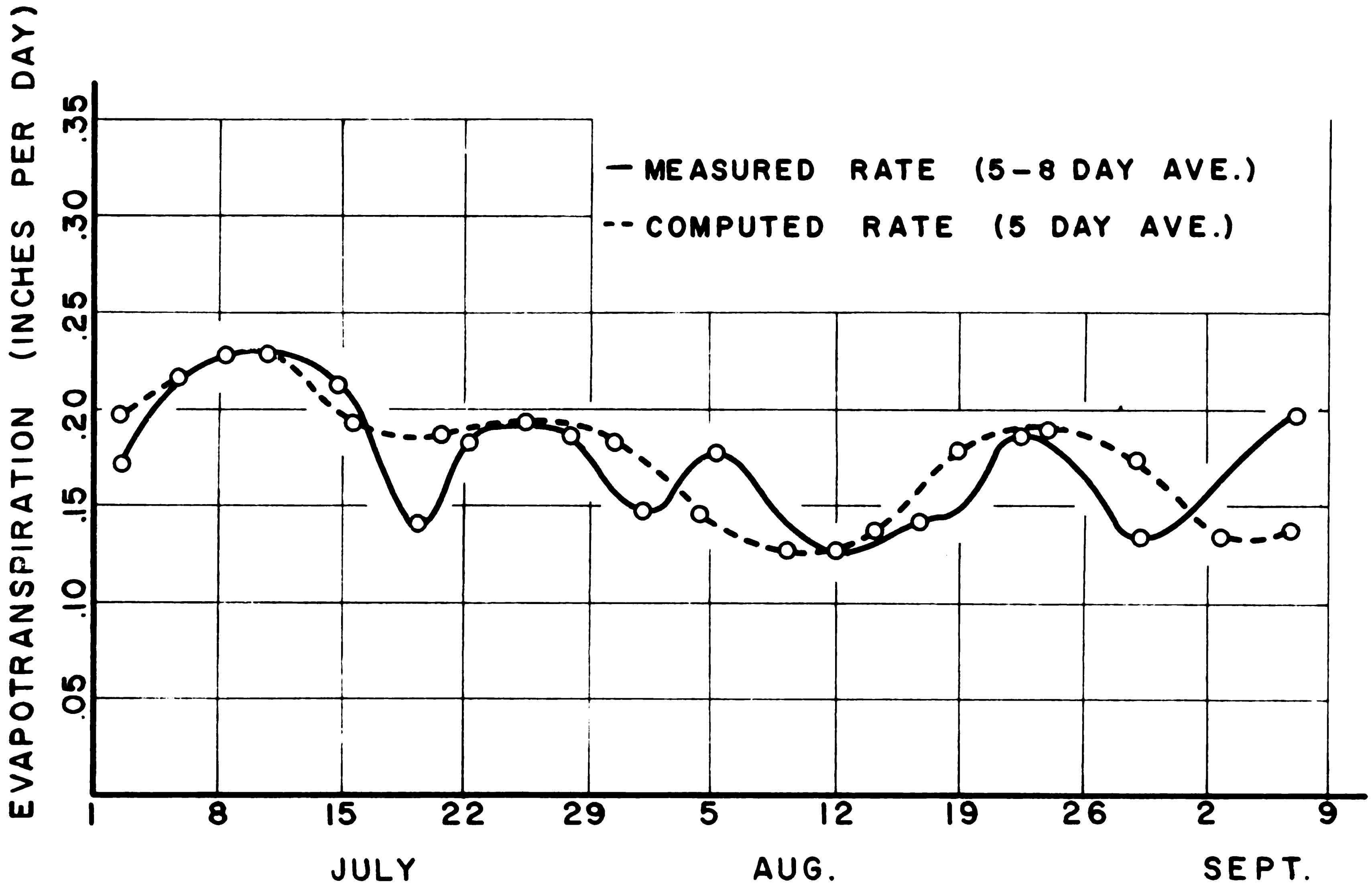

FIGURE 15 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND VAN BAVEL (SIMPLIFIED) VALUES FOR TOMATOES 1959

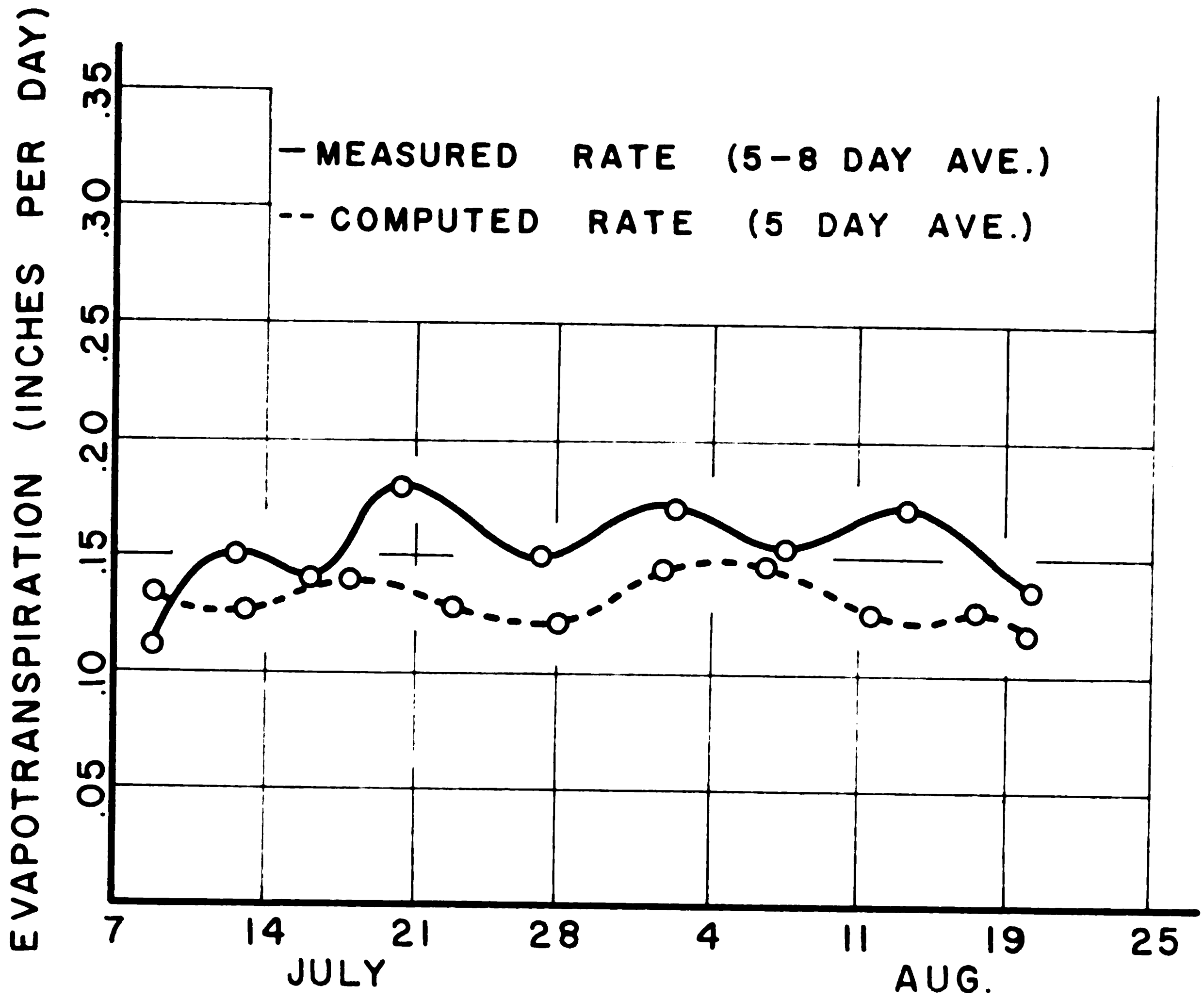

FIGURE 16 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND VAN BAVEL (DETAILED) VALUES FOR POTATOES 1958

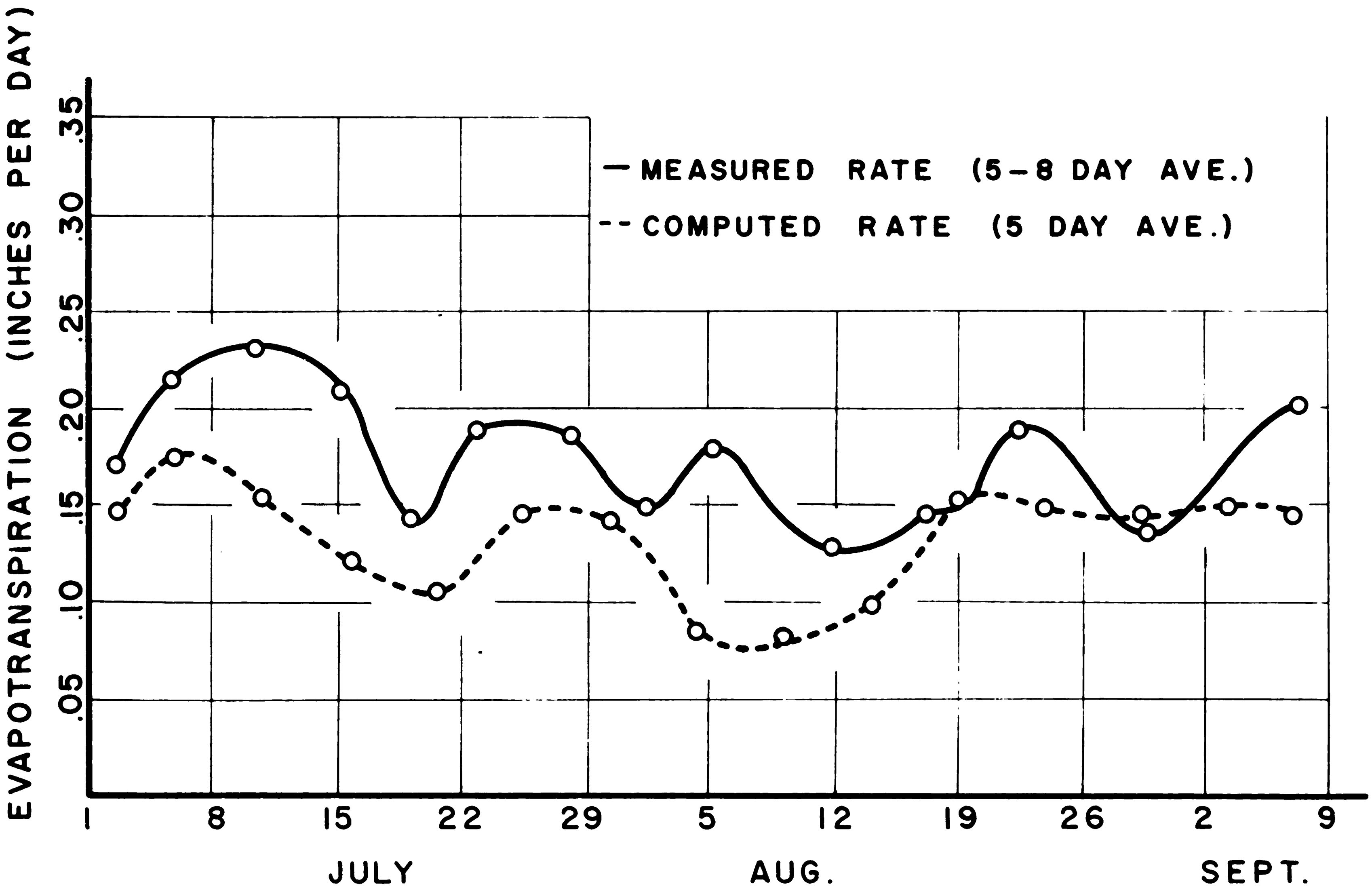

FIGURE 17 COMPARISON OF MEASURED EVAPOTRANSPIRATION AND VAN BAVEL (DETAILED) VALUES FOR TOMATOES 1959

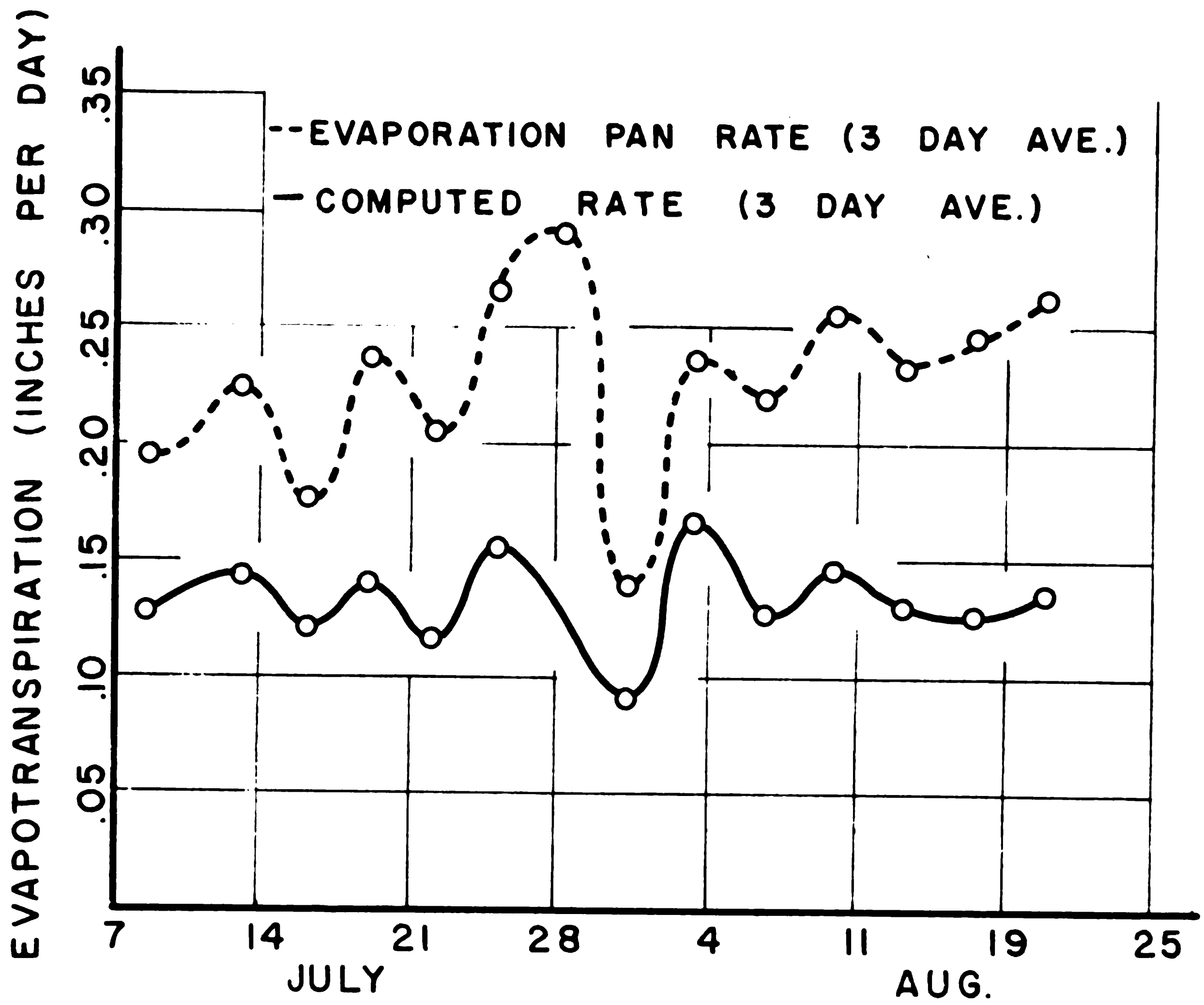

FIGURE 18 COMPARISON OF EVAPORATION PAN DATA AND VAN BAVEL (DETAILED) VALUES FOR POTATOES 1958

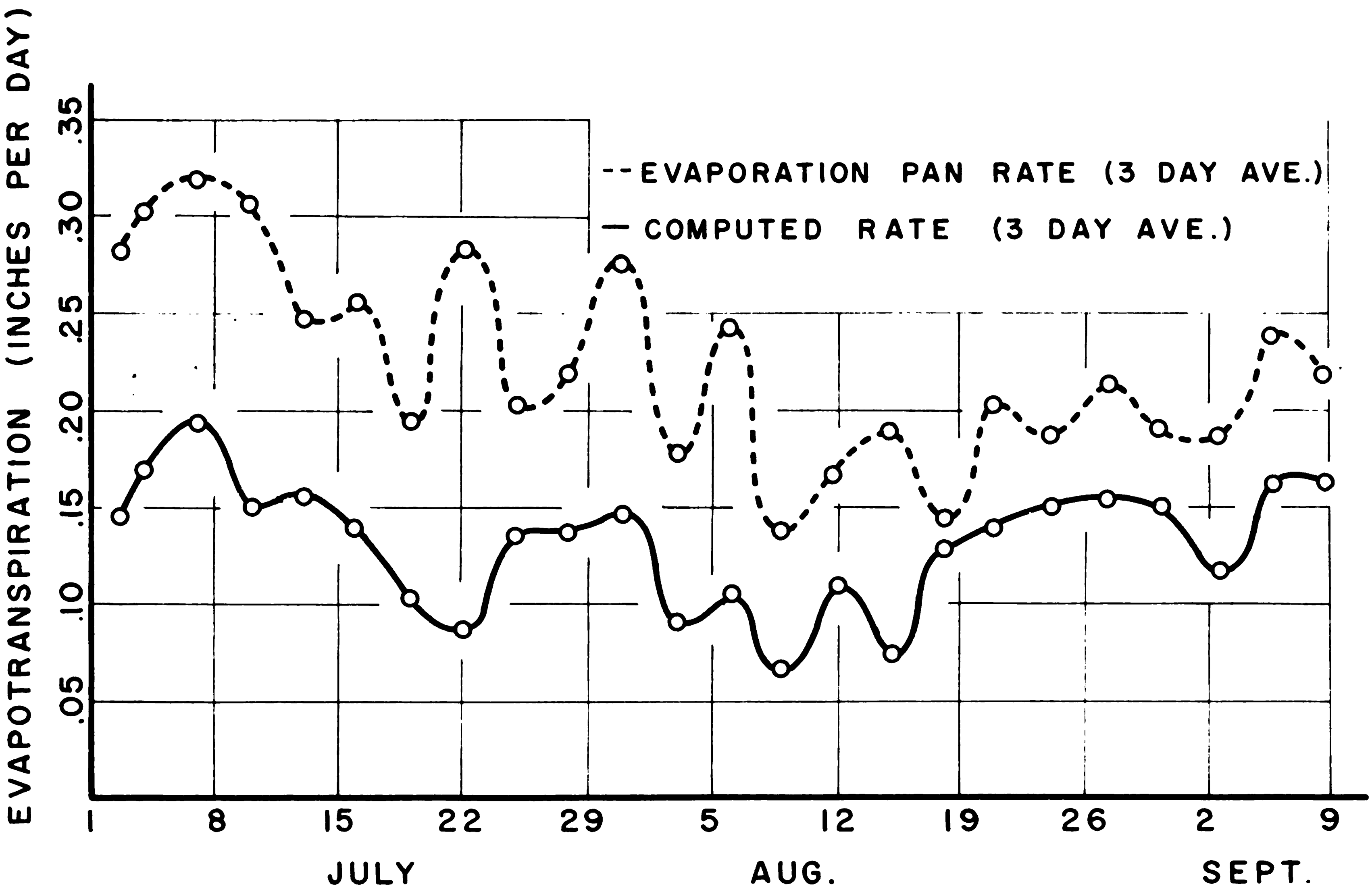

FIGURE 19 COMPARISON OF EVAPORATION PAN DATA AND VAN BAVEL (DETAILED) VALUES FOR TOMATOES 1959

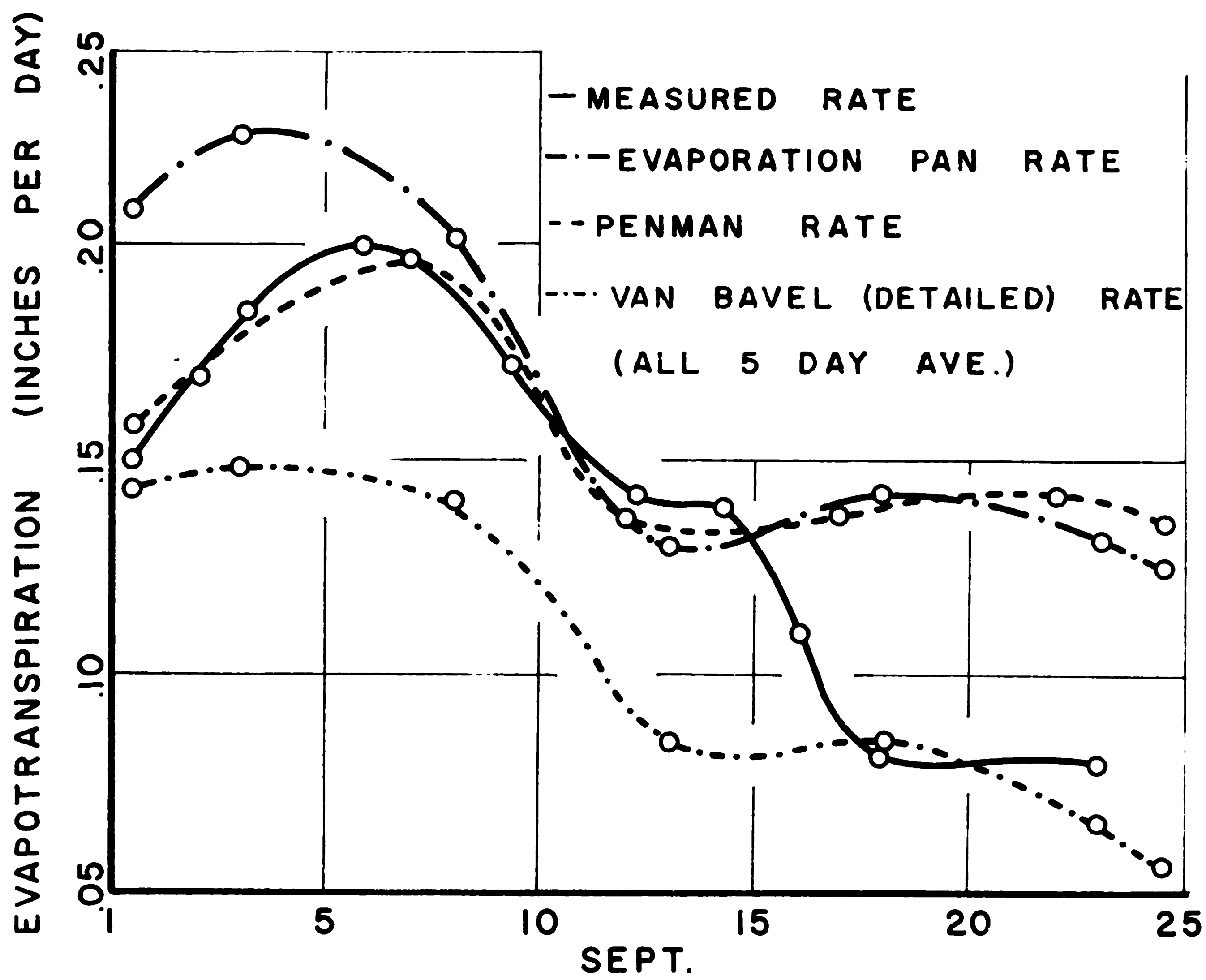

FIGURE 20 COMPARISON OF MEASURED EVAPOTRANSPIRATION, PENMAN, EVAPORATION PAN, AND VAN BAVEL (DETAILED) VALUES FOR TOMATOES 1959

Table 1

Results of Comparison of Measured to Calculated ET. - 1958

Methods of computing ET.	Season total of measured ET.	Season total of computed ET.	Largest over-est.	Length of largest over-est.	Period of largest over-est.	Largest under-est.	Length of largest under-est.	Period of largest under-est.
Adj. E. pan (3 day ave.)	6.47	6.59	0.28	6 days	July 24 - July 29	0.21	6 days	July 30 - Aug. 4
Adj. E. pan (5 day ave.)	6.47	6.58	0.16	7 days	July 24 - July 30	0.16	5 days	July 31 - Aug. 4
Adj. E. pan (7 day ave.)	6.47	6.47	0.08	8 days	July 22 - July 29	0.13	12 days	July 11 - July 21
B.C. (5 day ave.)	6.47	5.98	--	--	--	0.56	35 days	July 16 - Aug. 18
TH. (5 day ave.)	6.47	6.57	0.14	10 days	Aug. 5 - Aug. 14	0.15	6 days	July 18 - July 23
V.B. simplified (5 day ave.)	6.47	7.56	1.09	42 days	July 9 - Aug. 18	--	--	--
V.B. detailed (5 day ave.)	6.47	5.45	--	--	--	1.04	41 days	July 10 - Aug. 18

Key: ET. = Evapotranspiration, E. = Evaporation, B.C. = Blaney-Criddle,
TH. = Thornthwaite, V.B. = van Bavel, ET. in (inches of water)

Table 2

Results of Comparison of Measured to Calculated ET. - 1959

Methods of computing ET.	Season total of computed ET. (in. H_2O)	Season total of measured ET. (in. H_2O)	Largest over-est. (in. H_2O)	Length of largest over-est.	Period of largest over-est.	Largest under-est. (in. H_2O)	Length of largest under-est.	Period of largest under-est.
Adj. E. pan (3 day ave.)	11.75	11.85	.18	5 days	July 28 - Aug. 1	.24	9 days	Aug. 17 - Aug. 25
Adj. E. pan (5 day ave.)	11.78	11.85	.22	6 days	July 28 - Aug. 2	.23	21 days	Aug. 3 - Aug. 23
Adj. E. pan (7 day ave.)	11.89	11.85	.20	8 days	July 28 - Aug. 4	.15	12 days	Aug. 14 - Aug. 25
B.C. (5 day ave.)	11.12	11.85	.25	10 days	Aug. 8 - Aug. 17	.73	17 days	July 1 - July 17
TH. (5 day ave.)	11.83	11.85	.80	29 days	Aug. 4 - Sept. 1	.67	14 days	July 1 - July 14
V.B. (simplified) (5 day ave)	12.20	11.85	.43	20 days	July 14 - Aug. 2	.09	10 days	Aug. 3 - Aug. 12
V.B. (detailed) (5 day ave.)	9.04	11.85	--	--	--	2.81	69 days	July 1 - Sept. 7
Penman (5 day ave.)	2.66*	2.84*	--	--	--	--	--	--

Key: ET. = Evapotranspiration, E. = Evaporation, B.C. = Blaney-Criddle,
TH. = Thornthwaite, V.B. = van Bavel, *Sept. 1-16, ET. in (inches of water)

SUMMARY

In a controlled irrigation experiment at Michigan State University, measured evapotranspiration was compared to six different methods of estimating evapotranspiration in an effort to determine the accuracy and reliability of each. The comparisons have been made for short periods of time during two growing seasons to determine the behavior of each estimate during maximum and minimum water use periods.

Curves drawn from the computed values were compared to the curves of measured evapotranspiration, and periods of over and under estimation were determined for each method. Agreement or lack of agreement between the curves was explained. In cases of poor agreement adjustments to produce improved estimates were suggested.

CONCLUSIONS

(1) Evaporation pan values, when used with an adjustment factor, provide an accurate estimate of actual evapotranspiration.

(2) Factors that will correctly modify evaporation pan values will vary due to difference in crops, stage of crop growth, and the portion of the season under consideration.

(3) Blaney-Criddle and Thornthwaite estimates can be expected to provide a fair estimate of measured evapotranspiration during average water use periods.

(4) Blaney-Criddle and Thornthwaite estimates will run considerably lower than actual evapotranspiration during periods of extended high water usage by the plant-soil system.

(5) Thornthwaite estimates will overestimate actual evapotranspiration during extended periods of high temperatures.

(6) Actual evapotranspiration will experience a phase lag behind adjusted evaporation pan and Thornthwaite values.

(7) van Bavel (simplified) values should be tested further before use.

(8) van Bavel (detailed) values times a factor can be satisfactorily used to determine actual evapotranspiration.

(9) Penman values, when computed from measured net radiation readings, give indication of providing an excellent means of estimating actual evapotranspiration.

SUGGESTIONS FOR FURTHER STUDY

(1) More basic data and information is needed of the evapotranspiration rates and habits of different crops. A measuring device such as a lysimeter should be used as a check of the data now being obtained by moisture blocks.

(2) A field experiment making use of various methods of estimating evapotranspiration to determine time for irrigation, should be made. The test of each method's effectiveness would be the final yield of the crops.

(3) Additional basic comparisons between measured evapotranspiration and evaporation pan data should be made in order to determine more precise adjustment factors.

(4) Further investigation should be made of the validity of various methods of estimating actual evapotranspiration rates for this area.

(5) Net radiation readings should be taken for a crop during a complete growing season. Penman values computed from net radiation data would check the validity of his equation during longer periods of time.

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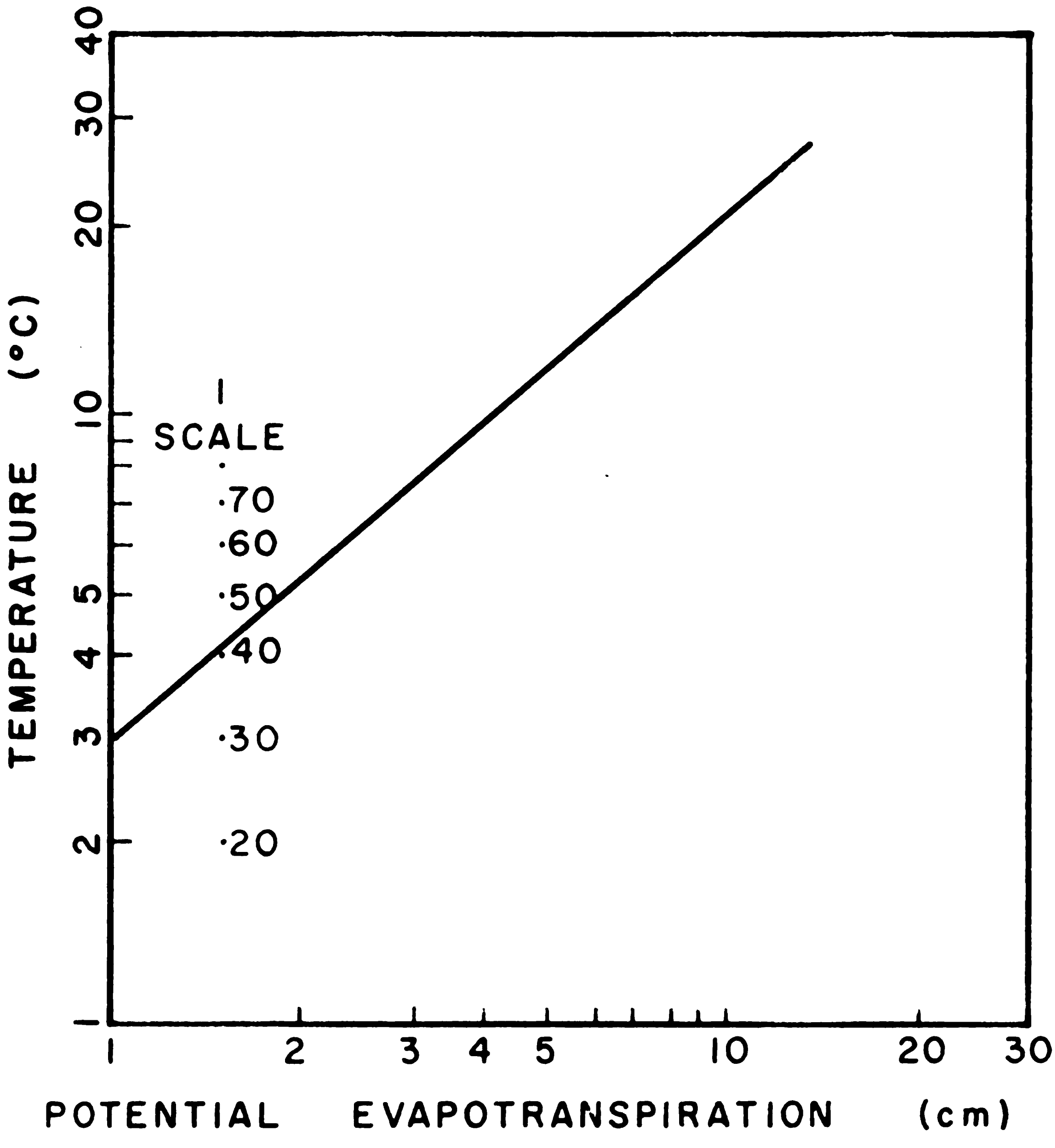
Appendix I



THORNTHWAITE'S NOMOGRAPH FOR DETERMINING POTENTIAL

FIGURE 21 EVAPOTRANSPIRATION

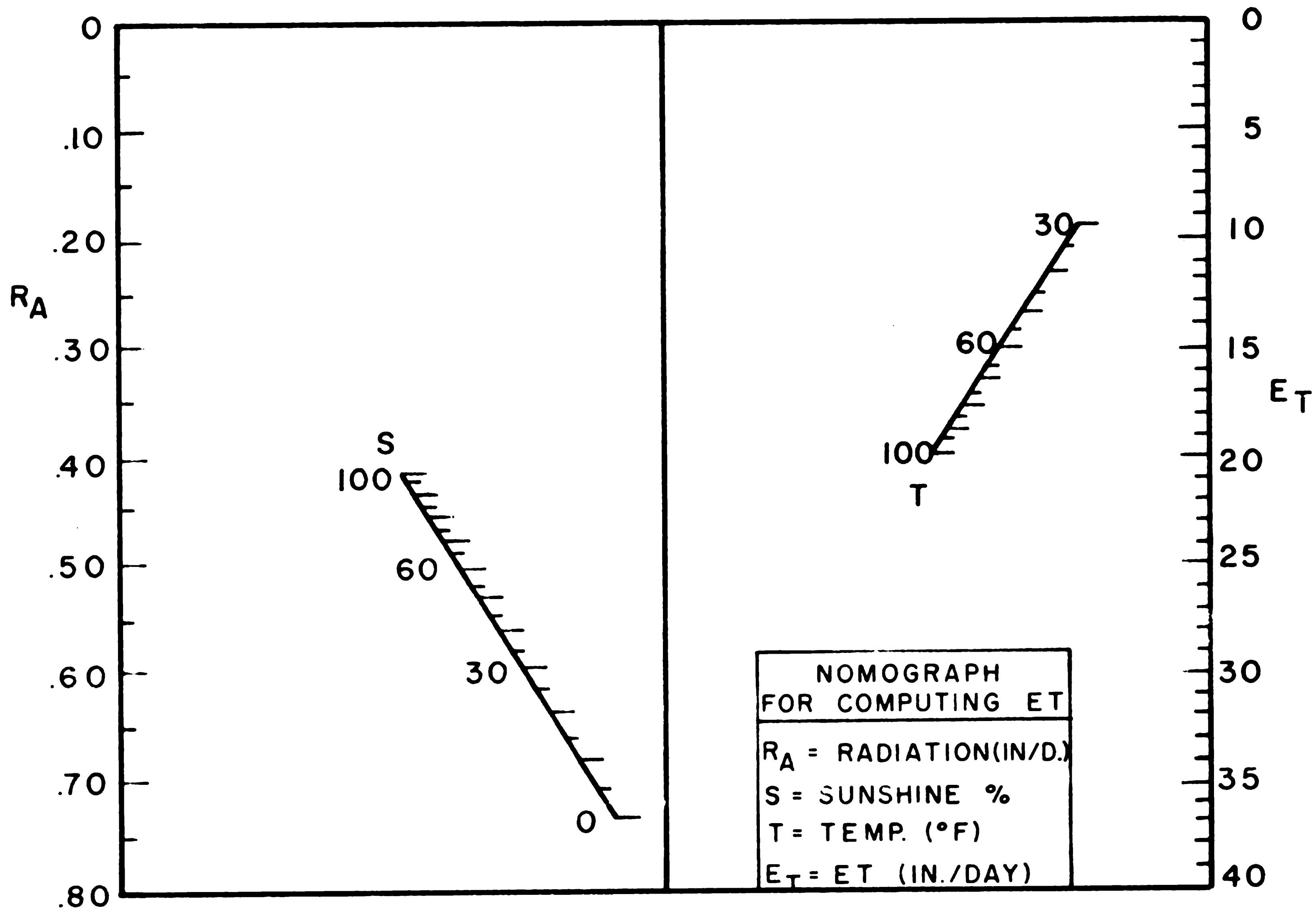


FIGURE 22 VAN BAVEL'S NOMOGRAPH FOR DETERMINING ET.

Appendix III

van Bavel Estimated Values of Daily Evapotranspiration

Latitude Between 40° and 34°

	Dull, Cloudy Weather (0-35%)*	Normal Weather (36-67%)*	Bright, Hot Weather (68-100%)*
April or September	.08	.11	.14
May or August	.11	.14	.19
June or July	.14	.17	.23

Latitude Between 30° and 34°

April or September	.09	.13	.16
May or August	.13	.16	.22
June or July	.14	.17	.23

*Per cent of possible sunshine

Appendix IV

Sample Calculation of Blaney-Criddle's Equation

$U=\frac{ktp}{100}$ k (daily crop factor) = 0.65 (potatoes)
t (average daily temperature) = 74.5° F
p (per cent of yearly sunshine) = 0.3339

Date: July 15, 1959

U = 0.65 x 74.5 x 0.3339/100 = 0.16 inches of water

Sample Calculation of Thornthwaite's Equation

Date: July 15, 1959 I (annual heat index) = 41.76
T (mean daily temperature) = 23.6° C

Unadjusted Potential Evapotranspiration = 35.1 cm. of water (Appendix I)

Adjustment factor for latitude and day length = 1.23

Adjusted Potential Evapotranspiration = 1.23 x 35.1 cm. = 43.17 cm. = 0.16 inches of water

Sample Calculation of van Bavel's (simplified) Method

Date: July 15, 1959

Per cent of possible sunshine = 96

Evapotranspiration = 0.23 (Appendix III)

Sample Calculation of van Bavel's (detailed) Method

Date: July 15, 1959

Radiation value = 0.628

Per cent of possible sunshine = 96

Mean air temperature = 74.5° F

Evapotranspiration = 0.20 inches of water (Appendix II)

Appendix V

Sample Calculation of Measured Evapotranspiration

(1) Plot C-2 -- during a period of no irrigation. 1959

Date	Per cent of Available Moisture	
August		
20	77	Number of inches of
21	75	Available Moisture = 4.14
22		
23	67	Moisture loss = 77-54 = 23%
24	67	4.14 x .23 = .9512 inches
25	59	
26	54	Average moisture loss
		0.9512/6 = 0.1585 inches/day

(2) Plot B-1 -- during a period of irrigation. 1959

Date	Per cent of Available Moisture	
August		
17	63	Moisture loss = Difference in
18*	68	moisture block readings +
19	87	amount added during irrigation
20	79	.63-.59 (4.14) + 1.25 =
21	84	1.4156 inches
22		Average moisture loss =
23	59	1.4156/6 = 0.2359 inches/day

*irrigated with 1.25 inches of water

(3) Average daily evapotranspiration rates (inches per day)

Date	B-1	D-1	A-1	D-2	C-2	B-2	Average
August 18	.24	.15	.13	.10	.19	.19	.16
19	.24	.24	.13	.10	.19	.19	.17
20	.24	.24	.13	.20	.19	.19	.19
21	.24	.24	.13	.20	.16	.19	.18
22	.24	.24	.13	.20	.16	.19	.18
23	.24	.24	.13	.20	.16	.19	.18
24	.09	.24	.13	.20	.16	.19	.16
25	.09	.24	.13	.20	.16	.19	.16
26	.09	.24	.15	.20	.16	.09	.14

Appendix VI

Sample Calculation of Penman's Equation

Date: September 8, 1959

$$E = \frac{\Delta H + 0.27\ E_a}{\Delta + 0.27/SD}$$

H (net radiation -- measured directly) = 308.21 gm-cal/cm^2/day

H = 308.21 x 1/590 cal/gm (water vapor) x 1cc/gm. water x 10mm/cm

H = 5.22 mm of water

Mean air temperature = 79.5° F

Δ (slope of the saturated vapor pressure curve -- Appendix VII)

Δ = 0.81 @ 79.5° F

$E_a = 0.35\ (e_a - e_d)\ (1 + 0.0098U_2)$ mm

e_a (saturation vapor pressure at mean air temperature -- Appendix VII)

e_a = 24.5 mm Hg @ 79.5° F

e_d (saturation vapor pressure at mean dew point temperature)

e_d = 13.7 mm Hg @ 56 per cent relative humidity

U_2 (wind speed in miles per day at two meters) = 60.2 miles

$E_a = 0.35\ (24.5 - 13.7)\ (1 + 0.0098 \times 60.2) = 6.01$ mm water

$S = L_a /\ (L_a + 0.16)$

$$L_a = 0.65\ (1 + 0.0098U_2)$$
$$= 0.65\ (1 + 0.0098 \times 60.2) = 1.03$$

$S = 1.03/\ (1.03 + 0.16) = 0.866$

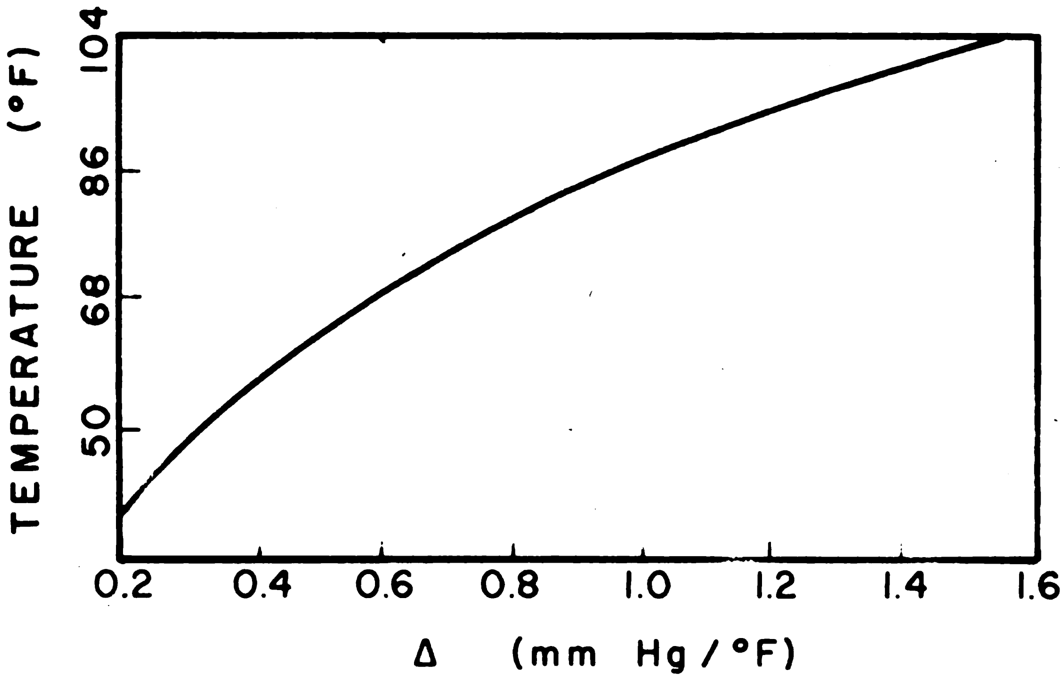
$D = N/24 + 1/\pi \ \sin N\pi/24$ N (hours from sunrise to sunset)

$$= 12.95/24 + 0.318 \sin 12.95/24\pi$$
$$= .54 + 0.318 \sin 83$$
$$= .54 + 0.318 \times 0.99$$
$$= 0.855$$

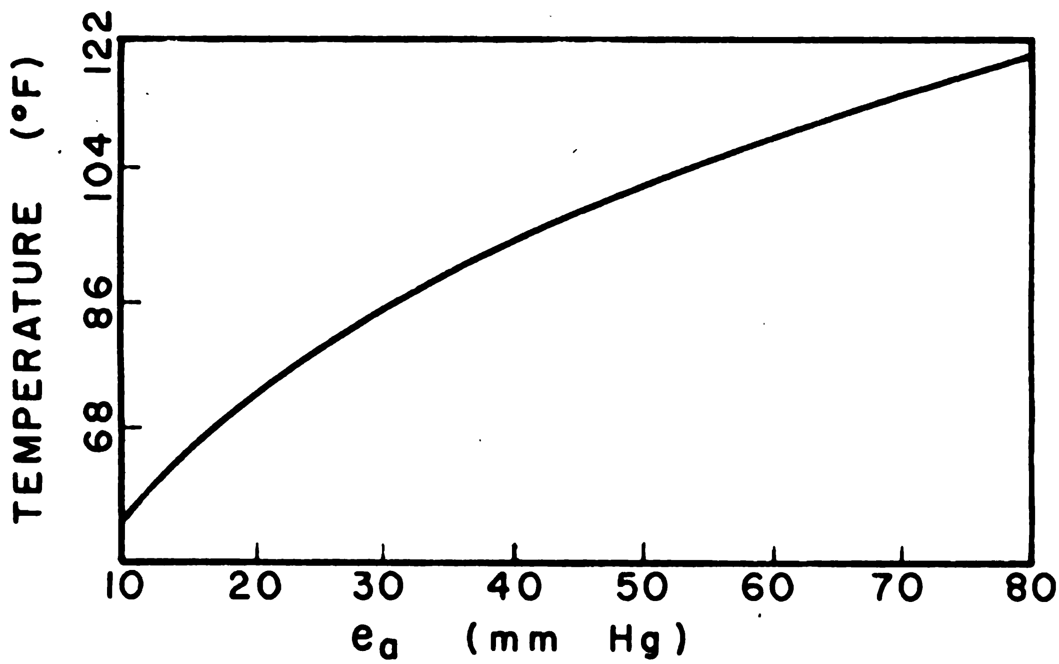
$$E = \frac{(0.81)\ (5.22) + (0.27)\ (6.01)}{0.81 + .27/(0.866)\ (0.855)}$$

$$E = \frac{4.98 \text{ mm water}}{25.4 \text{ mm/inch}} = 0.196 \text{ inches of water}$$

Appendix VII



TEMPERATURE VS. SLOPE OF SATURATED VAPOR PRESSURE CURVE



TEMPERATURE VS. SATURATION VAPOR PRESSURE