CROP EVAPORATION-TRANSPIRATION LOSSES RELATED TO WEATHER DATA

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INTRODUCTION

As population pressures on the land increase, more and more of the semi-arid areas are being reclaimed for the production of food and fiber by the application of irrigation water.

An increasing percentage of the available moisture precipitated in the watersheds as rain and snow is being conserved to provide water for the vast increase in irrigated areas, and in recent years there has been considerable research in an effort to improve the scheduling and efficiency of irrigations.

A review of the work to date has shown that insolation (solar radiation), vapor pressure deficit, wind movement, and temperature are factors that influence the amount of moisture transpired from a plant and evaporated from the soil surface. In addition to the meteorological factors, the type and depth of soil, the maturity of the plants, and variations in soil moisture also affect the consumptive use of vegetative crops.

So far as the theoretical aspects are concerned, the precision with which a prediction of evaporation or consumptive use may be made depends upon the relative number of the variable factors that are considered. One approach has been to measure one or all of the known meteorological factors, temperature, wind movement, relative humidity, insolation, and altitude to derive a formula that will indicate approximately the consumptive use of crops on irrigated fields. A second approach has been to consider evaporation from an open-water surface as the integrated effect of all the meteorological factors. If this is true, then meteorological factors can be related indirectly to consumptive use through pan evaporation. Investigations of this assumption have been made with promising results.

The overall objective of the research described in this thesis was to further investigate the relationship between consumptive use and evaporation from open-water surfaces in the Corvallis, Oregon, area. The consumptive use by three different types of crops was estimated by soil sampling. The water-surface evaporation was measured from various types of small pans.

Many workers have found that under given meteorological conditions evaporation of water from a pan varies with the size, shape, exposure, and color of the container. It was, therefore, proposed that the evaporation from one type of pan might correlate more closely with crop consumptive use than evaporation from a different type of pan. For this reason, evaporation data in this research were measured from five types of evaporation pans, all subject to the same meteorological conditions, but varying widely in size, shape, exposure, and color.

The field work was conducted on the Oregon State College experimental farms. All data were analyzed to determine the degree of correlation between consumptive use and pan evaporation.

REVIEW OF LITERATURE

Consumptive use, or evapotranspiration, includes loss of water by evaporation from the surface of the soil, loss from interception by the vegetative cover, plant transpiration, and water stored in the plant tissue. Consumptive use of water is one of the important elements in the hydrologic cycle and is increasingly significant, particularly in the expanding irrigated areas of Western United States. If the period of time is relatively short, such as one growing season, consumptive use is usually expressed as inches of depth, feet of depth, acre inches, or acre feet of water lost in a specified time (4, p.3).

The effect of sunshine and heat in stimulating transpiration was studied as early as 1691, according to a review of the literature by Abbe (1, pp.67-127).

Briggs and Shantz (10, p.155) used plants grown in sealed galvanized cans to study the march of transpiration during the growth period and the extent to which the daily transpiration is correlated with various weather factors.

Briggs and Shantz (10, p.211) wrote, "The transpiration of the different crop plants per unit area of plant surface shows less variation than the transpiration per unit weight of dry matter. In other words, the greater efficiency shown by certain plants in the use of water appears to be due more to a reduction in plant surface than to a reduction in transpiration per unit area of surface. The direct solar radiation received by the plants at Akron is usually not sufficient to account for the observed transpiration during the midday hours.

In some of the small grains the energy dissipated through transpiration is twice the amount received directly from the sun."

In an earlier study they found from automatic records that transpiration is at a minimum just before sunrise. In an effort to minimize experimental errors they weighed the pots in the morning as soon as there was adequate daylight.

The weather factors that were measured included solar radiation, air temperature, wet bulb depression, and wind velocity. Evaporation was measured by means of a shallow, blackened tank 6,540 square centimeters in area, 2.5 centimeters deep, exposed at the level of the plants and a large sunken tank, 8 feet in diameter and 2 feet deep, with the water surface at ground level. Readings were started when daily transpiration losses exceeded 0.1 kilogram on crops other than small grains. The water in the shallow black pan was automatically kept 1 centimeter deep. A planimeter was used to integrate temperature. The anemometer was 3 feet above ground level.

In this study the evaporation tanks were in the open and the transpiration measurements were made for the most part in screened enclosures. This would make some of the transpiration-evaporation ratios too low.

Transpiration losses from the different crops showed the best correlation with wet bulb depression and shallow tank evaporation.

Bowen (9, pp.779-787), in 1926, made a theoretical attempt to evaluate losses from bodies of water by conduction and convection in terms of easily measured climatic quantities, and to determine whether these losses were small enough to be neglected and, if not, how they may be corrected.

He derived an exact equation for the heat lost from any body of water that is thermally insulated on the sides and bottom:

$$I = S + LE\,(1 + R)$$

Where: I = the solar radiation received by the water surface

S = the heat represented by the change in temperature of the water

E = the evaporation during the same interval

L = the latent heat of evaporation

$$R = 0.46\left(\frac{T_w - T_a}{P_w - P_a}\right)\frac{P}{760}$$ = ratio of the heat loss by conduction to that by evaporation

Where: T_a and P_a are the original temperature and vapor pressure of the air passing over the water surface

T_w and P_w are the corresponding quantities for the layer of air in contact with the water surface

P = barometric pressure in mm. of Hg

Rohwer (38, pp.679-681) investigated the evaporation from several different pans and found the Bureau of Plant Industry (BPI) 6-foot diameter sunken pan evaporation data corresponds closely to that from large water surfaces. However, he observed that the Weather Bureau Class A land pan is used more than any other type and for general evaporation studies is probably the most satisfactory.

Rohwer took evaporation readings twice daily at approximately 7 a.m. and 7 p.m. He also advised cleaning the evaporation pans regularly to reduce the concentration of salts in the water which would occur (if the water contained appreciable amounts of salts) due to the evaporation.

Rohwer (39, pp.11,42) in discussing the operation of an evaporation station says that, "The maximum change in the evaporation station apparatus due to temperature change was the expansion of the water and tank at maximum temperatures and caused an apparent decrease in the evaporation as the temperature increased. By using a 24-hour period the effect of temperature on the apparatus would largely be eliminated."

He developed the following formula for calculating pan evaporation:

$$E = (1.465 - 0.0186B)(0.44 + 0.118W)(e_s - e_d)$$

Where: E = evaporation in inches per 24 hours

B = mean barometric reading, inches of Hg at 32° F

W = mean wind velocity in m.p.h. of ground or water-surface wind

e_s = mean vapor pressure of saturated vapor at temperature of water surface, inches of Hg

e_d = mean vapor pressure of saturated air at the temperature of the dewpoint, inches of Hg

Blaney and Morin (8, p.79) used per cent daylight hours, temperature, and relative humidity to estimate valley consumptive use. They developed the formula:

$$u = kc$$

Where: u = monthly consumptive use

k = coefficient developed for each crop

$c = f\ (114 - h)$ = monthly use index

$f = (t \times p)$ = monthly consumptive-use factor

t = mean monthly temperature in degrees F

p = monthly per cent of daytime hours of the year

h = monthly average relative humidity

Blaney and Criddle (7, p.15) later developed a modified formula using per cent daylight hours and temperature to estimate consumptive use:

$$U = KF = \text{sum of } kf$$

Where: U = consumptive use of crop (or evapotranspiration) in inches for any period

F = sum of the monthly consumptive-use factors

K = empirical consumptive-use coefficient (irrigation season or growing period)

t = mean monthly temperature in degrees F

p = monthly per cent of daytime hours of the year

$f = \frac{t \times p}{100}$ = monthly consumptive-use factor

k = monthly consumptive-use coefficient

$u = kf$ = monthly consumptive use in inches

In this formula "k" is calculated for each crop and the formula can be used to estimate the "farm consumptive use" as well as "valley consumptive use."

Davis, Evans, and Hazen (12, pp.11-17), Houston (19, pp.12-27), and Tileston and Wolfe (49, pp.25-31) have adapted the Blaney-Criddle method to particular areas.

Land and Carreker (25, pp.319-320, 322) state that the irrigation programs of the Soil Conservation Service in the southeastern region are based on estimated values of consumptive use of water obtained with the Blaney-Criddle method. In 1952, Land and Carreker calculated the daily evapotranspiration rate by the formula:

$$A = \frac{(B - C) + (D + E) - F}{G}$$

Where: A = evapotranspiration rate in inches per day

B = available soil moisture in inches at the beginning of the period

C = available soil moisture in inches at the end of the period

D = inches of rainfall during the period

E = inches of irrigation during the period

F = inches of runoff during the period

G = number of days in the period

They indicate that the depth from which roots can draw moisture will affect the quantity and frequency of irrigation applications.

Hedke (17) proposed a method of estimating consumptive use based on the principle that each crop requires a definite quantity of heat above its germinating temperature to bring it to maturity, and that moisture and plant food are required in proportion to the heat utilized. Available heat units were calculated by subtracting the minimum growing temperature from the mean monthly temperature and multiplying the difference by the number of days in the month. The same result could be obtained by multiplying the minimum growing temperature by the number of days in the month, which would be either 30 or 31 days during the growing season, and subtracting the appropriate product from the sum of the daily mean temperatures. The product or sum thus obtained represents the available heat units in day degrees. The sum of the monthly available heat units gives the available heat units for the growing season.

After making some assumptions, Hedke developed the following formula to relate consumptive use to the calculated available heat units:

$$U = K\,Q_h$$

Where: U = valley consumptive use in acre feet

K = Hedke's coefficient = 0.000423 (approx.)

Q_h = available heat in day degrees

Lowry and Johnson (26, p.1249), Lugo-Blanco (27, p.9), and Patil (29, p.3) discussed Hedke's method.

According to Patil this method applies best to a highly developed agricultural area.

Lowry and Johnson (26, pp.1248,1251), after a literature review and a study of the consumptive use on valley areas, or watersheds, by inflow, outflow, water table variation, and rainfall, or precipitation measurements, and adjusting the data to a common base, report that "Although solar radiation gives one of the best correlations with transpiration and evaporation, growing season temperatures more nearly parallel the cycle of plant growth." In their study daily temperature readings were taken. They calculated total effective heat by the formula:

$$\text{Total effective heat} = \sum(\text{daily maximum temperatures in degrees F} - 32^{\circ})$$

The growing season was defined as the period of time when a 9-day average of the daily minimum temperatures exceeded 32° Fahrenheit. The 9-day moving average of the daily minimum temperatures was found by using the following equation:

$$t = \frac{a + 2b + 3c + 4d + 5e + 4f + 3g + 2h + i}{25}$$

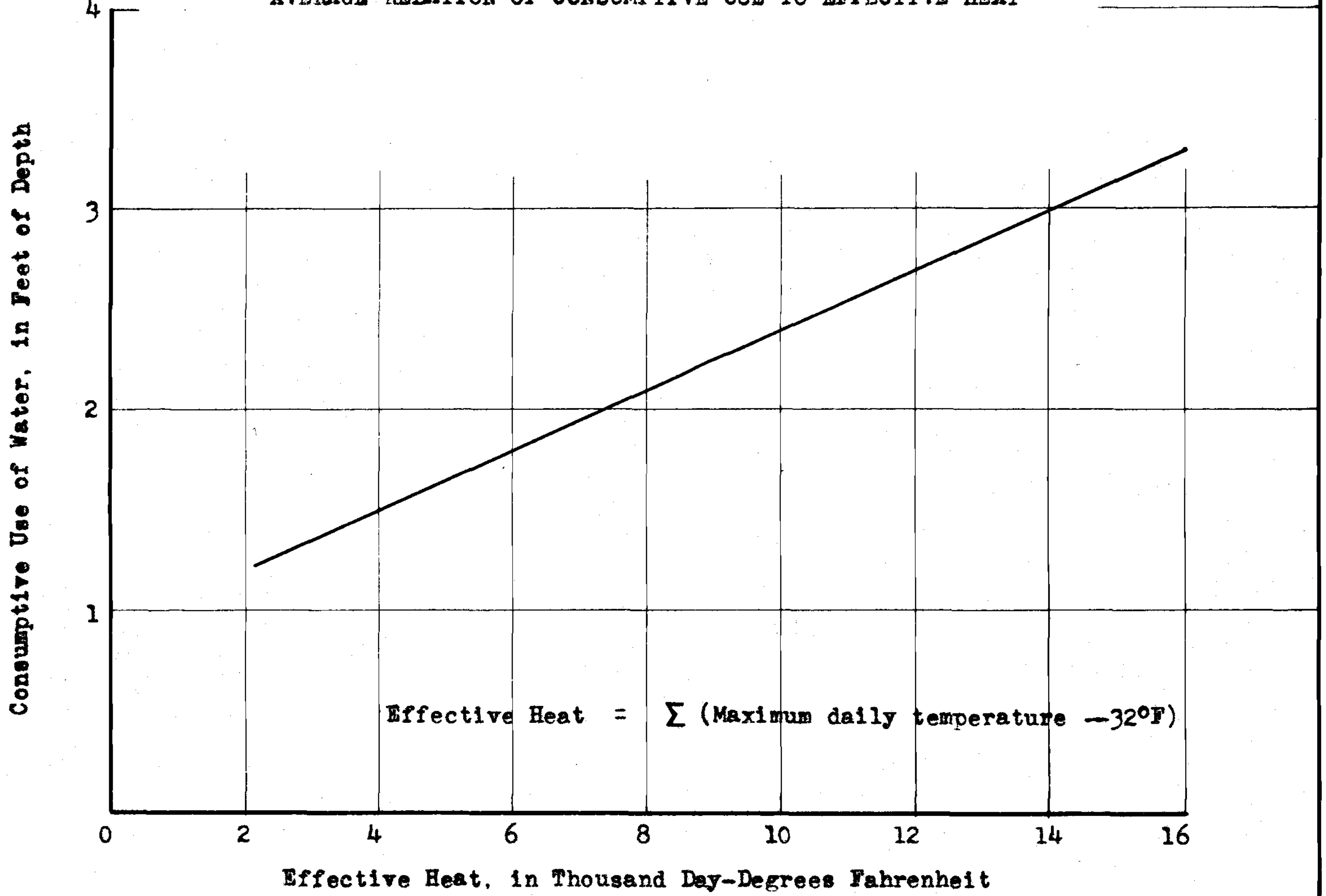
Where the letters, a, b, c, d, e, f, g, h, i, represent the nine successive minimum daily temperatures and the result is considered the minimum daily temperature for the middle day of the series.

Lowry and Johnson (26, p.1252) constructed a graph (Figure 1) by which effective heat could be converted into consumptive use.

Lugo-Blanco (27, pp.3-16) conducted a literature review and made a comparison of the Lowry-Johnson method, the evaporation method, and the water-variation method for estimating irrigation requirements for an area. He noted that Briggs and Shantz had found that evaporation

Figure 1

AVERAGE RELATION OF CONSUMPTIVE USE TO EFFECTIVE HEAT



continued at a reduced rate during the night while transpiration stopped. He also pointed out that Lowry and Johnson, in calculating their method, used the mean maximum daily temperatures for a period ranging from 9 to 57 years and that the consumptive use calculated by the Lowry-Johnson method was "valley consumptive use" and not "farm consumptive use."

Lugo-Blanco concluded that pan evaporation has been found to be the best general indication of "farm consumptive use" in any region.

Tomlinson (50, pp.459-460) compared measured consumptive use with consumptive use calculated by the Blaney-Criddle and the Lowry-Johnson methods. The result of his comparison was:

Calculated consumptive use by the Lowry-Johnson method ...	18.0"
Calculated consumptive use by the Blaney-Criddle method ..	8.9"
Actual consumptive use by measurement	8.4"

The Blaney-Criddle method of predicting consumptive use compared favorably with the measured consumptive use. The Lowry-Johnson method gave an unusually long growing season of 92 days for this location (Pindale area of the Green River Basin, Wyoming, elevation 7,100 feet).

In his computations Tomlinson used a 5-day moving average of the mean daily temperature to estimate the beginning and end of the growing season. If he had used the minimum daily temperature (26, p.1251) the length of the growing season would have been considerably shortened and the calculated consumptive use would have been reduced.

Penman (32, pp.29-32) observes that transpiration may be attacked from two directions:

1. Heat balance where the solar energy received is distributed various ways, one of which is transpiration, or the latent heat of evaporation.
2. "Aerodynamic" method, where the rate of transfer is calculated from simultaneous measurements of the vapor pressure gradient and of the wind velocity gradient above the crop, the latter determining the degree of turbulent mixing in the air.

The Rothamsted work has shown that an estimate of "potential transpiration rate" can be made with an adequate degree of accuracy from standard weather data. The quantities required are:

1. Duration of bright sunshine
2. Mean air temperature
3. Mean air humidity
4. Wind speed

Penman's equation (33, p.122) for evaporation is:

$$E_o = 0.35\,(e_s - e_d)(1 + u_2 \times 10^{-2})\ \mathrm{mm}/_{\mathrm{day}}$$

Where: E_o = evaporation from open-water surfaces

e_s = mean saturated vapor pressure (in mm. of Hg) at the water surface at T_s

e_d = mean vapor pressure (in mm. of Hg) in the air

u_2 = wind velocity in $\mathrm{mi}/_{\mathrm{day}}$ measured at 2 meters above ground level.

T_s = mean surface temperature of the water

Penman's equation, however, was designed to calculate the evaporation from an open-water surface and then a factor was applied to the calculated open-water-surface evaporation to estimate the consumptive use of a certain crop. Irrigations at the time, and of such a quantity as was indicated by the calculations from the meteorological data, increased crop yields.

Thornthwaite (44, p.186) agrees with others that transpiration increases with plant development until maturity is reached, due largely to the increase in the area of the transpiring surface and in the number of stomatal openings.

In an attempt to obtain a monthly evaporation factor, and to classify weather into regions, Thornthwaite (43, pp.89-90) related temperature and potential evapotranspiration by the formula:

$$e = ct^a$$

Where: e = monthly evapotranspiration in cm.

t = mean monthly temperature in degrees C

c and a = coefficients which vary from place to place

A correction for latitude is necessary when using this formula. Daily temperature was the only variable to be gathered.

Thornthwaite (45, p.83) indicated that one of the greatest needs of modern agriculture is the ability to estimate the time and quantity of a proper irrigation. He stated, "Only when we have learned how to measure evapotranspiration, both potential and actual, shall we be able to combat drought intelligently."

Thornthwaite and Holzman (46, p.6) demonstrated the practicality of estimating the evaporation from either land or water surfaces by the use of temperature, and wind and moisture concentration gradients above the surface. Although instrumentation was a problem, they developed several formulas, one of which is presented here:

$$E = \frac{17.1\ (e_1 - e_2)(u_2 - u_1)}{T + 459.4}$$

Where E = evaporation in inches per hour

e_1 and e_2 = vapor pressure in inches of Hg at the lower and upper levels, respectively

u_1 and u_2 = wind velocity in miles per hour at two different levels above the ground surface

T = temperature in degrees F

Krimgold (23, pp.705-706), with some reservations, found Thornthwaite's method of predicting consumptive use of irrigated crops to be practical and profitable.

Van Bavel and Wilson (52, p.418) found the correlation between computed evapotranspiration, using the Thornthwaite, Blaney-Criddle, and Penman formulas, and measured evaporation from an open-water surface was good. The maximum difference between the computed values and the observed values was 14 per cent. The location of this experiment was Raleigh, North Carolina.

Mortensen and Hawthorn (28, pp.466-469) found a positive correlation between consumptive use and evaporation from an open pan on a daily basis but not on an hourly or short-interval basis. Irrigations were scheduled on different test plots when cumulative evaporation had reached different predetermined amounts. They found that the age of the crop affected the rate of consumptive use irrespective of the pan evaporation. However, their results indicate that accumulated evaporation can be used as a guide when scheduling the time and amount of irrigation.

Blaney and Morin (8, p.77) report that for tules growing in a large tank within the confines of a swamp area at Victorville, California, the consumptive use was equal to 95 per cent of the evaporation from a nearby exposed Weather Bureau pan.

Gray, Levine, and Kennedy (13, p.531) found the difference in the seasonal consumptive use for two seasons to be closely approximated by the difference in the seasonal evaporation from a Weather Bureau Class A pan.

Schofield (40, pp.757-758,760-761) endeavored to find a relation between a 30-inch diameter sunken pan and representative irrigated areas in field crops. He placed the 30-inch sunken pan in a test area planted to grass, which he irrigated to insure maximum transpiration. According to Schofield, "Acceptance of the basic principle that, under irrigation, total evaporation remains at or near the maximum is essential before such a service (estimates of maximum evaporation from cropped areas) rests on a secure basis."

When using the hypothesis that transpiration will remain at or near a maximum value that is determined by meteorological factors, especially solar radiation, it is logical to assume that the amount and frequency of irrigations can be predicted from current meteorological factors and a knowledge of the initial conditions of the soil moisture.

Schofield proposed using a factor which was equal to the evaporation from subirrigated grass divided by the evaporation from an open-water surface to predict consumptive use from pan evaporation.

Patil (29, pp.16-24) studied the relation of consumptive use of water by barley and evaporation from three types of pans. He measured the consumptive use with calibrated gypsum blocks. The gypsum blocks were recalibrated during the growing season by taking several soil samples. Of the three evaporating pans used, the black barrel appeared to be the best indicator of consumptive use. He also found that the ratio of consumptive use to evaporation varied with time during the season.

Harrold (16, pp.671-672) also found that "Evapotranspiration rates for different crops vary notably throughout the growing season." He observed that during July and August consumptive use of corn is mostly transpiration, evaporation from the soil surface being a minor item. Alfalfa and timothy meadows show a greater use rate during May and June than corn because of the early development of rapid vegetative growth.

Veihmeyer and Hendrickson (53, pp.425-428) investigated the change in rate of transpiration with decreasing soil moisture. In their work they found very little decrease in transpiration as the soil moisture was depleted. However, little of their work was done near the wilting point.

Harrold (15, p.101) found that for a given moisture tension level evapotranspiration is greater on heavier soils than on lighter soils.

He also found that evapotranspiration is greater for similar crops when available moisture is abundant.

Reeve and Furr (36, pp.125-128) used the evaporation from a shallow black pan evaporimeter as an index of use of water by mature citrus trees. They reported, "Briggs and Shantz, who devised the shallow black pan evaporimeter, in several tests with different kinds of plants found correlation coefficients of .89 to .95 between the transpiration rate and evaporation rate from this pan."

Reeve and Furr found that the agreement between transpiration rate and evaporation rate from the shallow black pan was better than that from any of several types of atmometers, or from a deep pan evaporimeter. In their research these men employed a recording evaporimeter and a Mariotte reservoir evaporimeter. Both instruments were equipped with shallow black pans 25.23 inches in diameter and 1 inch deep.

They stated that, "The recording evaporimeter is in some respects very convenient, but is relatively expensive, and it is sometimes difficult, as a result of wind action or rain, to read the values from the chart."

These authors calculated an evaporation coefficient by dividing the seasonal soil moisture extraction by the adjusted seasonal evaporation. They found that the soil moisture extraction for any period could be predicted with a high degree of accuracy by multiplying the accumulated evaporation during that period by the evaporation coefficient.

Pruitt and Jensen (35, p.392) compared measured consumptive use with pan evaporation and found good correlation after the crop had become established. From twenty comparisons of consumptive use of water by alfalfa, they calculated a regression equation of:

$U = 1.38E$ with a correlation coefficient of 0.99

Where: U = crop consumptive use

E = pan evaporation

Pruitt (34, pp.180-181) designed and used (during the 1954 growing season) an irrigation scheduling guide which, when calibrated for the several crops, can be used to determine quickly when a crop has depleted the soil moisture to the point where an irrigation is necessary. This guide uses the cumulative evaporation from an evaporation pan to estimate the consumptive use of individual crops.

The accuracy of research dealing with consumptive use depends, of course, upon the accuracy with which the consumptive use can be measured. It has been standard practice to measure consumptive use from soil samples taken in the field. It is often assumed that a condition of field capacity is reached within a period of 2 to 3 days after an irrigation. Several researchers have investigated the accuracy of this method.

Robins (37, p.344) observed a measurable drainage of water within the soil profile in field plots for periods up to 8 days following an irrigation under an actively transpiring alfalfa crop. Total drainage from the 0- to 3-foot zone for the period of 2 to 8 days after an irrigation was 0.58 inch of water.

He reported, "This downward movement of water is shown to have material effects upon consumptive-use measurements and the soil moisture extraction pattern. A computed error of 23 per cent in consumptive use for the first 8 days following an irrigation is shown to have occurred in the present experiment as a result of drainage from the 0- to 3-foot zone." This project was on a Ritzville fine sandy loam. The soil profile was relatively uniform and contained no major stratification or profile development. Basaltic bedrock was at 5 to 5½ feet. A good stand of alfalfa was growing on the experimental plots. The alfalfa was allowed to deplete the moisture in the complete profile, then water was applied to place a wetted front at about 2½ feet. It is evident that water was moving from the upper 3 feet into the fourth and fifth foot zone for several days, even in the presence of an actively transpiring alfalfa crop.

Taylor (42, p.659) reported that the large errors in field studies of soil moisture are largely a result of real variation of moisture in the field. The factors causing variation in soil condition, water application, water removal, and soil make a coefficient of variability of less than 10 per cent unlikely.

Another variable which affects the accuracy of consumptive use measurements in the field is the depth of root zone. For some crops soil sampling throughout the entire depth of root zone is very difficult.

Scofield (40, pp.379-382), in 1942, installed tensiometers in a plot of third-year alfalfa at 12, 24, and 36 inches below ground surface at the U.S. Huntley Field Station, Montana. The tensiometers indicated that the roots of the alfalfa drew water from 36 inches and possibly below.

In 1943, tensiometers were set in the alfalfa plot at 6, 12, 24, 48, and 60 inches. The tensiometric data from 1943 shows that the alfalfa drew some water from the 48-inch horizon but probably did not draw much, if any, from the 60-inch horizon.

The soil at Huntley is a clay loam of recent alluvial origin. The subsoil contains layers of sand and gravel, which fill with water during the irrigation season. At the location of the tensiometers, an observation well that extended into gravel stratum showed that the ground water in July stood at about 8 feet below the ground surface.

At the U.S. Scotts Bluff Field Station, Nebraska, where the soil is classed as a very fine sandy loam and there is no ground-water table in proximity to the root zone, a review of the 1943 seasonal record of tensions (from tensiometers at 12, 24, 48, and 72 inches) shows that the active root zone of alfalfa was deeper than 48 inches but probably did not extend to 72 inches.

Kramer (22, pp.122-123) reported that roots of alfalfa have been observed to absorb water from a depth of 33 feet when growing on relatively coarse textured, well drained, and well aerated soils.

Step by step all of these men have contributed to our knowledge of the relationship between meteorological factors and consumptive use. Soil types, moisture tension, type of crop, and meteorological factors have been extensively investigated in an attempt to discover an accurate and feasible guide that can be easily and economically adapted to schedule irrigations on the farm.

PROCEDURE

Consumptive Use Measurements

Soil moisture data were gathered by soil sampling from three experimental farms, each growing a different crop. The three crops were grass and clover pasture, alfalfa, and corn. Each crop was sprinkler irrigated. There were two distinctly different soil types.

The pasture was a part of what is designated by the College as the South Farm. The predominant soil type in the pasture was Amity silt loam. Since this is a relatively heavy soil with a subsoil of low water conductivity, soil samples were taken to the three-foot depth only. Previous moisture studies with gypsum blocks on similar soils and crops had shown this depth to include all of the soil profile where roots actively extract soil moisture.

Soil samples were taken in the early morning every third day. When irrigations were scheduled, an effort was made to obtain soil samples immediately before the irrigation and again three days after the irrigation.

The grass and clover pastures were divided into plots, as shown in Figure 2. Three sampling plots, one in each pasture, were selected with the aid of a random-number table. These three sampling plots were subdivided into one hundred equal subplots with the columns and rows numbered as shown in Figure 4. Black numbers on a white background were fastened to the fences to identify these subplots. Numbers 7, 8, and 9 can be seen on the fence in the foreground in Figure 9A. Four subplots were selected for sampling each third day by drawing four pair of numbers from the random-number table. Three samples were taken in each of the four subplots. The three samples from the same depth, in each subplot, were combined to make one composite observation.

The alfalfa sampling plots were located in a field of third year alfalfa on what is known as the Beech Farm. The soil in this field was Chehalis sandy loam, with a few outcroppings of Newberg. The Newberg soil contained much sand and some gravel.

With the aid of an aerial photograph the alfalfa fields were divided into plots, each one-hundred feet square, as shown in Figure 3. These plots were numbered consecutively and three plots were selected for sampling from the random-number table. On two occasions selected plots were found to contain large gravel and were abandoned in favor of other plots, also selected by the use of the random-number table.

These three sampling plots were again divided into one hundred subplots and numbered as shown in Figure 4. Four-foot lath were driven into the ground at ten-foot intervals on two sides of the alfalfa sampling plots to identify the subplot boundaries (Figure 7A). A short length of 2 x 4 lumber was placed in the ground at each corner of the one-hundred foot square sampling plot and generously coated with white lime. The lath were removed each time the alfalfa was mowed (Figure 7B), and the white corner stakes greatly facilitated the relocation of the sampling plots.

As in the pasture, four subplots were randomly selected each third day for sampling locations. Three soil moisture samples were taken in each of the four subplots. The three samples from each foot increment of depth were combined to give one composite observation. Samples were taken to a depth of six feet.

The complete sample from each foot increment of depth was placed in a metal can and covered as it was taken in the field. The wet and dry weight of the sample was determined to one-half gram on samples which averaged 350 grams dry weight. The soil samples were dried in an electric oven at 105° Centigrade. Per cent moisture in the soil sample was determined by the formula:

$$\text{Per cent moisture} = \frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} \; 100$$

The apparent specific gravity of the soil in each sampling plot in the pasture and in the alfalfa field was determined. Ten sampling locations in each plot were selected from the random-number table. Undisturbed samples were taken at the 6-, 18-, and 30-inch depths on each of the three sampling plots in the pasture, and to the 6-, 18-, 30-, 42-, and 54-inch depths on each of the three sampling plots in the alfalfa.

A standard Pomona sampler was successfully used on the pasture in the Amity silt loam. However, some difficulty was experienced with lost and broken samples when using the regular sampler in the Chehalis soil on the alfalfa field. In an attempt to solve this problem a longer cutting head was machined from a length of seamless steel tubing. The new head proved to be satisfactory and is shown in Figure 5.

The soil and cylinder from the sampler were placed in a metal can and dried in an oven at 105° Centigrade until the sample had reached a constant weight. Each metal can had been previously matched to a brass cylinder and the two weighed. These weighed pairs were not separated during the entire apparent specific gravity determinations. The sample was weighed to one-tenth of a gram. The averages of the ten apparent specific gravity determinations for each level are shown in Appendix Table 1.

From the soil moisture percentage and the apparent specific gravity, the inches of moisture within each 12-inch increment of depth was computed by the formula:

$$d = \frac{P_w A_s 12}{100}$$

Where: d = inches of moisture in 12 inches of soil

P_w = the average value of per cent moisture from 4 sampling locations

A_s = the average value of 10 apparent specific gravity determinations

12 = 12 inches

The moisture within the profile to the depth of sampling was found by summing the moisture in the 12-inch increments. Consumptive use was taken to be the decrease in moisture in the soil profile between two sampling dates. In this research it was assumed that deep percolation after a three-day period was negligible and could be disregarded.

Consumptive-use data from the corn field, located in the Vegetable Crops Experimental Area, were furnished by the Soils Department. These data were obtained by soil sampling, two feet deep, in Chehalis soil.

Weather Data Measurements

The following equipment was used to collect weather and evaporation data:

1. One Class A pan
2. Two Young screened pans
3. One 55-gallon barrel
4. One shielded pan
5. One continuous-recording shallow black pan
6. One nonrecording raingage
7. One hygrothermograph
8. One totalizing anemometer

Most of the weather data and evaporation measurements were obtained from equipment located within a fenced enclosure on the Vegetable Crops Experimental Area. Figures 8A and 8B show the weather station and adjacent crops. The arrangement of the individual pieces of equipment within the weather station is shown in Figure 6. Observations were taken twice daily at 7 a.m and 7 p.m. New charts were placed on the constant recording devices at 7 a.m. each Monday.

The Weather Bureau Class A evaporation pan (4-foot diameter, 10-inch depth) was mounted on a wooden platform that conformed to Weather Bureau specifications. Measurement of the water surface elevation was made with a hook gage in a stilling well inside of the Class A pan. The pan was emptied and cleaned when necessary.

Two Young screened evaporation pans (24-inch diameter, 35-inch depth) were constructed for the Agricultural Engineering Department by the College Physical Plant. One of these pans was installed within the weather station, as shown by Figure 6. The pan was sunk in the ground to a depth of 32 inches with the top rim of the pan extending 3 inches above ground surface. The maximum water level was maintained at ground level. When the water surface fell approximately one inch the pan was refilled. Measurements of water level were taken with a hook gage in an outside stilling well. A one-quarter inch galvanized screen was placed horizontally in the pan midway between the rim and the water surface. This screen is conventional equipment on the Young pan and is designed to protect the water surface from birds, rodents, and debris.

It was decided to compare the Young screened pan with a more simple and less expensive evaporation device. A 55-gallon barrel was selected as a feasible, low-cost substitute. This barrel was installed in the weather station adjacent to the Young screened pan to determine how closely their respective evaporation losses would correspond. The barrel was first cleaned and given two coats of aluminum paint. It was then installed in the ground with only the top three inches protruding above ground level. This was done to duplicate as nearly as possible the conditions surrounding the Young screened pan. A stilling well was installed inside of the barrel on the north side and submerged as far as possible. No screen was used in the top of the barrel, as had been done in the Young screened pan. Observations of water level were made with a hook gage.

The shielded evaporation pan was constructed of two 26-inch lengths of galvanized corrugated steel culvert. The diameters of the two lengths were 24 inches and 30 inches. Galvanized culvert was selected because it is a standard product that should be easily available for many years.

A circular disk of galvanized sheet steel was riveted to one end of the 24-inch diameter culvert section and all joints were soldered. The vessel thus constructed was used to contain the water for the evaporation measurements.

The second length of culvert, 30-inch diameter, was shortened 5 inches, making it 21 inches long. Three adjustable legs were attached to this section and it was placed around the 24-inch diameter section. Both sections were mounted on level ground with the three legs adjusted to bring the top edge of the outer section level and even with the top edge of the inner section.

This outer shield was used to prevent the sun's rays from falling directly on the inner pan and transmitting heat to the water through the side of the pan. At the same time, air could circulate under the outer shield and up between the sections. This shielded pan is shown in Figure 10.

A constant-recording shallow black pan evaporimeter was made from a dual traverse Rain and Snow Gage, Model 775-B (Fries Instrument Division, Bendix Aviation Corporation). This instrument provided a continuous record of the evaporation loss directly in inches of water. The recording pen was actuated by the loss or gain in weight of the water in the shallow evaporation pan. The shallow pan was twenty-two and one-half inches square and one-inch deep. It was painted dull black on the inside. The original gage was designed to record precipitation to one-hundredth of an inch. For evaporation readings, however, an accuracy to one-thousandth of an inch was desired. Therefore, the area of the shallow black pan was established at ten times that of the original catch pan with which the gage was equipped. The movement of the pen was thus multiplied ten times for a given gain or loss of water depth.

A standard nonrecording raingage, accurate to one-hundredth of an inch, was used to determine the precipitation during the growing season. The precipitation records were compared to the precipitation records of a U.S. Weather Bureau station in this area and were found to be in good agreement.

A hair hygrothermograph yielded a constant record of the relative humidity and air temperature at the site of the weather station. An aspirating psychrometer was used to check the accuracy of the hair hygrothermograph when a new chart was installed.

A three-cup totalizing anemometer was installed on the northwest corner of the wooden platform for the Class A pan. The centers of the cups were six inches above the rim of the Class A pan. The anemometer was accurate to one-tenth mile. Observations were taken twice daily at 7 a.m. and 7 p.m.

The second Young screened evaporation pan was installed in the irrigated pasture of the South Farm, as shown in Figure 9B. This installation was essentially identical to that of the Young pan in the weather station. Both installations were surrounded by irrigated fields. The evaporation data from these two identical pans, situated approximately three miles apart, were used to compare the evaporation from two similar water surfaces separated by this distance. The pan on the South Farm also provided daily evaporation data to compare with consumptive-use measurements on the irrigated pasture.

Figure 2

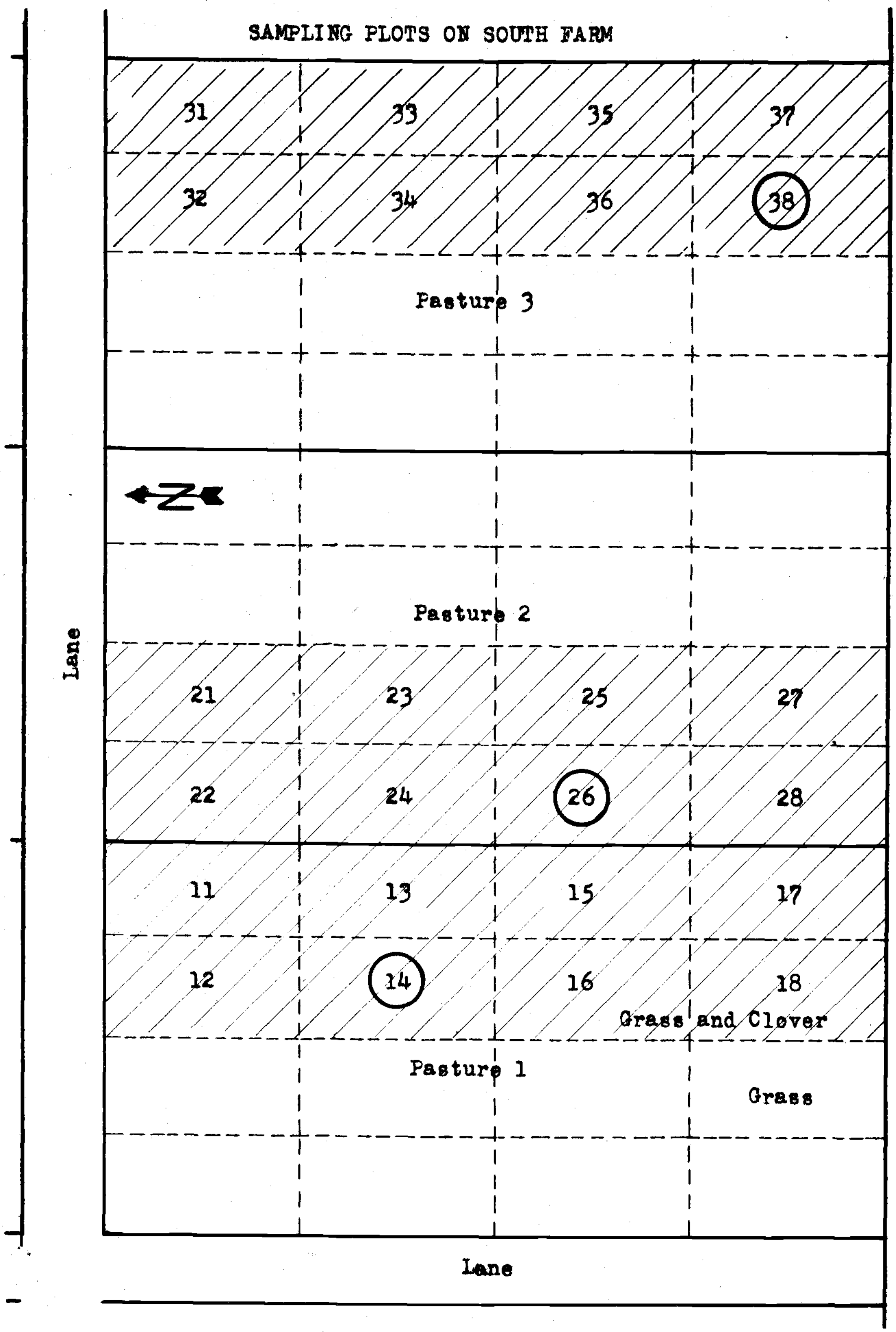
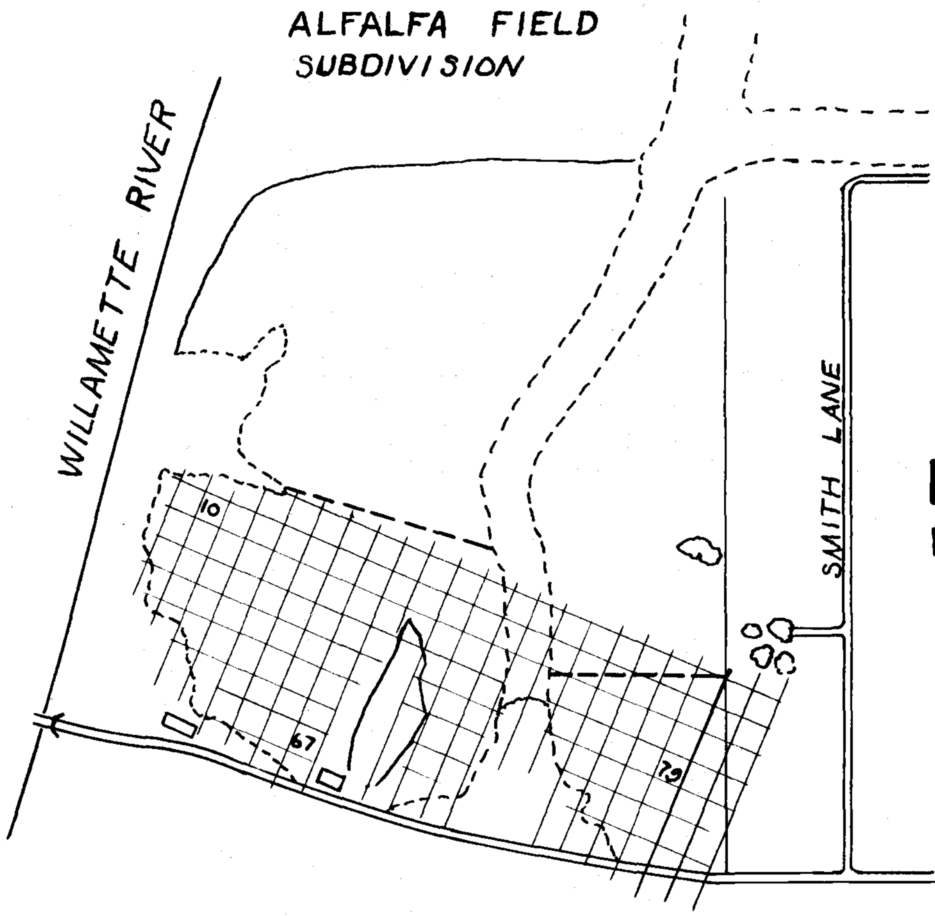

SAMPLING PLOTS ON SOUTH FARM
31
33
35
37
32
34
36
38
Pasture 3
N
Pasture 2
Lane
21
23
25
27
22
24
26
28
11
13
15
17
12
14
16
18
Grass and Clover
Pasture 1
Grass
Lane

FIGURE 3



Scale 660' = 1"

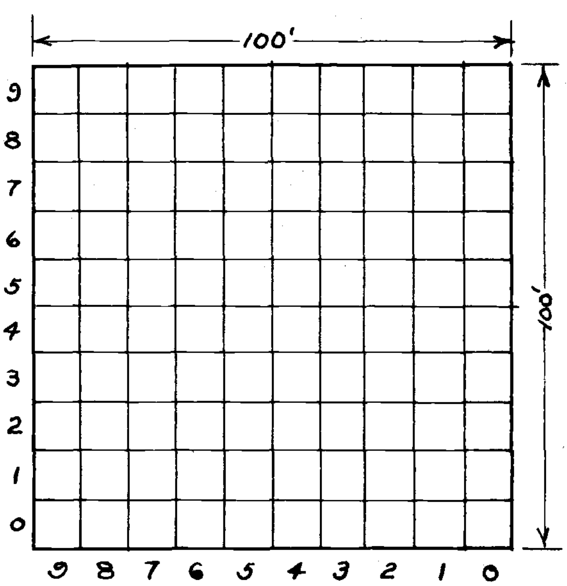


FIGURE 4

SAMPLING PLOT SUBDIVISION

MODIFIED POMONA SAMPLER

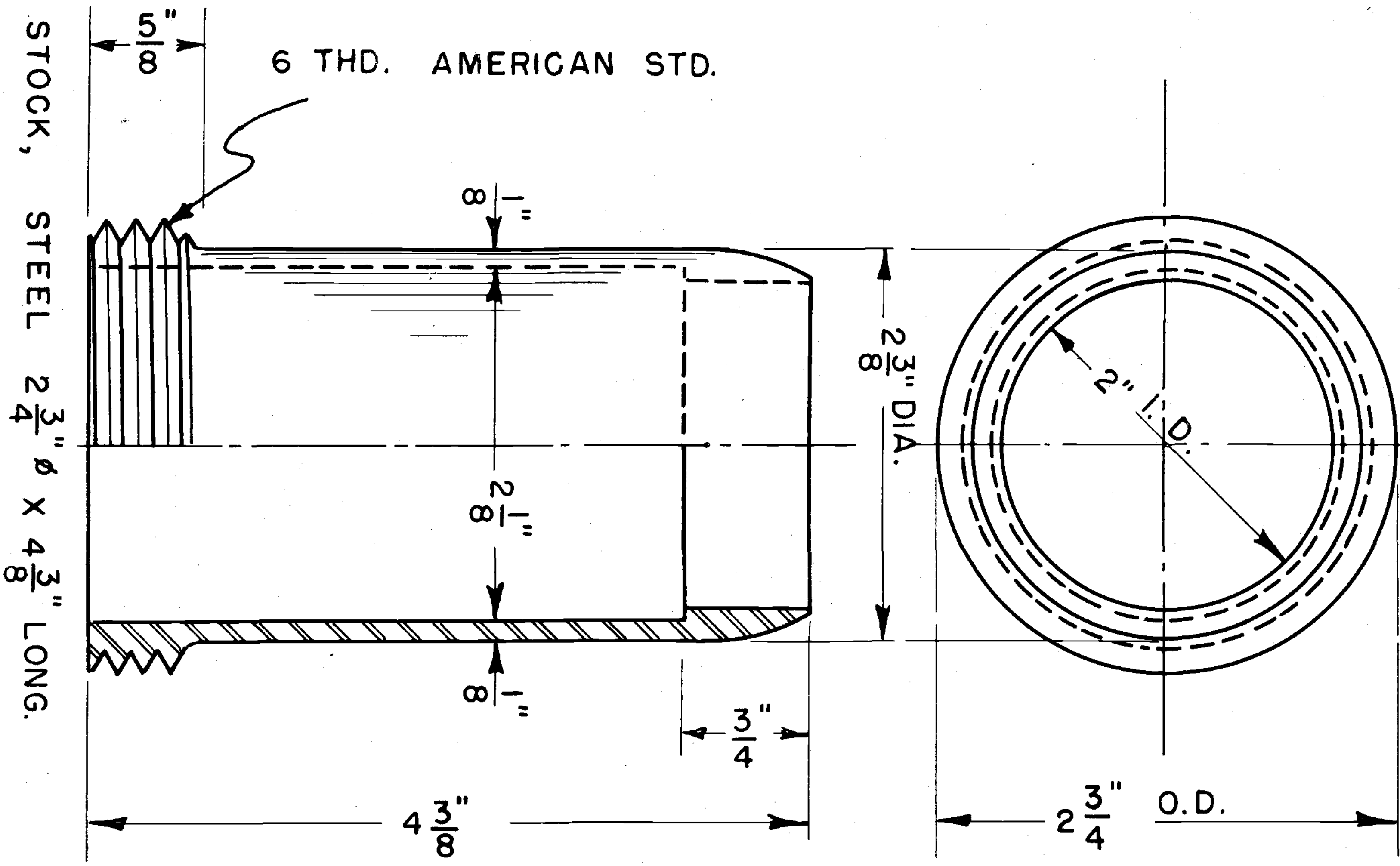


FIGURE 5

Figure 6

WEATHER STATION

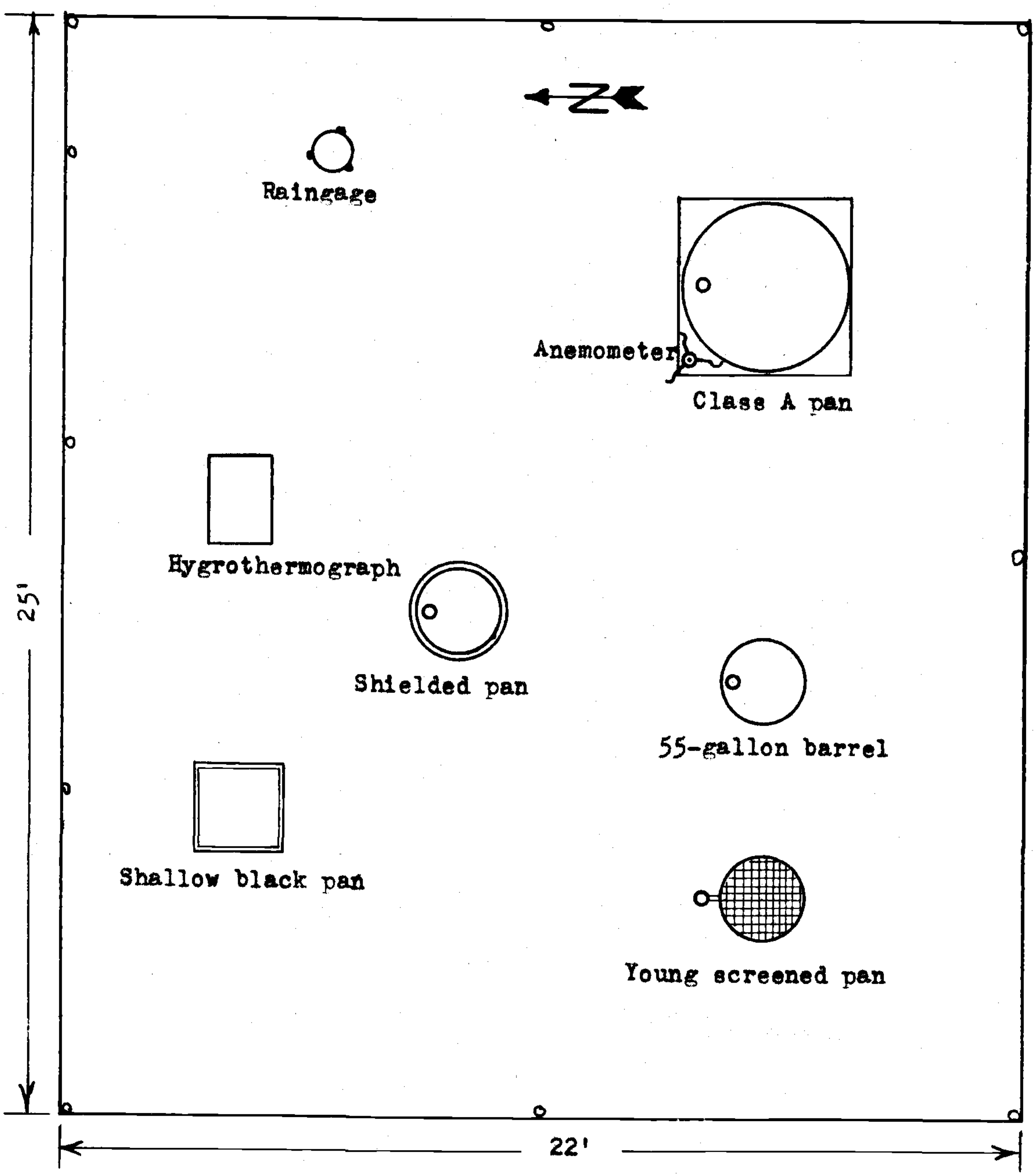
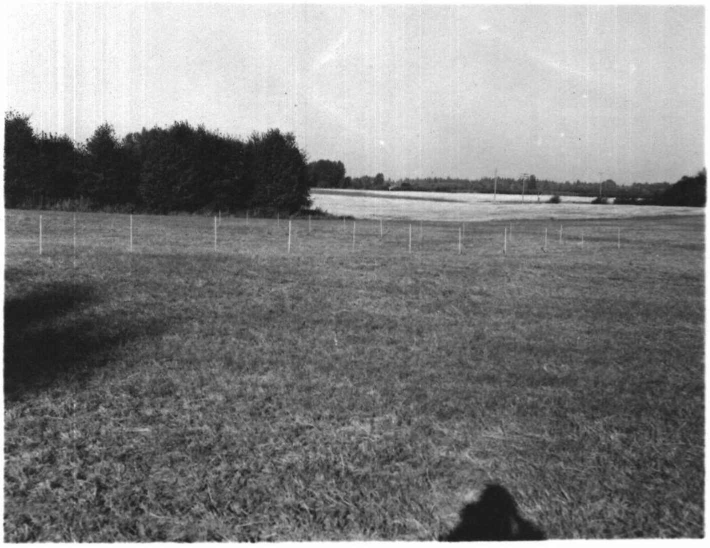


Figure 7A



SAMPLING PLOT IN ALFALFA FIELD

Figure 7B

CUTTING ALFALFA ON SAMPLING PLOT

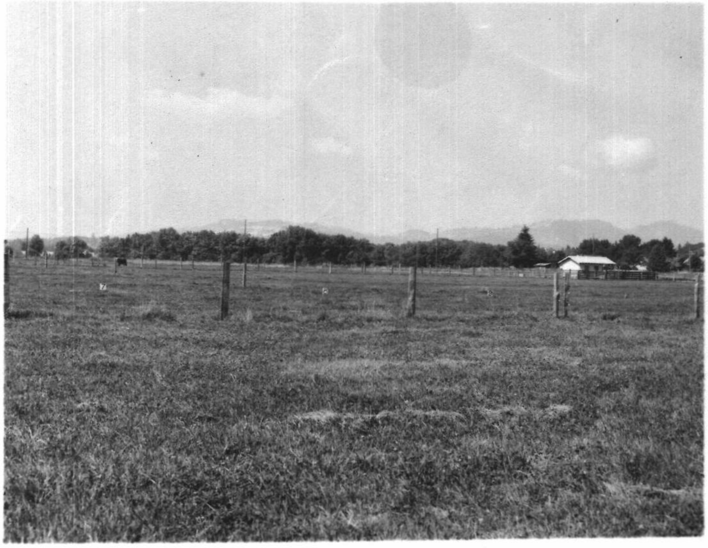
Figure 8A

WEATHER STATION ON VEGETABLE CROPS EXPERIMENTAL AREA

Figure 8B

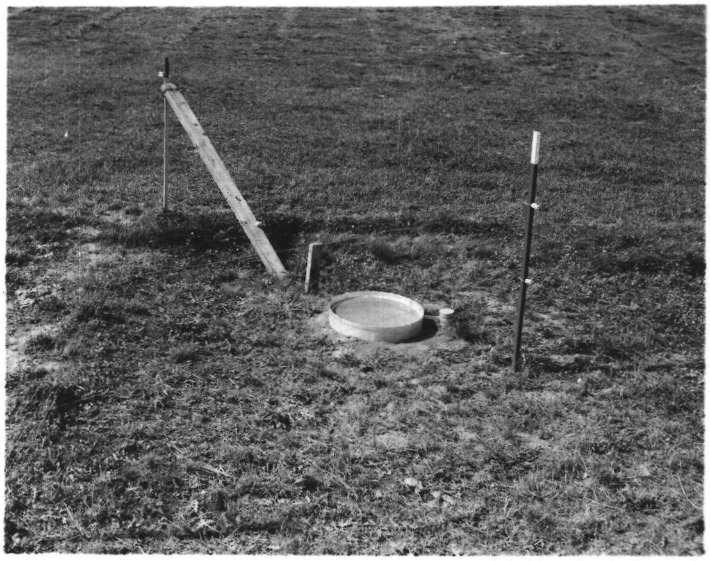
SHALLOW BLACK PAN, HOUSING FOR HYGROTHERMOGRAPH,
SHIELDED PAN, AND NONRECORDING RAINGAGE

Figure 9A



A SAMPLING PLOT ON SOUTH FARM

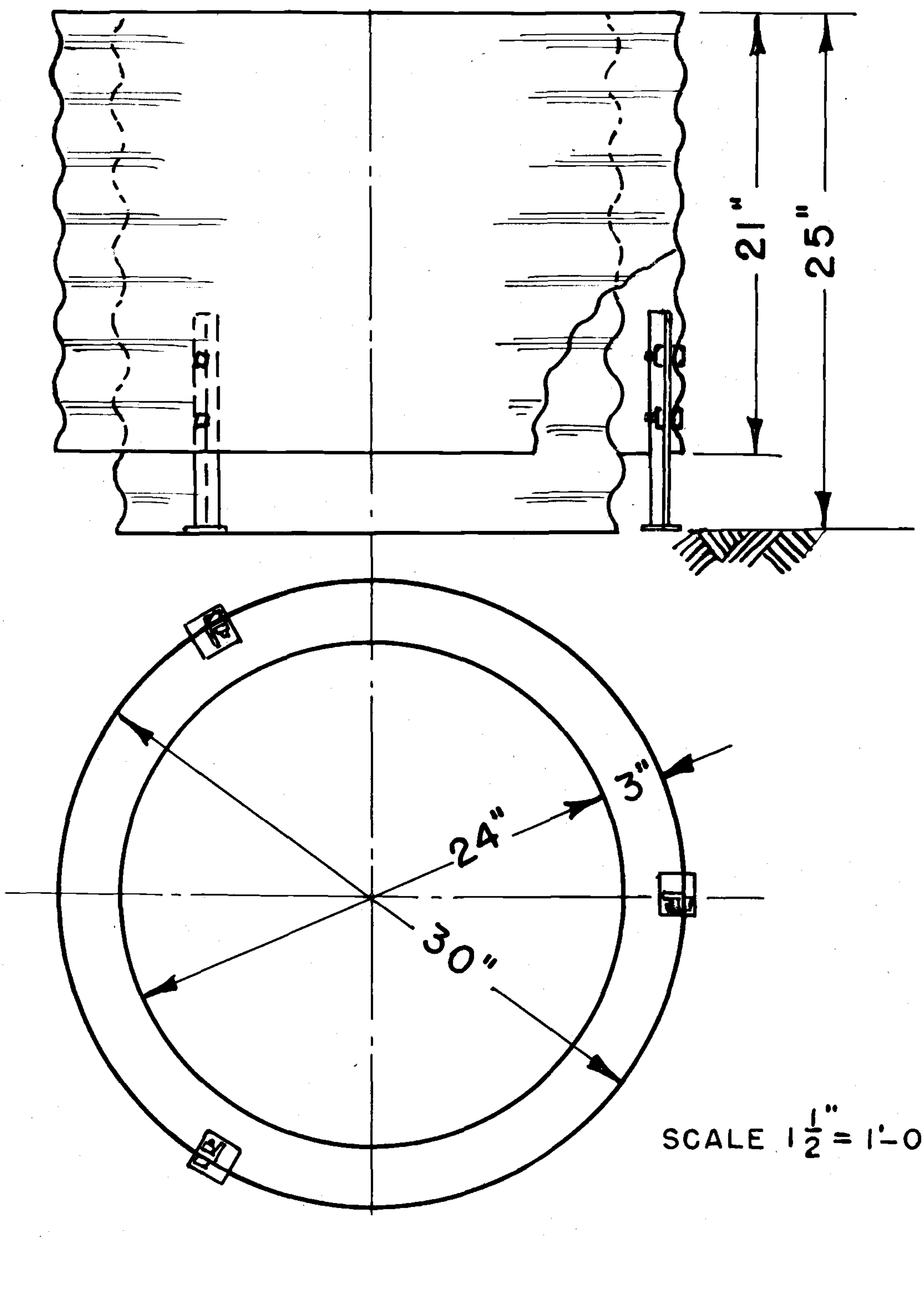
Figure 9B



YOUNG SCREENED PAN ON SOUTH FARM

FIGURE 10

SHIELDED PAN



SCALE $1\frac{1}{2}" = 1'-0"$.

RESULTS

Corn Consumptive Use and Pan Evaporation

The soil moisture data from the corn were selected for comparison with the evaporation from the five evaporation pans, since the corn plot was only a short distance from the weather station and it was considered that the meteorological conditions surrounding both were identical at any time. Evaporation data, on a three-day interval to coincide with the dates of soil moisture sampling in the corn plots, are shown in Appendix Table 2.

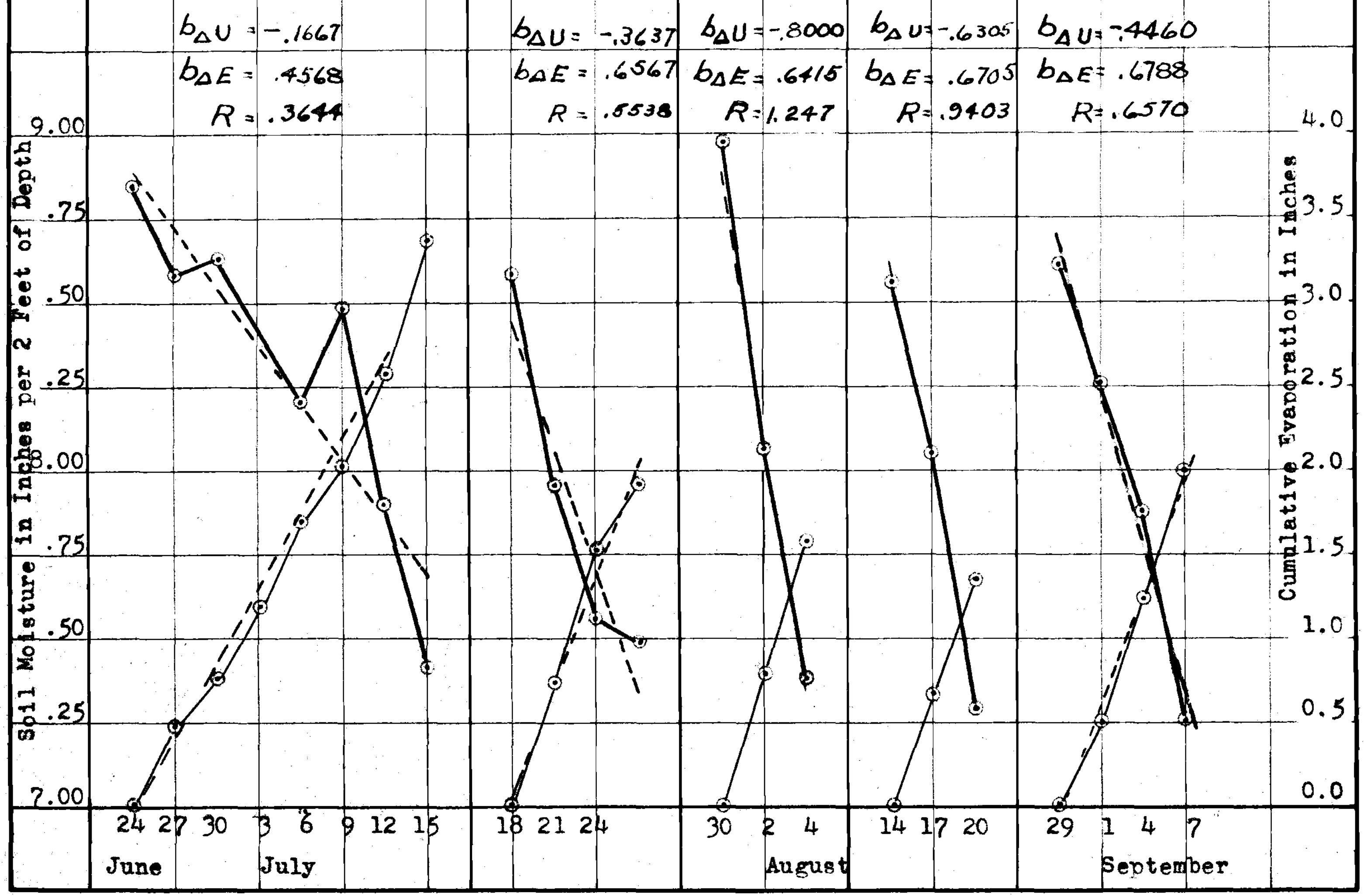
The values of soil moisture remaining in the corn plot M-1 on each sampling date, the evaporation from the Class A pan for identical three-day periods, and the cumulative evaporation from the Class A pan for the periods between irrigations are shown in Appendix Table 3.

By the method of least squares, a straight line was fitted to the soil-moisture and cumulative-evaporation data, shown graphically in Figure 11. Since the prime objective was to investigate the relationship between evaporation and consumptive use, and not the total seasonal consumptive use, no effort was made to extrapolate the curves in Figure 11 and to thus estimate the probable consumptive use during the time of irrigation. The method by which the line of regression was calculated is shown in Appendix Table 4.

A comparison of the slopes ($b_{\Delta U}$ and $b_{\Delta E}$) of the fitted lines was made for each period between irrigations. The ratios, R, obtained ($b_{\Delta U}$ divided by $b_{\Delta E}$) for each period (Figure 11) show that the consumptive use increased more rapidly than did evaporation until the

Figure 11

CUMULATIVE EVAPORATION (CLASS A PAN) VS SOIL MOISTURE IN CORN PLOT M-1



corn reached its maximum vegetative growth. At this point the consumptive-use evaporation ratio reached its maximum value.

The ratios of the rate of consumptive use in the M-1 corn plot and the evaporation rate from the remaining four evaporation pans were computed for each period between irrigations and are shown in Appendix Table 5.

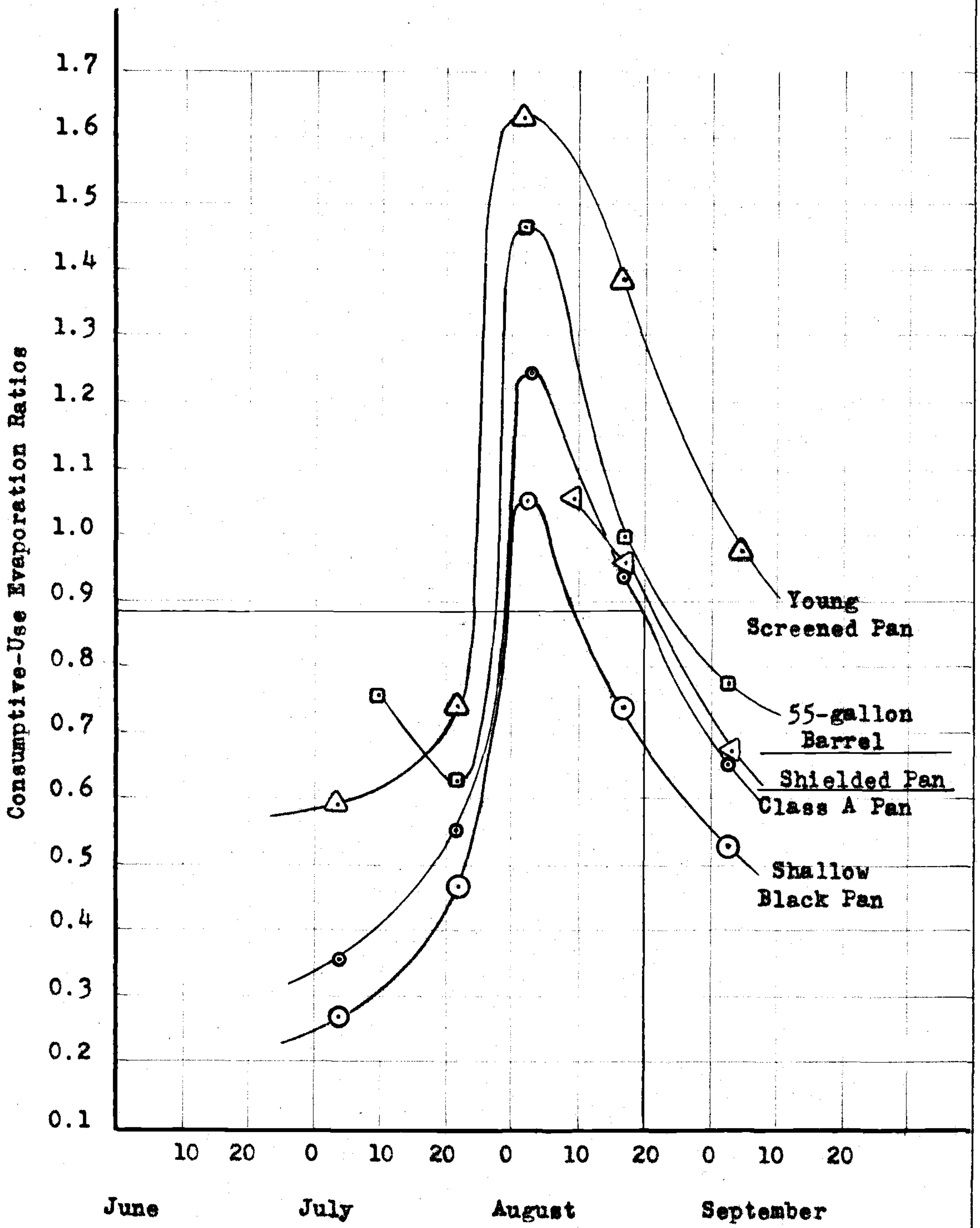
The consumptive-use evaporation ratios are plotted in Figure 12 with the value of the ratio for each interval between irrigations plotted on the middle day of the period. The curves of Figure 12 represent the day-to-day relation between consumptive use of water by the corn and the evaporation from five different evaporation pans for a part of the 1955 growing season. The curves with a flatter slope should give a more reliable estimate of the ratio to use when estimating consumptive use.

No explanation is known for the dip in the consumptive-use evaporation ratio for the 55-gallon barrel during the early summer. It appears from the data that the evaporation from this pan started at a low figure and increased for the first six days immediately after it was installed. However, a review of the data shows that all of the pans had a reduced evaporation rate from July 6 to 9 and, since these three days were 25 per cent of the July 3 to 15 period, they could have contributed materially to the abnormally high consumptive-use evaporation ratio of the 55-gallon barrel for that period.

The resulting curves in Figure 12 can be used to predict the consumptive use of water by the corn when cumulative evaporation for

Figure 12

RATIOS OF CONSUMPTIVE USE OF CORN TO PAN EVAPORATION



any period is known. For example, during the period from July 21 to 24 the cumulative evaporation was 0.798 inch from the Class A pan (Appendix Table 3). From Figure 12 the value of the consumptive-use evaporation ratio for this interval was approximately 0.58. Multiplication of the cumulative evaporation, 0.798, by 0.58 yields 0.46, the estimated consumptive use for this period. The actual consumptive use from soil sampling data was 0.40 inch.

The estimated consumptive use for a longer period can be found by summing the estimated consumptive use for several 3-day intervals, as shown below:

3-day Interval	Class A Pan Cumulative Evaporation In Inches	Ratio	Estimated Consumptive Use In Inches	Actual Consumptive Use In Inches
July 18 - 21	0.741	0.55	0.41	0.52
July 21-- 24	0.798	0.58	0.46	0.40
July 24 - 27	0.381	0.65	0.25	0.05
	Total for period		1.12	0.97

The accuracy of the curves were checked by estimating the consumptive use of water by the corn and comparing these values to the actual consumptive use. The estimated values were found by multiplying pan evaporation by the ratio found from the curves in Figure 12. The values of the ratios were found on any date by drawing a vertical line from the date to the curve for the appropriate pan. A horizontal line from this intersection gave the value of the ratio. For example (see Figure 12), on August 20 a vertical line is drawn to the curve for the Class A pan. A horizontal line from this intersection gave the value of the ratio for this date as 0.89.

The value of a ratio was found for each pan for the dates of soil sampling in the corn. These ratios and the cumulative evaporation from the different pans between soil sampling dates were used to estimate the consumptive use of water by the corn. The actual consumptive use, the estimated consumptive use (using evaporation data from each pan), and the ratio between these two values are shown in Table 1.

Each ratio between the estimated and actual consumptive use should ideally be equal to one. The deviations of these ratios from a value of one indicates inaccuracies in the shape of the curve.

A comparison of the actual and the estimated consumptive use for the season is given below. The estimated consumptive use was found for each 3-day interval in the periods between irrigations and these values were summed to give an estimate of the between-irrigation seasonal consumptive use. The actual consumptive use was from soil sampling data and represents only the consumptive use between irrigations. The estimated consumptive use expressed as a ratio of the actual consumptive use shows that on a seasonal basis the estimated consumptive use is quite close to the actual consumptive use.

Pan	Estimated Consumptive Use	Actual Consumptive Use	Ratio
Class A Pan	8.057	8.38	0.96
Young Screened Pan	8.194	7.66	1.07
Barrel	7.648	7.27	1.04
Black Pan	7.651	7.92	0.97
Shielded Pan	3.690	3.46	0.94

$$\text{Ratio} = \frac{\text{estimated consumptive use}}{\text{actual consumptive use}}$$

Table 1

COMPARISON OF ESTIMATED CONSUMPTIVE USE TO ACTUAL CONSUMPTIVE USE

Period Between Irrigations	Actual CU from Corn (Inches)	Class A Pan		Shallow Black Pan		Shielded Pan		Young Pan		Barrel	
		Est.CU (Inches)	Ratio	Est.CU (Inches)	Ratio	Est.CU (Inches)	Ratio	Est.CU (Inches)	Ratio	Est.CU (Inches)	Ratio
June 24-July 15	1.44	1.29	0.90	1.30	0.90						
June 27-July 15	1.18							1.26	1.07		
July 6-July 15	0.79									0.83	1.05
July 18-July 27	1.19	1.13	0.95	1.17	0.98			1.37	1.15	1.13	0.95
July 30-Aug. 4	1.60	1.60	1.00	1.61	1.01			1.69	1.06	1.57	0.98
Aug. 14-Aug. 20	1.27	1.23	0.97	1.21	0.95	1.20	0.95	1.23	0.97	1.14	0.90
Aug. 29-Sept. 7	1.36	1.27	0.93	1.26	0.93	1.25	0.92	1.33	0.98	1.31	0.96

$$\text{Ratio} = \frac{\text{estimated consumptive use}}{\text{actual consumptive use}}$$

The curves in Figure 12 show the progress of the consumptive-use evaporation ratios with time during the 1955 growing season. Since the growing season will occur earlier or later in other years than it did in 1955, some means of shifting the consumptive-use evaporation curves to fit a particular season is needed. Two indicators that might be used to shift the curves to fit the season are:

1. Pan evaporation
2. Crop development

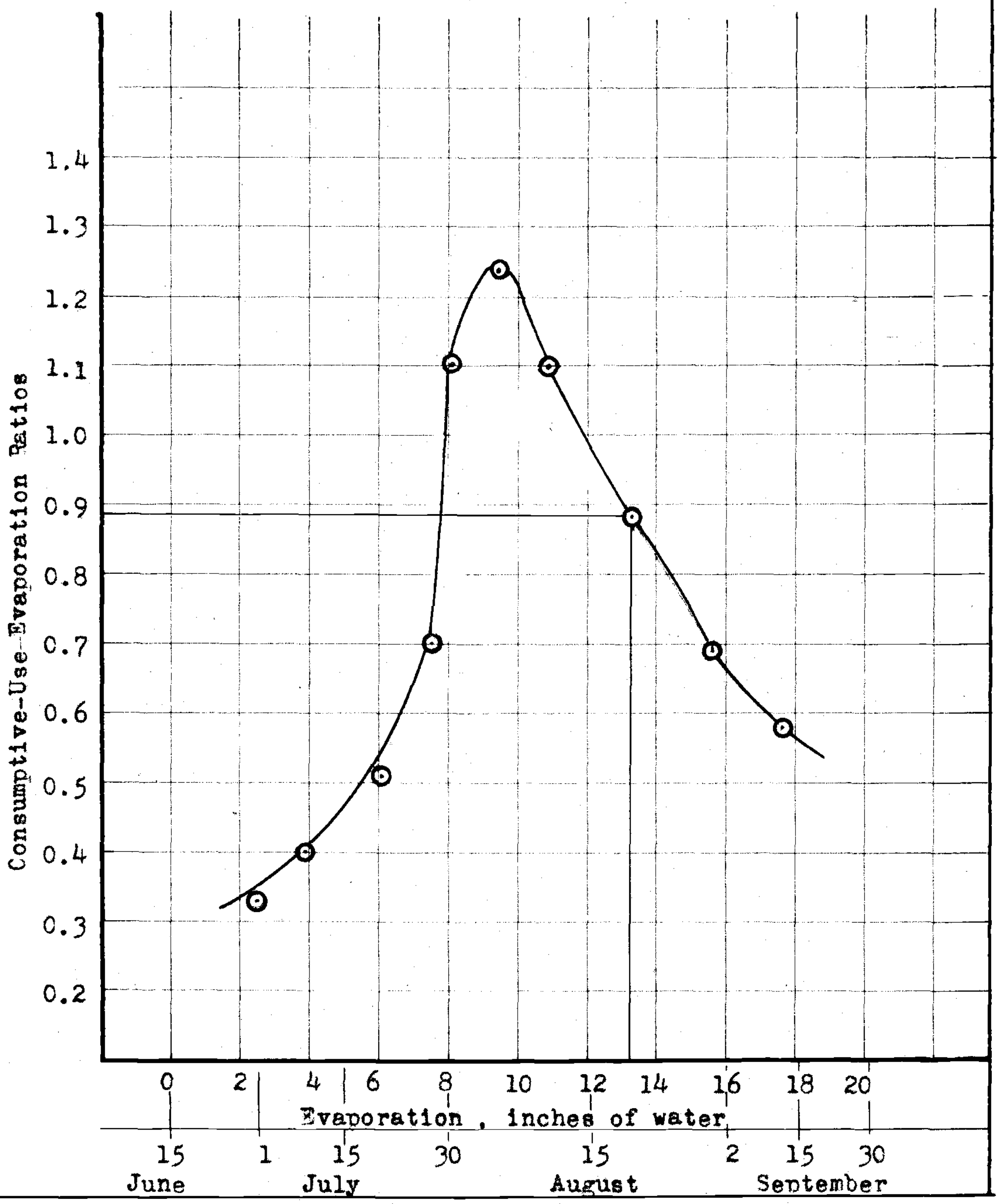
If pan evaporation were used to shift the curves to fit the season, the abscissa of the graph in Figure 12 should be transformed to become cumulative evaporation from a pan and not fixed calendar dates. Then the ratio between consumptive use and pan evaporation would depend on the progress of cumulative evaporation during a growing season.

The cumulative evaporation from the Class A pan was calculated for each day from June 15 to October 1. Values of the consumptive-use evaporation ratio and the cumulative evaporation from the Class A pan were determined for several days during the growing season. These values were plotted in Figure 12A. A comparison of Figure 12 and Figure 12A shows that the central portion of the curve was elongated due to the higher evaporation rates at this time of the growing season.

The most advantageous time to start cumulative evaporation readings might be found by comparisons of evaporation data for several seasons. Consumptive use of water by corn was still quite low during June and, for the cool spring of 1955, May 1 would have been soon

Figure 12A

RATIOS OF CONSUMPTIVE USE OF CORN TO EVAPORATION FROM A CLASS A PAN PLOTTED AGAINST CUMULATIVE EVAPORATION FROM A CLASS A PAN



enough to start cumulative evaporation readings for most pasture crops. The relationship between crop development and the consumptive-use evaporation ratio is not known to the author at the present time.

Pasture Consumptive Use and Pan Evaporation

The values of soil moisture from pasture 1 and the cumulative evaporation from the Young screened pan, installed nearby, were plotted as shown in Figure 13. The regression formulae were determined and plotted for the soil moisture data. Because the cumulative evaporation curves were already quite straight, the regression curves for the evaporation data were not plotted. The slopes of the regression lines, $b_{\Delta U}$ and $b_{\Delta E}$, were compared for each interval between irrigations. The ratios obtained by dividing $b_{\Delta U}$ by $b_{\Delta E}$ for each interval are also shown in Figure 13. These ratios were plotted on the middle day of each interval between irrigations and a curve drawn through them, as shown in Figure 14. This curve indicates that the consumptive use of water by clover and grass pasture increased more rapidly than did the evaporation from the Young screened pan during the spring and early summer. After reaching a maximum value during the growing season, consumptive use decreased faster than did evaporation from this pan.

Comparison of Pan Evaporation Rates

A comparison was made between the evaporation rates of the five different evaporation pans that were installed adjacent to each other in the weather station. This comparison was primarily to find the

Figure 13

CUMULATIVE EVAPORATION (YOUNG SCREENED PAN) VS SOIL MOISTURE IN PASTURE 1

$b_{\Delta U} = -0.756$	$b_{\Delta U} = -1.58$	$b_{\Delta U} = -0.62$	$b_{\Delta U} = -0.42$
$b_{\Delta E} = 0.397$	$b_{\Delta E} = 0.471$	$b_{\Delta E} = 0.475$	$b_{\Delta E} = 0.376$
$R = 1.91$	$R = 3.37$	$R = 1.30$	$R = 1.12$

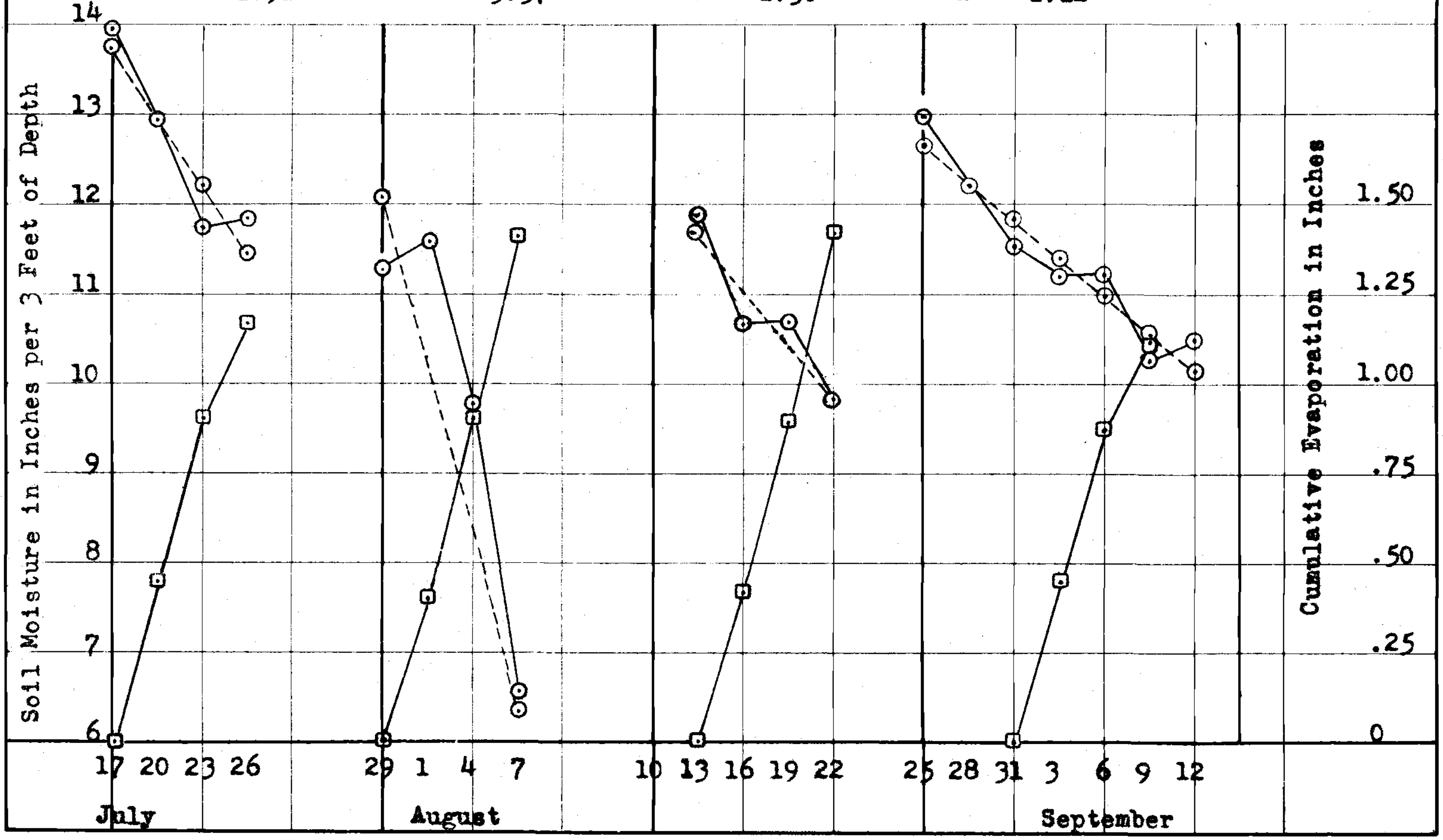
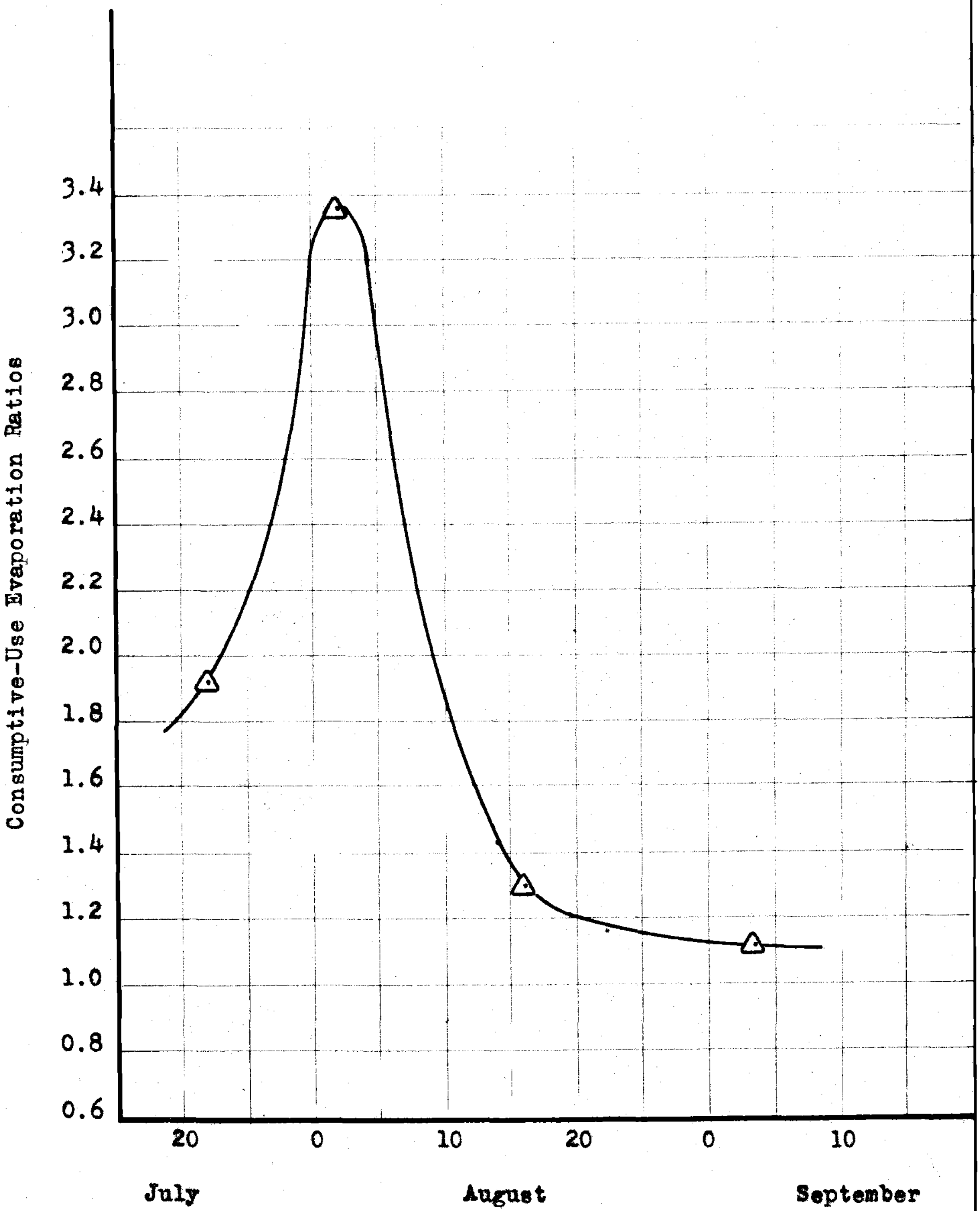


Figure 14

RATIOS OF CONSUMPTIVE USE OF CLOVER AND GRASS PASTURE
TO EVAPORATION FROM A YOUNG SCREENED PAN



relation between the evaporation rates of the Young screened pan and the 55-gallon barrel. The other comparisons between pans were performed to see how closely the evaporation rate of one pan would correspond to the evaporation rates of the other four pans.

The pan evaporation data as shown in Appendix Table 2 were used. The calculations for the ten comparisons are shown in Appendix Table 6. The correlation coefficients, r, and the coefficients of determination, r^2, are listed in Tables 2 and 3.

From Table 2 we see that the evaporation from the 55-gallon barrel compared favorably with the Young screened pan. This was almost expected because of the similarity of pans and installations. On the basis of the limited amount of data, obtained in one season, it would seem that the Young screened pan could be replaced by an ordinary barrel under most conditions. The analysis of data revealed good correlation between the three above-ground pans--the shallow black pan, the Class A pan, and the shielded pan. On the other hand, the degree of correlation between these three pans and the two sunken pans was low.

A correlation coefficient of 0.423 was found between the Young screened pans when daily evaporation was used. This low correlation coefficient indicates that the evaporation from identical pans installed similarly at different locations (as in this instance where they were three miles apart) will have different daily evaporation patterns. Appendix Table 7 shows sample calculations of the correlation coefficient between the daily evaporation rates of the two Young screened pans. When using three-day intervals the correlation

STATISTICAL COMPARISONS OF 1955 EVAPORATION DATA

Table 2

Correlation Coefficient (r)

	Young Pan	55-gallon Barrel	Shielded Pan	Black Pan
Class "A" Pan	.91	.91	.95	.96
Young Pan		.96	.91	.81
55-gallon Barrel			.92	.80
Shielded Pan				.96

Table 3

Coefficient of Determination (r^2) x 100

	Young Pan	55-gallon Barrel	Shielded Pan	Black Pan
Class "A" Pan	82.8	82.8	90.2	92.2
Young Pan		92.2	82.8	65.6
55-gallon Barrel			84.6	64.0
Shielded Pan				92.2

coefficient was found to be 0.719, indicating that the relation between the cumulative evaporation from the two pans becomes closer as the time interval increases. For instance, while the daily evaporation for the two Young screened pans differed widely, the total seasonal evaporation from July 4 to September 9 differed by only approximately three per cent, the total evaporation from the two pans being 8.472 and 8.701 inches, with a difference of 0.229 inch.

Soil Sampling

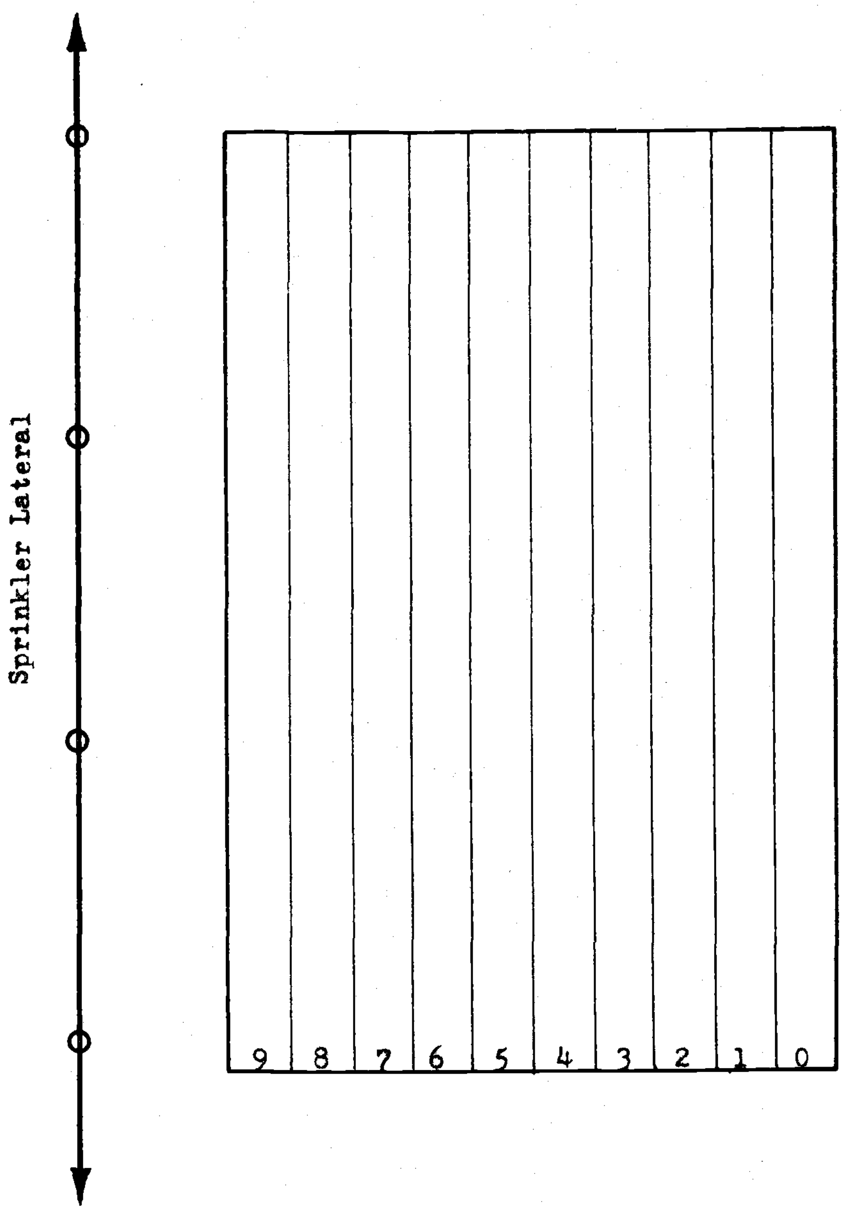
An analysis of variance was made on the soil moisture data obtained from pasture 2, to estimate the variance of the calculated mean inches of water in the soil on each sampling date.

To facilitate this analysis, the sampling plot was divided into 10 strata that were approximately 8 by 124 feet, with the strata paralleling the sprinkler lateral. This direction for the strata was selected because less variation between samples within strata was expected parallel to the sprinkler lateral than in a line perpendicular to the sprinkler lateral. These strata were assigned the same location and number within the sampling plot that an identical area had been given during the growing season. This stratification is shown in Figure 15.

The soil moisture data from individual sampling locations were tabulated by strata according to the strata from which the data were obtained. Particular attention was given to strata which contained more than one sampling location on a given sampling date.

Figure 15

STRATIFICATION OF A SAMPLING PLOT



The results of the analysis of variation are given below:

Source of Variation	d.f.	Mean Square	Mean Square is an Estimate of
Days	29	7.2955	
Strata in days	80	1.4820	$\sigma_s^2 + 1.10\,\sigma_L^2$
Samples in strata in days	12	0.4486	σ_s^2

In pasture 2, using the data for the 1955 growing season, the estimated variation between samples treated alike, σ_s^2 , was 0.4486 and the variation associated with difference between strata, σ_L^2 , was 0.9394. The variance of the mean inches of water estimated for a sampling plot on any sampling date may be obtained as follows:

$$V_{\bar{x}} = \frac{\sigma_s^2 + s\,\sigma_L^2}{sL}$$

Where: $V_{\bar{x}}$ = variance of the mean inches of water in the soil on any sampling date

σ_s^2 = sample-to-sample variation

σ_L^2 = strata-to strata variation

s = total number of samples for each sampling date in one sampling plot

L = number of strata sampled for each sampling date in one sampling plot

The variance of the mean inches of water in the soil in pasture 2, with the sampling pattern used in 1955, is shown below:

Number of Strata Sampled	Number of Sampling Locations per Strata	$V_{\bar{x}}$, In Inches
1	4	1.0516
2	2	0.5818
4	1	0.3470

Estimates of the variation of the mean inches of water in the soil, $V_{\bar{x}}$, when using different sampling patterns were calculated. These are shown in Table 4. Thirty-six samples were chosen as a basic figure for the number of samples to be taken on any one sampling date, because this was found to be the maximum number of samples that could be handled conveniently each morning. The values arrived at in Table 4 are based on the assumption that all 36 samples would be taken in only one sampling plot whose area would be approximately equal to the sampling plots of the 1955 season.

Alfalfa Root Distribution

Because erratic values of total soil moisture were obtained from soil moisture sampling in the alfalfa field, it was decided to investigate the water table level and the depth of root penetration in the sampling plots. Some methods for excavating a hole large enough to enable research personnel to study the undisturbed root system in the

Table 4

THE EFFECT OF DIFFERENT SAMPLING PATTERNS
ON THE VARIANCE OF THE MEAN $V_{\bar{x}}$

Number of Strata Sampled	Samples per Stratum	$V_{\bar{x}}$, In Inches
1	36	0.9519
2	18	0.4822
3	12	0.3256
4	9	0.2473
6	6	0.1690
9	4	0.1168
12	3	0.0907

Where: $\sigma_s^2 = 0.4486$

$\sigma_L^2 = 0.9394$

$$V_{\bar{x}} = \frac{\sigma_s^2 + s\sigma_L^2}{sL}$$

vertical section of the soil profile were discussed. Using a small "bulldozer" to excavate a trench to the desired depth was accepted as the most feasible method.

Some doubt was entertained as to the eventual results of disturbing the soil by excavating a trench of the dimensions anticipated in the alfalfa field, especially in one of the lower locations that was selected. Erosion presented a real danger, as the Willamette River, when flooding, would inundate the lower portions of this alfalfa field with flowing water.

Caving of the vertical walls would present a hazard to personnel and equipment during the excavation of the trench and also later during the research procedures. This danger could be minimized by shoring the vertical walls with timbers.

However, it was inconvenient to obtain the necessary equipment during the summer season and the plan to investigate the root depth of the alfalfa in the undisturbed soil was abandoned for the 1955 growing season.

As a partial substitute, it was decided to use an eight-inch soil auger to obtain some indication of the relative distribution and depth of the roots for this season. Electrical metallic tubing, commonly called "Thinwall", was used for extensions on the handle of the auger. Since it was considered best to exclude the crown of the alfalfa plant from the determination of the root distribution, the test holes were located between the alfalfa plant crowns in an area where the plant cover was representative of most of the sampling plot.

It was found necessary to keep the soil auger extremely sharp to prevent the auger from pushing the larger alfalfa roots away instead of cutting them.

The first record hole was augered in the number ten sampling plot to a depth of 15 feet. Small gravel was encountered at the 8-foot level. Increasingly larger gravel was found as the depth increased. The digging was discontinued at 15 feet, because of excessive gravel which prevented further penetration of the soil auger. The gravel at 15 feet below ground surface was quite moist but the water table had not been encountered. On this first hole only one-half of the soil sample by volume was saved to obtain only the relative distribution of the alfalfa roots with depth.

In plot number 67 the first auger hole penetrated to a depth of 8 feet where the auger encountered a large rock which prevented further progress. The hole was abandoned, and a second hole was started approximately 15 feet away. Small gravel was again encountered in small amounts at 8 feet and became increasingly abundant as the depth increased. At 12 feet a definite gravel layer was entered. Caving of the hole below the 12-foot level became a problem and the amount of soil withdrawn by the auger per foot of depth was doubled. The sampling was continued to a depth of 16 feet where progress was stopped because of the size of gravels in the soil profile. The water table was not encountered although the gravel at the lowest level was quite moist. All of the soil from the hole was saved in an attempt to ascertain the quantity and relative distribution of the roots in the soil.

Extracting the roots from the soil sample by hand was attempted but this consumed an excessive amount of time. The sample was then placed in a 5-gallon can and elutriated to see if more roots could be recovered. A few small roots were recovered that had been missed by the hand picking.

A soil sample was elutriated to remove the roots and then examined by hand to see if the elutriation process had missed any large roots which might have been too heavy for the water to carry from the soil sample into the nest of screens. No large roots were found in the elutriated sample. Subsequently, all soil samples were carefully elutriated without a hand check.

A nest of two Tyler sieves, 10 and 28 meshes per inch, were used to recover the roots from the stream of muddy water. Some little difficulty was experienced with the very fine sandy particles clogging the finer sieve. Gravels and the large sand particles remained in the bottom of the can and did not appear in the sieves.

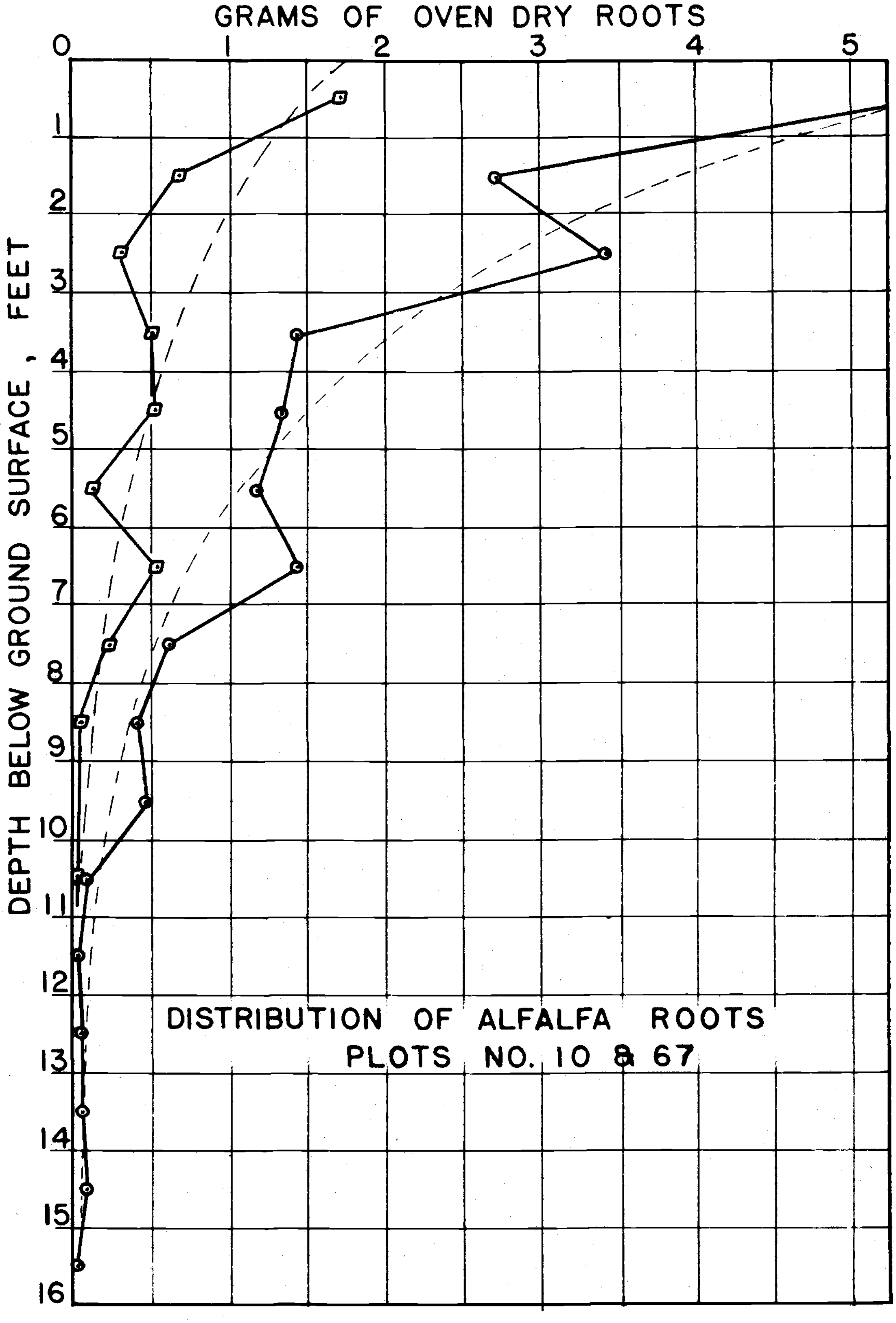
The actual amount of roots recovered are listed in Table 5 and shown in Figure 16. It should be noted that below the 12-foot level caving was experienced in the hole on plot number 67, and the tabulated value should be reduced approximately one-half.

Table 5

OVEN DRY WEIGHT OF ALFALFA ROOTS RECOVERED FROM
TWO AUGER HOLES

Foot Depth Below Ground Surface	Plot #10		Plot #67
	Weight in Grams	Max. Dia. in Inches	Weight in Grams
0 - 1	1.720	0.112	15.747
1 - 2	0.680	0.054	2.684
2 - 3	0.270		3.400
3 - 4	0.500	0.055	1.414
4 - 5	0.510		1.381
5 - 6	0.127	0.035	1.196
6 - 7	0.531	0.040	1.413
7 - 8	0.235	0.038	0.638
8 - 9	0.040	0.012	0.420
9 - 10	trace		0.484
10 - 11	0.015	0.025	0.085
11 - 12	0.001		0.007
12 - 13	trace		0.138
13 - 14	trace		0.062
14 - 15	trace		0.069
15 - 16			0.015

FIGURE 16


GRAMS OF OVEN DRY ROOTS
0
1
2
3
4
5
DEPTH BELOW GROUND SURFACE, FEET
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
DISTRIBUTION OF ALFALFA ROOTS
PLOTS NO. 10 & 67

CONCLUSIONS

Consumptive use of water by crops can be predicted from pan evaporation with fair accuracy for periods between irrigations but not on a day-to-day basis. However, since the relation between consumptive use and pan evaporation varied with the maturity of the plants considered in this study, seasonal curves, as in Figure 12, appear necessary to make predictions during all of the growing season.

Sufficient pan evaporation data were not secured on all of the evaporation pans to allow a determination of the pan best suited for estimation of consumptive use of water by crops.

The correlation coefficient of 0.96 between the Young screened pan and the 55-gallon barrel indicates that the 55-gallon barrel would be a satisfactory substitute for the Young screened pan under normal conditions in this area.

The correlation coefficients between the two Young screened pans, which were located three miles apart, indicates that it is advisable to install the evaporation pan adjacent to the irrigated fields for which an estimate of the consumptive use is desired.

It is possible that the erratic variations in soil moisture in the alfalfa field and South Farm pastures were due partly to variations in soil moisture between sampling locations, rather than the variation of soil moisture with respect to consumptive use. Therefore, a sampling method should be devised for future studies which will minimize the effect of the location-to-location variation in soil moisture.

RECOMMENDATIONS

For future projects where soil moisture is determined by soil sampling, it appears advisable to use only one sampling plot for each crop and increase the number of samples taken in each sampling plot on any sampling date. The overall size could readily be enlarged from 100 feet square to 120 by 120 feet. It could then be divided into 12 strata, 10 by 120 feet, with the longest dimension parallel to the sprinkler lateral. Each strata should then be divided into 12 equal plots.

As many strata as possible should be sampled on each sampling date. Therefore, a minimum of 12 samples is suggested, one sample in each strata. If less than 12 samples are taken, the strata to be sampled should be selected at random. If more than 12 samples are selected, each strata should be sampled and the individual sampling locations within a strata should be selected at random.

With this sampling scheme the mean amount of water in the soil would be estimated most precisely for a given total number of samples.

Allamaras and Gardner (3, p.17) initiated an irrigation experiment in 1952 to study the effect of frequency and time of irrigation on corn production. The amount of soil moisture was determined by soil sampling. They performed forty analysis of variance on the 1952 soil sampling data. The sources of variability contributing to the total variation were studied. By rearranging their sampling pattern they decreased the number of samples taken by 50 per cent and increased the efficiency of estimating the mean feet of water in the soil of each treatment by 10 per cent. They originally picked four sampling locations in each treatment and took three samples per location. In the rearranged pattern they picked six locations but took only one soil sample per location.

Two daily observations of the evaporation from the pans made the data very flexible. However, in similar studies when evaporation is compared to consumptive use, daily observations would be sufficient if the studies followed a similar pattern. If it were necessary to reduce the number of evaporation observations to the minimum, the observations should be taken on the morning of soil sampling. If soil samples were taken every third day as was done in this study, the period between evaporation observations would therefore be three days. This period would be satisfactory for all the evaporation pans except the shallow black pan, which required refilling each day. A device to keep the water surface at a predetermined level in this pan could, however, be arranged.

Water from the irrigation well on the Vegetable Crops Experimental Area should not be used to refill the evaporation pans. A storage reservoir for water should be installed near the weather station to allow the water, used to refill the evaporation pans, to become the same temperature as the water in the pans. This is most important when the pans are emptied and refilled.

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APPENDIX

Table 1

VOLUME WEIGHT DETERMINATIONS

South Farm (Amity Silt Loam)			
Location	Depth	Apparent Specific Gravity	Average Apparent Specific Gravity for Three Pastures
Pasture No.1 Plot No.14	0-1	1.34178	1.29921
	1-2	1.33537	1.32914
	2-3	1.317549	1.33097
Pasture No.2 Plot No.26	0-1	1.349490	
	1-2	1.349920	
	2-3	1.301139	
Pasture No.3 Plot No.38	0-1	1.206267	
	1-2	1.302060	
	2-3	1.374150	

Alfalfa Field (Chehalis Soil)			
Location	Depth	Apparent Specific Gravity	Average Apparent Specific Gravity
Plot No.10	0-1	1.30441	
	1-2	1.18753	
	2-3	1.12082	
	3-4	1.19508	
	4-5	1.15695	
			Plot Nos.10 and 67
Plot No.67	0-1	1.30177	1.30309
	1-2	1.17249	1.18001
	2-3	1.12961	1.12522
	3-4	1.13890	1.16699
	4-5	1.15738	1.15716
			Plot Nos.10, 67, and 79
Plot No.79	0-1	1.19016	1.26544
	1-2	1.14974	1.16992
	2-3	1.17088	1.14043
	3-4	1.20748	1.18048
	4-5	1.22068	1.17833

Table 2

1955 EVAPORATION DATA IN INCHES OF WATER

Date	Class "A" Pan	Young Pan	55-gallon Barrel	Shielded Pan	Black Pan
June 12	0	-	-	-	0
15	0.541	-	-	-	0.698
18	0.508	-	-	-	0.654
21	0.726	-	-	-	0.922
24	0.440	-	-	-	0.600
27	0.487	-	-	-	0.643
30	0.265	0.270	-	-	0.336
July 3	0.431	0.268	-	-	0.535
6	0.505	0.530	-	-	0.660
9	0.357	0.224	0.291	-	
12	0.530	0.281	0.390	-	0.685
15	0.788	0.460	0.483	-	1.063
18	0.547	0.457	0.461	-	0.670
21	0.741	0.477	0.595	-	0.865
24	0.798	0.552	0.666	-	0.960
27	0.384	0.430	0.457	-	0.452
30	0.595	0.402	0.510	-	0.585
Aug. 2	0.755	0.503	0.617	-	0.861
5	0.828	0.542	0.707	-	0.994
8	0.816	0.553	0.723	0.804	1.025
11	0.733	0.506	0.673	0.611	0.860
14	0.703	0.521	0.665	0.593	0.825
17	0.653	0.453	0.564	0.551	0.795
20	0.688	0.460	0.609	0.747	0.917
23	0.758	0.531	0.700	0.635	0.906
26	0.572	0.462	0.576	0.495	0.677
29	0.677	0.449	0.576	0.580	0.827
Sept. 1	0.501	0.362	0.454	0.428	0.650
4	0.740	0.460	0.587	0.719	0.930
7	0.775	0.544	0.677	0.768	0.891
10	0.355	0.291	0.375	0.314	0.448
13	0.402	0.260	0.364	0.335	0.601
16		0.185	0.192		
19	0.431				0.535
22	0.450				0.530
25	0.442	0.280	0.371	0.372	0.643
28	0.459	0.305	0.313	0.338	
Oct. 1	0.211	0.214	0.267	0.246	0.427

Table 3

SAMPLE CALCULATIONS: CONSUMPTIVE USE ON CORN PLOT M-1
VS EVAPORATION FROM CLASS A PAN

Date	Inches of Soil Moisture	3-day Evaporation Class A Pan	Cumulative Evaporation Class A Pan
June 9	8.15		
12	8.07		
15	7.83		
18	8.48		
21	8.26		
24	8.84		0
27	8.58	.487	.487
30	8.63	.265	.752
July 3	8.42	.431	1.183
6	8.21	.505	1.688
9	8.48	.357	2.045
12	7.90	.530	2.575
15	7.42	.788	3.363
18	8.58		0
21	7.96	.741	.741
24	7.56	.798	1.539
27	7.49	.384	1.923
30	8.98		0
Aug. 2	8.07	.755	.755
4	7.38	.528	1.283
8	8.05		0
11	7.41		
14	8.56		0
17	8.05	.653	.653
20	7.29	.688	1.341
23	8.60		0
26	8.10		
29	8.62		0
Sept. 1	8.26	.501	.501
4	7.88	.740	1.241
7	7.26	.775	2.016
10	9.08		0
16	9.18		

Table 4

ANALYSIS OF CONSUMPTIVE USE ON CORN PLOT M-1 VS EVAPORATION FROM THE CLASS A PAN

June 24 to July 15

U

y_i	8.84	8.58	8.63	8.42	8.21	8.48	7.90	7.42	$(x_i - \bar{x})y$	$\bar{y}$	$\bar{x}$
$(x_i - \bar{x})$	-7	-5	-3	-1	1	3	5	7	-14.00	8.31	3.5

$b' = -14.00/168 = -0.08333$

$b = -2(0.08333) = -0.1667$

$y = 8.31 - 0.1667\ (x - 3.5) = 8.89 - 0.1667x$

E

y_i	0	.487	.752	1.183	1.688	2.045	2.575	3.363	$(x_i - \bar{x})y$	$\bar{y}$	$\bar{x}$
$(x_i - \bar{x})$	-7	-5	-3	-1	1	3	5	7	38.365	1.512	3.5

$b' = 38.365/168 = 0.2284$

$b = 2\ (0.2284) = 0.4568$

$y = 1.512 + 0.4568\ (x - 3.5) = 0.4568x - 0.0868$

Table 4 (cont.)

ANALYSIS OF CONSUMPTIVE USE ON CORN PLOT M-1 VS EVAPORATION FROM THE CLASS A PAN

July 18 to July 27

U

y_i	8.58	7.96	7.56	7.49	$(x_i - \bar{x})\, y$	$\bar{y}$	$\bar{x}$
$(x_i - \bar{x})$	-3	-1	1	3	-3.67	7.90	1.50

$b' = -3.67/20 = -0.1835$

$b = 2(-0.1835) = -3.67$

$y = 7.90 - 3.67\ (x - 1.50) = 8.45 - 0.37x$

E

y_i	0	.741	1.539	1.923	$(x_i - \bar{x})\, y$	$\bar{y}$	$\bar{x}$
$(x_i - \bar{x})$	-3	-1	1	3	6.567	1.0508	1.50

$b' = 6.567/20 = 0.3283$

$b = 2(0.3283) = 0.6567$

$y = 1.0508 + 0.6567\ (x - 1.50) = 0.6567x - 0.0658$

Table 4 (Cont.)

ANALYSIS OF CONSUMPTIVE USE ON CORN PLOT M-1 VS EVAPORATION FROM THE CLASS A PAN

July 30 to August 4

	U					
y_i	8.98		7.38	$(x_i - \bar{x})\, y$	$\bar{y}$	$\bar{x}$
$(x_i - \bar{x})$	-1	0	1	-1.60	8.14	1

$$b = -1.60/2 = -0.80$$

$$y = 8.14 - 0.80\,(x - 1) = 8.94 - 0.80x$$

	E					
y_i	0	.755	1.283	$(x_i - \bar{x})\, y$	$\bar{y}$	$\bar{x}$
$(x_i - \bar{x})$	-1	0	1	1.283	.6793	1

$$b = 1.283/2 = 0.6415$$

$$y = 0.6793 + 0.6415\,(x - 1) = 0.6415x - 0.0378$$

Table 4 (cont.)

ANALYSIS OF CONSUMPTIVE USE ON CORN PLOT M-1 VS EVAPORATION FROM THE CLASS A PAN

August 14 to August 20

U						
y_i	-8.56	8.05	7.29	$(x_i - \bar{x})\,y$	$\bar{y}$	$\bar{x}$
$(x_i - \bar{x})$	-1	0	1	-1.27	7.97	1

$$b = -1.27/2 = -0.6350$$

$$y = 7.97 - 0.64\,(x - 1) = 8.61 - 0.64x$$

E						
y_i	0	0.653	1.341	$(x_i - \bar{x})\,y$	$\bar{y}$	$\bar{x}$
$(x_i - \bar{x})$	-1	0	1	1.341	0.6646	1

$$b = 1.341/2 = 0.6705$$

$$y = 0.6646 + 0.6705\,(x - 1) = 0.6705x - 0.0059$$

Table 4 (cont.)

ANALYSIS OF CONSUMPTIVE USE ON CORN PLOT M-1 VS EVAPORATION FROM THE CLASS A PAN

August 29 to September 7

	U						
y_i	8.62	8.26	7.88	7.26	$(x_i - \bar{x})\, y$	$\bar{y}$	$\bar{x}$
$(x_i - \bar{x})$	-3	-1	1	3	-4.46	8.00	1.50

$$b = 2(-4.46/20) = -0.4460$$

$$y = 8.00 - 0.4460\,(x - 1.50) = 8.68 - 0.45x$$

	E						
y_i	0	0.501	1.241	2.016	$(x_i - \bar{x})\, y$	$\bar{y}$	$\bar{x}$
$(x_i - \bar{x})$	-3	-1	1	3	6.788	0.9395	1.50

$$b = 2(6.788/20) = 0.6788$$

$$y = 0.9395 + 0.6788\,(x - 1.50) = 0.6788x - 0.0787$$

Table 5

RATIOS OF CONSUMPTIVE USE FROM CORN PLOT M-1 AND EVAPORATION FROM DIFFERENT EVAPORATION PANS

Pan	Irrigation Period	$b_{\Delta U}$	$b_{\Delta E}$	Ratio $b_{\Delta U}/b_{\Delta E}$
Shielded pan	Aug. 14 to 20	-0.6350	0.6490	0.9784
	Aug. 29 to Sept. 7	-0.4460	0.6464	0.6899
Shallow black pan	June 24 to July 15	-0.1667	0.6302	0.2640
	July 18 to 27	-0.3670	0.7791	0.4710
	July 30 to Aug. 4	-0.8000	0.7560	1.0582
	Aug. 14 to 20	-0.6350	0.8560	0.7418
	Aug. 29 to Sept. 7	-0.4460	0.8343	0.5345
Young screened pan	June 30 to July 15	-0.1812	0.3036	0.5968
	July 18 to 27	-0.3670	0.4929	0.7445
	July 30 to Aug. 4	-0.8000	0.4895	1.6343
	Aug. 14 to 20	-0.6350	0.4565	1.3910
	Aug. 29 to Sept. 7	-0.4460	0.4561	0.9778
55-gallon barrel	July 6 to 15	-0.2950	0.3882	0.7599
	July 18 to 27	-0.3670	0.5820	0.6305
	July 30 to Aug. 4	-0.8000	0.5440	1.4710
	Aug. 14 to 20	-0.6350	0.6145	1.0333
	Aug. 29 to Sept. 7	-0.4460	0.5711	0.7809

Table 6

ANALYSIS OF 1955 EVAPORATION DATA

x_a	x_b	n	Σx_a	Σx_b	Σx_a^2	Σx_b^2	$\Sigma x_a x_b$	SSx_a	SSx_b	SP	r
x_1	x_2	29	17.009	11.867	10.877093	5.197503	7.463498	.901021	.341445	.503298	.91
x_1	x_3	26	15.808	13.671	10.366082	7.679105	8.863918	.754818	.490788	.551950	.91
x_1	x_4	16	9.485	8.536	6.094605	5.031580	5.510975	.471778	.477624	.450727	.95
x_1	x_5	34	19.776	24.670	12.435814	19.079926	15.357309	.933162	1.179664	1.008076	.96
x_2	x_3	27	11.164	13.863	4.964504	7.715969	6.171467	.348397	.598089	.439373	.96
x_2	x_4	16	6.651	8.536	2.955183	5.031580	3.824085	.190445	.477624	.275777	.91
x_2	x_5	27	11.338	20.088	5.054302	15.974348	8.881439	.293182	1.028876	.445967	.81
x_3	x_4	16	8.494	8.536	4.849446	5.031580	4.901706	.340194	.477624	.370157	.92
x_3	x_5	24	13.067	18.557	7.496455	15.139627	10.541753	.382018	.791200	.438240	.80
x_4	x_5	15	8.198	11.422	4.917336	9.145822	6.669317	.436856	.448350	.426813	.96

x_1= Class "A" Pan
x_2= Young Pan
x_3= 55-gallon Barrel
x_4= Shielded Pan
x_5= Black Pan

Σ = the sum of
n = number of observations
SS = sum of squares
SP = cross product
r = correlation coefficient

Table 7

CALCULATION OF CORRELATION COEFFICIENT
BETWEEN TWO YOUNG SCREENED PANS

x		xy		y	
Σx	= 8.472			Σy	= 8.701
$(\Sigma x)^2$	= 71.774784	$\Sigma x \Sigma y$	= 73.714872	$(\Sigma y)^2$	= 75.707401
$\frac{(\Sigma x)^2}{N}$	= 1.216521	$\frac{\Sigma x \Sigma y}{N}$	= 1.258105	$\frac{(\Sigma y)^2}{N}$	= 1.291877
Σx^2	= 1.377530	Σxy	= 1.296737	Σy^2	= 1.360817
ss_x	= 0.121009	SP	= 0.038632	ss_y	= 0.068940

$N = 59$

$r^2 = 0.1788$

$r = 0.423$