WATER USE BY APPLE TREES AND ITS CORRELATION WITH CLIMATIC DATA

by

Mohammed Taha Hanbali

A Thesis Submitted to the Faculty of Agricultural Sciences in Partial Fulfillment of The Requirements for the Degree of MASTER OF SCIENCE IN AGRICULTURE

Major: Irrigation-Agronomy

Minor: Soils

Approved:

Salim Makhoul
In Charge of Major Work

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ACKNOWLEDGEMENT

The author wishes to express his sincere gratitude to Dr. Salim Wadi Macksoud for his valuable advice, constructive suggestions, assistance and correction of the manuscript.

Special thanks are due to Mr. M.Nima for his help in the use of the Neutron Probe.

ABSTRACT

A 15-month study was carried out in a terraced apple orchard in Dahr-al-Baydar for evaluating the irrigation practice and determining water use by apple trees and its correlation with climatic data.

Changes in moisture content throughout the growing season were determined by regular periodic sampling of the soil and by the use of Bouyoucos gypsum resistance units. The neutron scattering method was used for part of the growing season.

In general, the irrigation of the orchard was unsatisfactory, because the soil moisture was allowed to reach the permanent wilting percentage and even below it during the growing period of the crop.

In 1963, daily average rate of water use ranged from 0.89 to 7.63 millimeters with an average of 3.12 millimeters for the whole growing season. Peak water use was in the months of July and August. Early in the season the rate of water use was greatest from the shallow soil layers, but as the season advanced the rate of water use was approximately the same throughout the soil profile down to 120 centimeters. By the end of the growing season almost all of the soil profile down to 120 centimeters had reached the permanent

wilting percentage.

Water use as reflected by the Bouyoucos resistance units showed a significant correlation with actual water use for the top 120 centimeters of soil.

Correlations between rates of estimated potential evapotranspiration by Blaney-Criddle formula, Penman equation and the difference in evaporation from black and white atmometers were highly significant, but the correlations between rates of actual water use and estimated potential evapotranspiration were not significant.

In 1964, comparisons of rates of water use as determined by the neutron scattering method and by gravimetric method did not indicate a significant correlation. This was probably due to faulty calibration of the neutron probe, as the correlation between neutron counting rates and soil moisture content was significant down to a depth of 80 centimeters.

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INTRODUCTION

Apple production plays a major role in the economy of Lebanon, coming second only to citrus in export trade. One of the main factors limiting apple export is their high cost which is due to both high production costs and low returns of first class products. Irrigation plays a serious role in both aspects constituting one of the major costs in apple production, and influencing the quality of the produced fruit. Proper irrigation can only be practiced if a reasonable knowledge of the rates of water use by apple trees is available.

The present study was designed to obtain information about the rate of water use over short periods throughout the growing season. With such information an apple grower can be sure of the time for irrigation and of the quantity of water to apply and would save both water and money and grow better apples at the same time. Moreover, this study further attempts to evaluate the effectiveness of a given irrigation practice, and to recommend a simple method for estimating water use, and consequently irrigation requirements.

The field work was carried out on a terraced apple orchard in the mountain regions of Lebanon. Water use for short intervals was determined by means of the gravimetric method. Water use was estimated by the use of gypsum resistance units and the neutron scattering method as well as by the use of the Blaney-Criddle formula, the Penman equation and the difference in evaporation between black and white atmometers.

Though carried out for the first time in Lebanon and only for one season, and part of the following one, this study promises to be of value not only in the orchard where it was carried out but for the whole apple industry. In the orchard itself it showed the ineffectiveness of the irrigation schedule followed which subjected the maturing apple trees to injurious high soil moisture tensions. For the industry, on the whole, it established a first attempt of quantitative determination of rates of water use and a local evaluation of the most commonly used methods of estimating such use. It is hoped that if such work could be repeated in other areas and over a period of years data that would help reduce irrigation costs and assure proper irrigation schedules and practices would be obtained. This might be the salvation of the apple industry in Lebanon.

REVIEW OF LITERATURE

The ultimate objective of irrigation is to counteract drought by making certain that the plants are not deprived of water at any time during their development. It is not possible to determine to what extent rainfall fails to supply the needs of plants for water without knowing their water use. Therefore the determination of the rates and amounts of water use under different types of cover has been a research problem of major importance for a long time.

Factors Affecting Water Use by Plants

Water use by plants is affected by soil, plant, and meteorological factors.

Penman (48) indicates no great difference in the evapotranspiration rates of different crops grown under similar soil and climatic conditions provided the soil is covered with vegetation and moisture is adequate for maximum transpiration. Allison *et al*. (4) found a direct and high degree of correlation between evapotranspiration and dry weight of the crop produced regardless of the crop rotation or fertility level. His data indicates that the kind of crop is not an important factor except as it effects dry weight. Krogman and Lutwick (38) found that the differences in the seasonal water use by various crops were more dependent upon the length of growing season than upon the kind of crop grown. Munro and Wood (46) Prashar and Singh (52) and Fritschen and Shaw (20) showed that the rate of water use varies with the stage of growth of the crop. Hutchinson et al. (30) showed that evapotranspiration of cotton in Uganda over the growing period was proportional to the leaf area with an allowance for evaporation from bare soil in the early stages, they concluded that "the within-season pattern of water requirement of an annual arable crop is shown to be more dependent on its state of development than on the pattern of a physical model based on calculations of energy available".

Veihmeyer and Hendrickson (71, 72) concluded, from their own studies extending over many years and from the work of others that transpiration is independent of soil moisture so long as the moisture content of the soil in contact with the absorbing portion of the root is above the permanent wilting percentage. Doss et al. (18) found that the total amount of water used depended more upon the amount of available moisture in the soil than on plant species. Moisture was first extracted at shallow depth beneath the plant and then at successively lower depths. Iljin (32) reported that plants adjust themselves to drought in various ways such as by limiting transpiration to a minimum, or by getting sufficient water from the deep soil layers.

When all plant factors are constant and favorable for maximum transpiration, evapotranspiration depends upon two closely related groups of factors (64).

1. Those which affect the availability of heat at the surface.
2. Those which affect the availability of water for evaporation at the soil surface and in the leaf tissue.

Lemon et al. (42) reported that net radiation, which is the difference between the incoming and outgoing radiation, is the main source of heat for evapotranspiration. As the soil dried out the percentage of net radiation used for evapotranspiration decreased.

Determination of Water Use

Water use is commonly estimated through soil moisture studies, growing crops in tanks or lysimeters, and area wide studies of ground water fluctuations or inflow and outflow conditions. Of these, only soil moisture studies will be discussed.

Soil Moisture Studies

A. Direct Soil Sampling - The Gravimetric Method

The gravimetric method is the most accurate method now available (24). The standard procedure requires removal of soil samples in the field with a soil tube or auger. The moist soil is transferred to a closed container and weighed. The container is then opened, placed in an oven, and dried at 105°C

The soil sample is reweighed when it has reached constant weight. The loss in weight represents soil water and may be expressed as a percentage of the dry soil. If the bulk density of a field sample is known, this amount of water can be expressed as a percentage of the bulk volume or in depth of water per unit of soil depth. This procedure is repeated after an interval of time. The difference in soil moisture between the two determinations is considered as the amount of water use for the interval of time.

Although all other methods of measuring soil moisture are calibrated against the gravimetric method (19) it is laborious and time consuming. Furthermore, the information obtained by such a method must be related to the properties of each individual soil type. In addition, repeated sampling cannot be made at exactly the same location, and the method is all but impossible to use in stoney soils (55). In small plots it is inadvisable to use this method because of the destruction of plant roots and the relatively serious disturbance of the soil profile that might result from frequent and numerous deep samplings. For best results, with a reasonable number of samples, uniform soil is essential. Furthermore, to reduce the influence of downward seepage of water, samplings should not be taken before several days after each irrigation.*

B. Indirect Determination of Soil Moisture

1. Soil Moisture Tension Method

Tensiometers are most useful under conditions of high acre-yields and where succulent crops such as citrus, potatoes, vegetables, and forage are grown. These instruments do require regular attention and must be kept filled with water. However they do not operate under dry soil conditions, such as those existing where irrigation water supplies are limited (55).

2. Electrical Resistance Units

The more common units are made of plaster of paris, though nylon and fiberglass units provide greater sensitivity in the higher ranges of soil moisture. One objection to their design and use in the field arose from imperfect contact with the soil when alternately wet and dried (24). The outside metal enclosure, which minimizes the tendency for electrical currents to pass through the soil outside the unit, apparently prevents intimate contact between the fiber and soil particles.

The method is not entirely free of shortcomings. The main disadvantage is that it is not entirely successful in mucks, peats, extremely sandy

* In personal communication from Dr. Macksoud, S.W.

soils and in salt-affected soils. Probably the greatest drawback is its poor accuracy in salty soils (10). Temperature also affects the resistance reading of all units, but the magnitude of resistance change is small relative to other sources of variation. Taylor (63) at Utah State Agricultural College found that the variation between plaster of paris blocks arises largely from two sources - random variation among blocks and drift from calibration. The coefficient of variability between blocks was about 15 percent. The variation could be minimized by selection of units which did not differ by more than 50 ohms after plunging in water. Calibration drift of some units caused changes of as much as 1 atmosphere tension in a single season. The magnitude of the change depends on the number of drying intervals and the number of days between each drying interval. Changes in calibration were greater in the wet range (low resistance values) than in the drier moisture range (63). Units treated with nylon resin were more resistant to changes in calibration, becoming considerably more stable after 10 wetting and drying cycles. The nylon and fiberglass units are relatively stable in comparison with either the plaster or resin-impregnated blocks.

Resistance blocks do have a few advantages over tensiometers. They can indicate the moisture content of relatively dry soils; this is a useful feature in areas with limited irrigation water or with crops such as small grains which don't need high soil moisture during the ripening state (10, 55). Also the cost of adding extra units for testing more locations is less than with tensiometers (55).

3. Neutron Scattering Method

This method rests primarily on two considerations: first, hydrogen is, practically, the only material that will slow fast neutrons, second, hydrogen in soils is present almost entirely in the form of water (22).

The main features of this method include a neutron counting unit, and a probe unit. The latter contains both a source of fast neutrons which is usually a mixture of radium and beryllium and a detector of slow neutrons (55).

The probe unit is lowered into an aluminum, or other metal, access pipe to various soil depths. At underground levels, the fast neutrons are projected out into the soil in all directions. Some of them are slowed down by hydrogen atoms and deflected back to the counter tube. They are then registered by the counting unit. Since most of the hydrogen atoms in soil are associated with water, the slow neutron readings are related to water content of the soil. Only a single chart is needed for all or most soil types in order to get an accurate measure of water availability(55).

It appears that a definite relationship exists between the soil moisture content and the counting rate of neutrons. This relationship appears to be the same for five soils, including a sand and a clay and varying specific gravity from 62.2 to 94.4 pounds per cubic foot. The relationship is true, however, only if the moisture content is expressed in terms of a unit volume of soil (22). McGuinness _et al_. (45) reported that the evaluation of soil moisture changes with neutron method agreed closely with that obtained from the weighing lysimeters. The correlation of the neutron reading with the gravimetric determinations was 0.95 for the 44 calibration points.

This method is assumed to be temperature independent as long as the temperature is below 32°C. The probe gave incorrect counts when its temperature was above 32°C (15). Taylor (63) found a linear relationship between neutron counts and water content of the soil. Stolzy and Cahoon (60) and Stone _et al_. (61) found a curve relationship for a field calibration curve. The field calibration curve was in closer agreement with the moisture content obtained by sampling than was a calibration curve developed in the laboratory. Stolzy and Cahoon (60) reported that Horonjeff and Javek in Australia found an S-shaped curve obtained in a laboratory calibration.

The neutron scattering method is the most promising soil moisture method for determining evapotranspiration since the soil moisture is determined on depth fraction basis directly (no bulk density measurement required) and because the sampling statistics are greatly improved (the periodic measurements are made at the same site and depth with an absolute error of about ± 0.5% on a depth fraction basis) (64).

Estimation of Water Use

Both direct and indirect methods for determining water use, require large numbers of measurements to avoid serious statistical errors and are laborious. In addition, tensiometric and electrical conductivity methods are subject to moisture hysteresis ambiguities (64). Therefore, attempts have been made to determine use of water by crops from the climatic data of the area in which they are grown. Some of the more important empirical methods have been developed by Blaney and Criddle, Thornthwaite and Penman. These methods can be grouped into three categories.

1. Those based on empirical relationships between evapotranspiration and one or more common climatic factors such as that of Blaney and Criddle (6, 7, 8) Lowry and Johnson (43) and Thornthwaite (65). On this category, the Blaney-Criddle method provides a rapid method of transferring the results of careful measurements of evapotranspiration made in several areas to other areas of similar climate (7). Briefly, the procedure is to correlate existing measured monthly consumptive use data with monthly temperature, percent of day time hours, precipitation, growing period, or irrigation season. Coefficients so developed for different crops are used to transpose consumptive use data for a given area to other areas for which only climatological data are available (1959). Expressed mathematically, $U = KF = \Sigma kf$ where

   U is the consumptive use in inches for any period

   F is the sum of the products of mean monthly temperature in degrees Fahrenheit (t) and monthly percent of annual day time hours (p) and

   K Empirical coefficient (irrigation season or growing period)

   $f = (t \times P)/100$ monthly use factor

   k is the monthly use coefficient

According to Stork (62) it is not justifiable, to supply the same K factor to other regions without sufficient knowledge of the physical conditions of the region. Pruitt and Jensen (53) found that a high correlation coefficient resulted from statistically comparing estimated evapotranspiration by the Blaney-Criddle method with actual evapotranspiration. Moreover, the value of the crop factor should vary throughout the growing season. According to Blaney and Criddle (8) the seasonal coefficient (K) for each crop appears to be approximately constant for most areas where irrigation is practiced. However, the coefficients do not appear to be constant for consecutive short periods during the growing season. Moreover, adjustments can be made in areas where data are available. For short periods and higher temperatures, the coefficient (k) appears to be larger but temperature has its own particular growth and water use pattern. Thus for short periods, use coefficients vary, depending upon temperature, and stage of growth.

The empirical equation developed by Thornthwaite (65) which relates evapotranspiration to mean temperature is $PE^x = 1.6\ (10T/I)^a$ where T is the monthly air temperature (^oC); I is a heat index for the station which depends upon long period mean monthly air temperature; "a" is a function of I (both "a" and "I" can be found from tables); and PE^x is the monthly evapotranspiration in centimeter. The PE^x is an "unadjusted" value based on a 12-hour day and 30-day month and is corrected by actual daylength in hours, h, and days in a month, N, to give the adjusted PE

$$PE = PE^x \ (\frac{h}{12}) \ (N/30).$$

Decker (16) found that Thornthwaite's method produces very precise estimates under Missouri's climatic conditions, for average values over long periods. This method produced biased estimates when shorter periods of time were concerned. Both the Blaney-Criddle and Thornthwaite methods have been used successfully in design of irrigation system, and errors incurred are generally not too serious (57). According to Pelton et al. (47) the success of "adjusted" mean temperature methods for monthly growing season and annual estimates of actual evapotranspiration is due in large part to low variability of the radiation, evapotranspiration, and mean temperatures for all periods from year to year. In addition the lag of temperature behind radiation (which arises from the thermal storage of the soil) which causes great error in monthly estimates of evapotranspiration was very low.

Mean temperature methods cannot be used for short period estimates of actual and potential evapotranspiration (47). The Thornthwaite method was found unreliable for daily, 3-day, and 6-day period estimates. It fails for short period estimates principally because mean temperature is not a suitable physical measure of the energy either available for or used in evapotranspiration. According to Van Wijik and De Vries (69) no method based on monthly temperature can be expected to give reliable results for different regions. The temperature of the air lags behind solar radiation at moderate and high latitudes and, therefore, the amount of energy available for evaporation in spring is quite different from that available in the autumn, if periods with the same temperature are compared. For the Netherlands, for instance, this difference amounts to nearly 300% between the two months of March and November, with average temperatures of 5.0°C and 5.4°C respectively.

2. A second general type of equation is the so-called "heat budget" or "energy balance" concept which has been described by Penman (48), Halstead and Covey (27), Tanner (64) and others. This procedure employs the concept of allocating incident net radiation to the various processes in which it is

consumed, namely evaporation of water, heating the soil, heating the air and use in photosynthesis. Penman has incorporated certain aspects of aerodynamic theory that crudely incorporates vertical energy gradients in accounting for energy disposition. Tanner recently elaborated on the vertical energy balance and resulting implications. Penman (50) found that the meteorological estimates for water use were in acceptable agreement with the value measured by soil sampling and also the best yields of sugar came from those plots that were watered at a rate a little below the computed potential transpiration rate. Israelson and Hansen (31) reported that a very good correlation has been obtained between computed and measured consumptive use values. Penman formula applies better under humid areas not far from the ocean and essentially covered with growing vegetation than in arid-low humidity areas where temperature and radiant energy may not be as nearly balanced. It appears to Van Bavel and Harris (68) that the Penman method can provide reasonably accurate data on maximum evapotranspiration. Decker (16) found that the Penman method estimated the average daily evapotranspiration with considerable precision where the soil moisture was maintained at or above field capacity. When the soil surface is dry the Penman method overestimated evapotranspiration by about 70%. Gerber and Decker (23) found that the Penman method overestimated the evapotranspiration when the soil surface was dry, even though abundant sub-surface moisture was present, but gave reliable estimates when the soil surface was wet. Hearn and Wood (28) studied the relationship between estimated evapotranspiration as found by Penman and evaporation as measured by an open pan. They found that from July to October (dry season) the estimated evapotranspiration by open pan exceeds Penman by a steadily increasing ratio. As this difference is closely correlated to the actual value of the Penman estimate, correlation between the pan and Penman is good: from May to November the correlation for 10-day means gave a coefficient of determination of $r^2 = 0.9532$, $n = 35$. Hutchinson et al. (30) asserted that an annual crop, starting with bare soil at planting and progressing to full cover, departs from Penman's model of a complete cover and suggested that the crop water use will increase proportionally to leaf area from 0.3 Eo (the estimated evaporation from a free water surface) at planting to a maximum of 1.4 Eo, as determined by the energy limit.

3. A third general method for indirect estimation of

evapotranspiration is use of evaporimeters such as evaporation pans and atmometers. Use of atmometers has been proposed by Halkias <u>et al</u>. (26) and involves a correlation of difference in evaporation from black and white atmometers with measured evapotranspiration from crops. However, Stork (62), in Iraq, found no relationship. Correlations with evaporation pans have been proposed by Pruitt and Jensen (53) and by Bouwer (11). The basis for use of such devices is the assumption that they will successfully integrate the evaporative factors and through correlation give a reasonable estimate of evapotranspiration.

It is worth noting that the empirical crop factors relating evapotranspiration to water loss from evaporimeters are generally constant for a given crop and a fixed environment for the evaporimeter, after development of complete crop cover. This is in contrast to such factors in empirical relationships based on measured climatic indices in which marked seasonal variation in the crop factor is usually required, (25). This indicates that such evaporimeters when installed in a suitable environment will reasonably integrate evaporative factors and therefore are more adaptable for estimating evapotranspiration for short-time periods. It should be pointed out, however, that the common practice of accumulative plotting of data tends to mask short-term deviations in such estimates. Extremely high linear correlations may be obtained between cumulative evapotranspiration and water loss from evaporimeters, yet deviations for weekly or shorter intervals may be appreciable. (57). According to Thornthwaite and Mather (66) the most reliable measurements of evapotranspiration that can be related to climatic factors, in an effort to obtain a valid and practical relationship, are based on the monthly or seasonal data from irrigation and drainage projects and on daily observations from carefully operated evapotranspirometer tanks. This is in accord with the findings of Wilcox (73) and Prashar and Singh (52) that better estimates of evapotranspiration can be obtained by using evaporation records than by using only one weather record by itself. Pruitt and Jensen (53) and Shigeyoshi and Fukuda (59) found that during periods of good crop cover, tank evaporation rates gave a much closer estimate of actual water use rates than either the Blaney-Criddle or Thornthwaite procedure. It appears to Fritschen and Shaw (20) that pan evaporation may be used to estimate evapotranspiration and irrigation requirements, provided that a relationship between the crop to be irrigated and pan evaporation has been established for the given area.

General limitations of indirect methods for estimating evapotranspiration:

Major limitations of the many indirect methods for estimating evapotranspiration fall into three categories: (1) with the exception of the turbulent transfer and energy balance procedures, each of the methods depends upon empirical relationships between factors employed and the basic energy transformations involved in evapotranspiration; (2) in all cases, except for the turbulent transfer and energy balance methods, factors such as crop geometry, stage of plant development, rooting behavior, season of the year, etc., are composited by empirical correlation into one or more crop factors; (3) most of the procedures are best adapted to conservative situations and are either not applicable or difficult to apply in the more general case of advected heat (which is the case for areas similar to the western parts of the United States) (57).

According to Halstead and Covey (27) it is found that the majority of equations involving the concept of potential evapotranspiration or consumptive use tend to assume a homogenious soil moisture regime infinite in horizontal extent. Therefore, it has been difficult to apply these equations to irrigation practices which obviously must create isolated areas above normal moisture. Moreover, several possible sources of error, which are common to a number of these equations, result from assuming either explicity or implicity, that (1) size of the area is not a factor, (2) temperature and evapotranspiration, which are only correlated, are uniquely related physically, (3) the effect of wind may be determined by its speed at one level, and (4) mean values can be used instead of instantaneous values.

Application of Penman's method and other methods as Blaney-Criddle and Thornthwaite is possible only when certain restrictions are imposed. The crop must be never short of water and must be of uniform height. The crop must also be a green crop, actively growing and completely shading the ground (17).

Water Use By Apple Trees

1. Effect of Soil Depth

A number of investigators have reported that they have found the rate of consumptive use of water in deciduous orchards to be normally greatest near the surface, and to decrease progressively with increase in depth.

Veihmeyer (70) found decreasing moisture use with greater depth in irrigated prunes in California. Some moisture was used, however, from a depth of 12 feet. Aldrich *et al.* (2), in tests with pear trees in Oregon, reported that the percentage of water lost from the top four feet of soil were 34, 28, 22, and 16 percent respectively. Jensen et al. (34) working on apple orchard irrigation in Washington found that little water was removed below seven feet and about 60 percent of the total water used come from the top 2 1/2 feet of the soil. Wilcox and Mason (74) found that the rate of consumptive use by apple trees was greatest in the top foot, and decreased progressively with an increase in depth. In older apple orchards there was still some consumptive use at a depth of six feet. Moreover in most cases the rate of consumptive use was negligible below a depth of four feet. This is in accordance with Aldrich et al.(2) who found that smaller amounts of water were used from below the top four feet of soil under unirrigated conditions. Wilcox and Mason (74) found that early in the season the rate of consumptive use was greatest near the surface and decreased with increases in depth. As the top foot of the soil dried out, however, the rate of water use increased in the second and third foot, and later still in the fourth and fifth foot. By the end of the season almost all of the soil to the fourth foot had dried down to the wilting point. Markov (44) found that the top layer (0-20 cm.) gained more moisture from rainfall than the lower layers (60-80 and 80-100 cm.) and lost more by evaporation. The lower layers showed a reduction in moisture content over the months from spring to autumn.

Among the factors that have been found responsible for reduced moisture absorption at lower depths are the lesser concentrations of fibrous roots at those depths, colder temperatures, and lack of aeration. Workers have commonly found (2,29) a reduction in concentration of absorbing roots at greater depths. Aldrich, *et al*. (2) reported high positive correlations between the rate of consumptive use and the count of fibrous roots of pear trees. It has also been found that the soil is normally colder at greater depths during the summer (36), and that its atmosphere contains a higher ratio of carbon-dioxide to oxygen at greater depths. (12,21). In addition, it has been found that both colder temperatures (37) and an unfavourable ratio of carbon-dioxide to oxygen (13) reduce the rate of water absorption by plant roots.

2. Effect of Distance From Tree on Rate of Consumptive Use:

A number of workers have investigated the effect of distance from a fruit tree on the rate of consumptive use of water from the soil. Aldrich *et al*. (2), working with pear trees in Oregon, found considerable variations in rate of consumptive use, with the greatest consumptive use at a distance of 4 to 8 feet from the trunk. Veihmeyer and Hendrickson (86), working with walnut, peach, and prune trees in California found very little effect of distance from the tree on moisture use from the soil. Wilcox *et al*. (75)found that the rate of consumptive use by apple trees often varies from point to point throughout the root area in the soil.

The variation in consumptive use across a tree panel depended to some extent on the age and size of the trees. With the smaller trees, there was a tendency for the rate of consumptive use to decrease from the trunk out to the center of the tree square. With the larger trees, however, the reverse held true. Observation indicated that these results were closely associated with the degree of concentration of fibrous roots; that is, these roots were most concentrated within six to eight feet of the trunk with the younger trees, and in the centers of the panels with the older trees. Markov (44) found that in apple orchards the average moisture content, from July to September, at a distance of 2 meters from the trunk was 2.6% less in the 0-20 centimeter layer, and 1.6% less in the 20-40 centimeter layer on the southern side of the tree than on the northern side. Measurements taken in August showed that the soil moisture content increased with increasing distance from the tree.

3. Water Use and its Correlation with Climatic Data:

Wilcox *et al*. (75) found a highly significant positive correlation between the rate of evaporation from an open water tank and the rate of consumptive use by apple trees. Aldrich and Work (1) in Oregon reported a positive relationship between the rate of evaporation and the rate of transpiration, and a negative relationship between the rate of evaporation and the rate of enlargement of pear fruits.

4. Time of Irrigation:

Richard and Wadleigh (56) reported that Veihmeyer and Hendrickson have made extensive field tests to determine the most efficient irrigation practices in California. On the basis of their observations on perenial fruit crops, they have reported that moisture is equally available over the range from field capacity to near the permanent wilting percentage. They state that their studies with grapevines, peaches, prunes, appricots, apples, and pears in field plots and containers and with sunflowers in containers show that there is no single percentage of moisture above the permanent wilting percentage which could be considered as optimum for plant growth. Their experiments show that favorable conditions of soil moisture extend from the field capacity to about the permanent wilting percentage. The extensive data of Aldrich et al. (3) on pear fruit growth show that trees subjected to moisture stress early in the fruiting season have abnormally low rates of enlargement; and even though these rates approached the ideal, or maximum following an irrigation, the loss in cumulative size was never regained. Boynton (12) obtained comparable data on the growth of apples in relation to soil moisture supply. He also found a definite decrease in growth of apples on a shallow soil in New York, if the soil moisture content of the surface 2 feet decreased to the wilting percentage. Kenworthy (35) made a greenhouse study of the effect of soil moisture on the growth of young apple trees. He used tensiometers to indicate soil moisture tension, and spaced his irrigations so that in four treatments the trees used 20, 40, 60, and 80 percent of the available water before irrigation. In the fifth treatment the trees were irrigated when observable wilting symptoms appeared. Significant growth decreases occurred, however, with less frequent irrigations corresponding to the lower moisture levels in the available range. In the arid climate of the south-eastern Volga region, sprinkler irrigation is most suitable for seedling apple root stocks. When various dates of application were tested it was found that the critical dates are those of the start and end of intensive growth (33). At East Malling (58) it has been shown that apples can be increased in size by irrigation, even in a wet year. Research there suggests that it is undesirable to let the tree reach the wilting point, and it is beneficial to apply water when about 50 percent of the available water has been used.

5. Rate of Water Use by Apple Trees:

Wilcox _et al_. (75) found that the maximum consumptive use during any one length of irrigation interval ranged from 0.435 inch per day with a 5-day interval to 0.153 inch per day with a 40-day interval. Jensen _et al_.(34) found by keeping the available soil moisture at 75% throughout the growing season that the average monthly use of water in inches by apple orchard (grass cover crops) was 2.4, 6.0, 8.3, 10.2, 8.6, 5.3 and 0.9 from April till October.

MATERIALS AND METHODS

This study was conducted during the periods of May 9th to October 15th in 1963, and of July 16th to August 20th in 1964. It consisted of both field and laboratory work. The field work was conducted on a terraced apple orchard in Dahr-al-Baydar, Lebanon, situated at an elevation of 1510 meters above sea level and a latitude of 33° 49" north of the equator.

The region of Dahr-al-Baydar, has very cold and wet winters and warm summers with frequent foggy afternoons. Precipitation ranging from 900 to 1300 millimeters annually, occurs between October and May and is heaviest during December, January and February.

There are no wells or springs but winter runoff is stored in reinforced concrete reservoirs for irrigation in summer. Because there is little or no rainfall during the growing season, all summer crops and trees depend on irrigation for most of their water needs. An under tree sprinkler system was used in this study for irrigation.

The soil in Dahr-al-Bayder is undeveloped, heterogenious, and stoney throughout the soil profile. This is so because originally the land was a rough mountainside, that was cleared from rocks then terraced by buldozers creating a highly heterogenious soil consisting of stones, gravel, and different kinds of soil texture. Surface and subsurface texture range from sandy clay loam in the upper 80 centimeters to sandy clay in the following 40 centimeters.

A small plot of mature apple trees was chosen. The plot consisted of five uniformly large healthy trees adjacent to one another in a straight line and spaced at 4.2 meters.

Field Work

The changes in soil moisture content and evaporation from atmometers were determined throughout the growing season. Besides, measurements of water applied by sprinklers, field capacity and volume weight were made. Three methods for determining the changes in the soil moisture content were used. One was direct oven-drying of soil samples, the other was use of gypsum electrical resistance blocks, and the third was use of a neutron scattering method.

Direct-oven-drying method.

Gravimetric moisture measurements of soil samples taken at three different depths from the root zone in the test plot were made. Because of textural variability, the moisture content and water use by the trees for each 40 centimeter depth of soil was determined separately.

Three sets of soil samples were taken, one just after an irrigation, the second before the subsequent irrigation and a third between the two.

Four sampling sites were chosen in the plot, each site being halfway between two trees in the diagonal direction. At each sampling period separate samples, free of stones, were taken with a 3-inch soil conservation bucket type auger at depths of 20, 60, and 100 centimeters. This was done at each sampling site and no samples were composited. After the first sampling at each site, subsequent samples were taken within 40 centimeters of the first auger hole.

The soil samples thus obtained were held in closed cans until they could be weighed. After weighing they were dried to constant weight at 105°C and were weighed again. The water content was expressed as a percentage of the ovendry weight of the soil. The difference between these moisture contents and those of the subsequent soil samples were multiplied by the product of depth and bulk density to give the water use in centimeters during this interval.

Resistance-block method.

Gypsum blocks were used to follow the changes in available soil water.

The resistance block used in this study has two bare electrodes imbedded in a block of Plaster of Paris. Two insulated wires are connected to the electrodes and these extend upward beyond the soil surface.

Resistance blocks were placed at depths of 20, 60, and 100 centimeters in each of four sites. Each site being halfway between two apple trees in the plot. The resistance of the blocks was read at the same time direct soil samples were taken using a Bouyoucos moisture meter.

Neutron scattering method.

Soil moisture measurements were made by the neutron scattering technique. Six access steel pipes, 2 inches in diameter and 1.35 meters long, were located each 1 meter away from an apple tree. Moisture measurements were made following the same timing as that for other moisture determinations. These measurements were taken at depths of 30, 70, and 110 centimeters in all six pipes and at 50 and 90 centimeters in only two of them. Previous calibration of the probe was made in the laboratory and had produced a graph relating counting rate and soil moisture percentage by volume. This graph allowed rapid determination of the soil moisture at various depths.

Volume weight.

Volume weight was determined by weighing cores of undisturbed soil, 7.3 centimeters in diameter and 6.8 centimeters high, taken at depths of 20, 60, and 100 centimeters in the field. The soil was oven-dried at 105°C for a period of 72 hours. Volume weight was calculated by dividing the weight of the oven-dry soil, stones removed, by the volume of the core.

Water applied by sprinklers:

The amount of water applied at each irrigation was accurately measured.

Sprinklers were fitted in the orchard 20 feet apart from each other. A sufficient number of circular cans each 7.55 centimeters in diameter and 5.15 centimeters high was placed around each sprinkler to measure representative water application rates. After running the sprinklers for one hour, the water collected in each can was measured with a graduated cylinder. The depth of water was determined by dividing the volume of water by the area of the can. This was repeated twice and the average of the depth of water applied was calculated by totalling the depth of water in all the cans and dividing by the number of the cans.

Field capacity determination.

After flooding the soil with water for 6 hours, the soil surface was covered by wooden boards to prevent evaporation, After two days, soil samples were taken at depths of 20, 60, and 100 centimeters and the moisture content of the samples was determined on an oven-dry basis.

Measurements of evaporation by atmometers.

In order to obtain records on the rate of evaporation two sets of black and white Livingston spherical, porous porcelain atmometers were set out at two different places at a height of 3.5 meters in the apple orchard.

Each set had two atmometers, one black and the other white. Each atmometer consisted of a hollow-porous porcelain sphere 5 centimeters in diameter and about 3 millimeters in thickness. It was filled with distilled water and connected to a glass tube leading to a supply bottle of distilled water. Ventillation in the bottle takes place through a second tube the top of which is open to the air. A one way valve was provided to prevent the rainwater that might be absorbed by the porcelain sphere from reaching the bottle. The original level of water in the bottle was indicated by a mark around its neck.

The evaporation for each period was determined by measuring the amount of distilled water required to refill the bottle to the mark on the neck. To compensate for the slight variations in the size of these spheres each reading was multiplied by a standardization coefficient. Differences in evaporation from one set were used in this study because the other set was contaminated with fungi after two months from the beginning of the experiment.

Climatic records.

Daily climatological records of the fraction of sky covered with clouds, minimum and maximum air temperature, wind velocity, relative humidity and precipitation were taken from the Dahr-al-Baydar weather station.

Laboratory Work

Determinations of the Mechanical analysis of the soil, its permanent wilting percentage, 1/3 to 15 atmosphere percentages, and moisture equivalent were run in the laboratory.

Mechanical analysis of soil was made by the Bouyoucos hydrometer method (9). Permanent wilting percentage was determined by the sunflower method as described by Piper (51). Moisture equivalent of the soil was determined by the method described by Piper (51). The method of Richard (55) was used for the 1 to 15 atmosphere percentage. The one third atmosphere percentage was determined, as described in U.S.D.A. Handbook 60 (67).

Empirical Equations Used

Two empirical equations were used in this study to estimate evapotranspiration. These were the Blaney-Criddle formula (6, 7, 8) and the Penman equation (48, 49, 50).

Penman's Equation.

Penman (49) has developed a method of estimating open-water surface evaporation, which he successfully applied to the irrigation requirements of sugar beets. His formula representing the evaporation from a free water surface (Eo) is as follows:

$$Eo = (.27\ Ea + \Delta H)/(.27 + \Delta)\ \text{mm./day} \quad \ldots\ (3)$$

with values of H and Ea given by

$$H = .95\ R_A(.18 + .55n/N) - \sigma\ Ta^4(.56 - .09\sqrt{{}^{e}d})(.10 + .90n/N) \quad \ldots\ldots\ldots\ldots\ldots\ (2)$$

$$Ea = .35\ ({}^{e}a - {}^{e}d)\ (1 + u/100)\ \text{mm./day} \quad \ldots\ldots\ldots\ldots\ldots\ (1)$$

where

H is the daily heat budget at surface in mm H_2O/day

R_A is the theoretical radiation intensity at the surface in the absence of an atmosphere (in millimeters, where 1 mm. evaporation = 59 Cal./cm^2).

n/N is the ratio of actual to possible duration of bright sunshine hours.

$\sigma\ Ta^4$ is the theoretical black radiation that would leave the area in the absence of an atmosphere, Ta being the mean air temperature and σ being Stefans constant.

${}^{e}d$ is the saturation vapour pressure at dew point temperature. (mm. Hg.)

e_a is the saturation vapour pressure at mean air temperature in (mm.Hg.) and

u is the run of the wind in miles/day.

Δ is the slope of vapour-pressure curve at mean air temperature. (mm.Hg/°F).

He further proposes to set m/10 = 1-n/N (48) and $(e_a - e_d) = e_a(1-h)$. (50).

Where

m/10 is the fraction of the sky covered by clouds and h is the mean relative humidity of the air.

The following example shows how Eo may be found by the use of the Penman equation.

Required the evaporation from a free water surface for the period of 9 to 24 May 1963; given the following climatic data

Latitude = 33° 49"

Mean air temperature = 11.2°C

Mean relative humidity (h) = 75%

Mean run-of-wind (u) = 248 miles/day

Fraction of sky covered with cloud (m/10) = 0.49

Solution

n/N = 1-m/10) = (1 - .49) = .51

From the Smithsonian Tables (41) we can find the following:

1. R_A: Since the available data in tables give one or two readings per month only, and since we are

interested in several determinations per month it was deemed advisable to prepare a graph showing the variation of R_A, from which daily readings could be obtained easily. The graph is shown in Figure 1. From this R_A equals 16.05 mm./day.

2. e_a for 11.2°C = 13.295 m.b.

= 13.295 X .750062 mm.Hg.

(1 m.b. = .750062 mm.Hg.)

= 9.973 mm.Hg.

Since

$$(e_a - e_d) = e_a(1-h)$$

$$(e_a - e_d) = 9.973\ (1-.75) = 2.49 \text{ mm.Hg.}$$

and e_d = 7.48 mm.Hg.

3. Δ for 11.2°C = .8825 m.b.

= .8825 X .750062 = .66 mm.Hg.

4. σTa^4 for 11.2°C = .5305 Cal/cm²/min.

= .5305 X 60 X 24/59 = 12.95 mm. evaporation per day.

First we use equation (1) to find Ea

$$Ea = .35\ (e_a - e_d)\ (1 + u/100 =$$

$$= .35\ (2.49)(1 + 248/100) = 3.03 \text{ mm. evaporation per day.}$$

Then we use equation (2) to find H

$$H = .95\ R_A(.18+.55\ n/N)-\sigma Ta^4(.56-.9\ e_d)(.10+.90\ n/N)$$

$$= .95 \times 16.05(.18+.55 \times .51)-12.95\ (.56-10\ 7.48)(.10+.90 \times .51)$$

= 4.77 mm. evaporation per day.

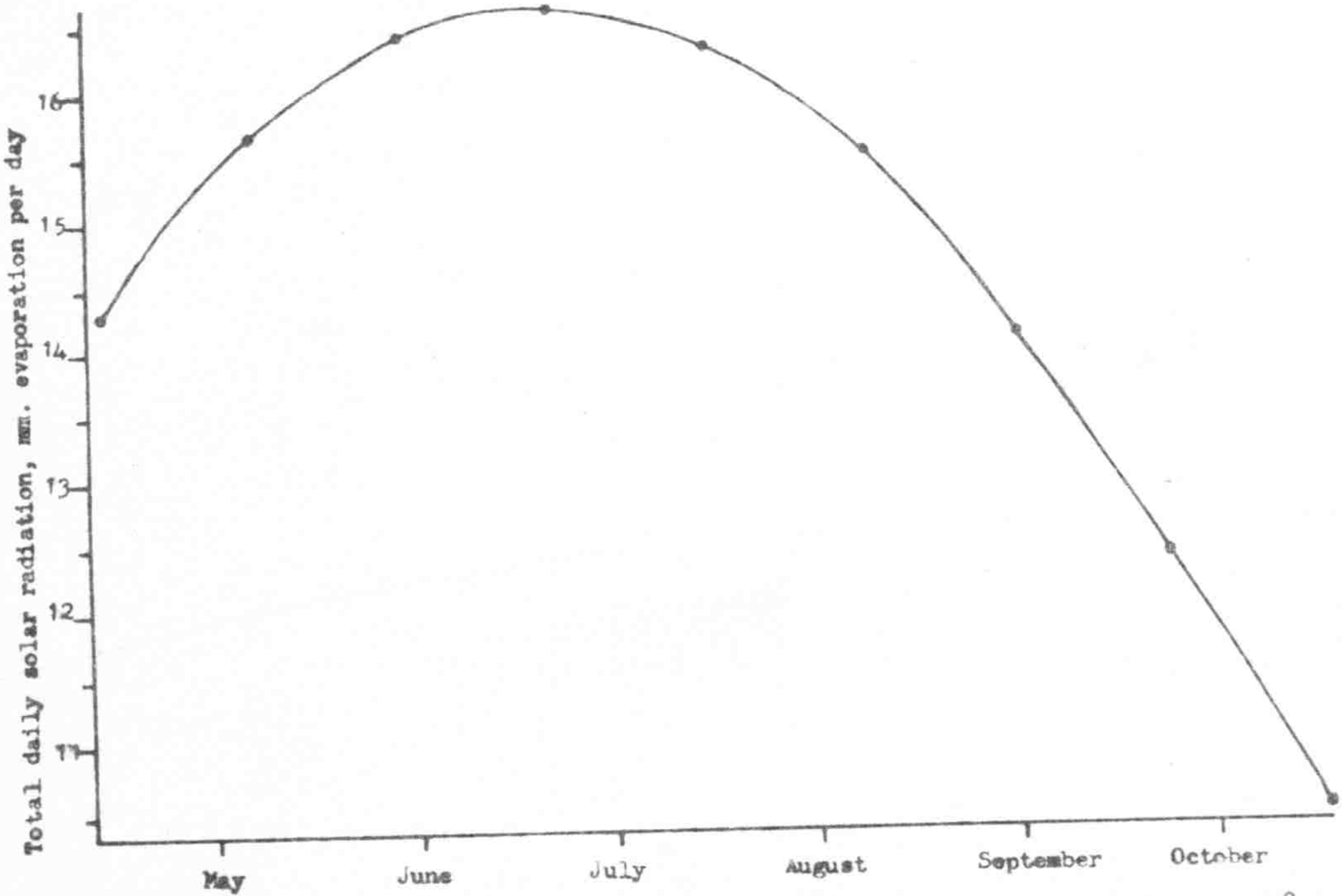

Figure 1. Total daily solar radiation (at the top of the atmosphere) at 33:49° North latitude.

Finally Eo may be computed from equation (3).

$$Eo = (.27Ea+\Delta H)/(.27+\Delta) \text{ mm. evaporation per day}$$

$$Eo = (.27X3.03+.66X4.77)/(.27+.66)$$

$$Eo = 4.26 \text{ mm. evaporation per day.}$$

or $$4.26 X 15 = 63.9 \text{ mm. for the two week period.}$$

The term ((potential evapotranspiration)) as used in this study refers to values of Eo or estimated evaporation from a free water surface in Penman's equation and to values of $\frac{(t \times p)}{100}$ or the monthly consumptive use factor in Blaney-Criddle's formula.

Also the following terms, water use, consumptive use, and evapotranspiration, will be used interchangebly in this study as the sum of the volume of water used by vegetative growth of a given area in transpiration or building of plant tissue and what evaporated from the adjacent soil.

Correlations between actual evapotranspiration and estimated evapotranspiration, were determined according to Le Clerg *et al*. (39) finding the correlation value "r".

RESULTS AND DISCUSSION

A 15-month study was undertaken to determine the actual water use by apple trees. This was obtained by the soil moisture determination method using both direct soil sampling and indirect soil moisture determinations, checking these with soil moisture determinations by means of the neutron scattering method. This water use was correlated with potential evapotranspiration calculated by the Penman equation, Blaney-Criddle formula and the differences in evaporation between black and white atmometers. A summary of the results is presented in Table 2 through Table 10. Calculations of actual and estimated potential evapotranspiration and analysis of variance appear in the appendix.

The various laboratory and field analyses of the soil samples taken from the Dahr-al-Baydar orchard yielded the following basic data:

Soil characteristics

The top 80 centimeters of the field have a sandy clay loam texture, while the lower 40 centimeters have a sandy clay texture (Table 1).

The average bulk density was 1.34, 1.38 and 1.28 for the top middle and lower 40 centimeter layer (Table 1) with no significant difference between layers (Table 11). Since the weight of stones was not included in the determination of bulk density, the bulk density reflects only the soil that has a water holding capacity (5). These determinations were made with the soil halfway between field capacity and permanent wilting percentage and no appreciable shrinkage was observed at drier stages.

Moisture holding characteristics

The field capacity as determined in the field ranged from 19.05 to 20.57 percent with an average of 19.77 in the top 40 centimeters of soil, from 17.33 to 19.54 percent with an average of 18.13 in the middle 40 centimeters, and it ranged from 21.26 to 23.48 percent with an average of 22.08 in the lower 40 centimeters of soil (Table 1). Statistical analysis of this data indicated that the top and middle layers could be assumed similar (at the 5% level of significance) but both differed from the lower layer (Table 12).

The moisture equivalent as determined by the centrifugal method was 19.41 percent for the top 40 centimeters of soil, 17.44 for the middle and 21.62 percent for the lower 40 centimeters (Table 1). These results are in agreement with Lehane and Staple in Canada (40) who found that moisture equivalent is lower than field capacity when the field capacity did not exceed 24 percent.

The permanent wilting percentage as determined by the sunflower method was 11.51, 10.92 and 12.18 percent for the top, middle and lower 40 centimeter layer (Table 1).

Table 1. Soil texture, soil moisture constants and available soil moisture capacity. Apple orchard, Dahr-al-Baydar, Lebanon, 1963.

	Mechanical analysis			Bulk density[x]	1/3 atmos. percentage	15 atmos. percentage	Moisture equivalent	Field capacity	Permanent wilting percentage	Available moisture capacity	
	Sand %	Silt %	Clay %	(gms/cc)						%	cms.
Top 40 cms. of soil	57	11	33	1.34	21.08	12.6	19.41	19.77	11.51	8.26	4.43
Middle 40 cms. of soil	61	8	31	1.38	16.19	10.2	17.44	18.13	10.92	7.21	3.98
Lower 40 cms. of soil	55	9	36	1.28	23.04	15.2	21.62	22.08	12.18	9.90	5.07

x Bulk density of soil as calculated by mass of dry soil (without stones) divided by total volume of soil plus included stones.

Moisture release curves for the top, middle and lower 40 centimeters of soil are shown in Figure 2. Soil moisture percentage at the 15 atmosphere pressure was higher than that of the permanent wilting percentage (Table 1). This is in complete agreement with the findings of Lehane and Staple (40).

Water applied by sprinklers

Water applied by sprinklers in the four irrigations was as follows 8.02, 7.93, 7.69 and 7.72 centimeters respectively, with a total of 31.36 centimeters.

Climatic data

The climatic conditions at the orchard were assumed to be similar to those of the Dahr-al-Baydar weather station located two kilometers further inland but at the same latitude and with similar hydrologic characteristics. Monthly averages for the period of May to October were as follows.

	May	June	July	Aug.	Sept.	Oct.
Temperature, °C:	10.96,	17.05,	18.4,	20.61,	18.24,	15.29
Relative humidity, Percent	73,	52,	59,	48,	59,	62
Wind velocity, miles per day:	238,	267,	300,	315,	194,	180
Fraction of sky covered with cloud:	0.51,	0.16,	0.13,	0.09,	0.19,	0.38
Precipitation, millimeters per month:	17.4,	0,	0,	0,	16.6,	80.2

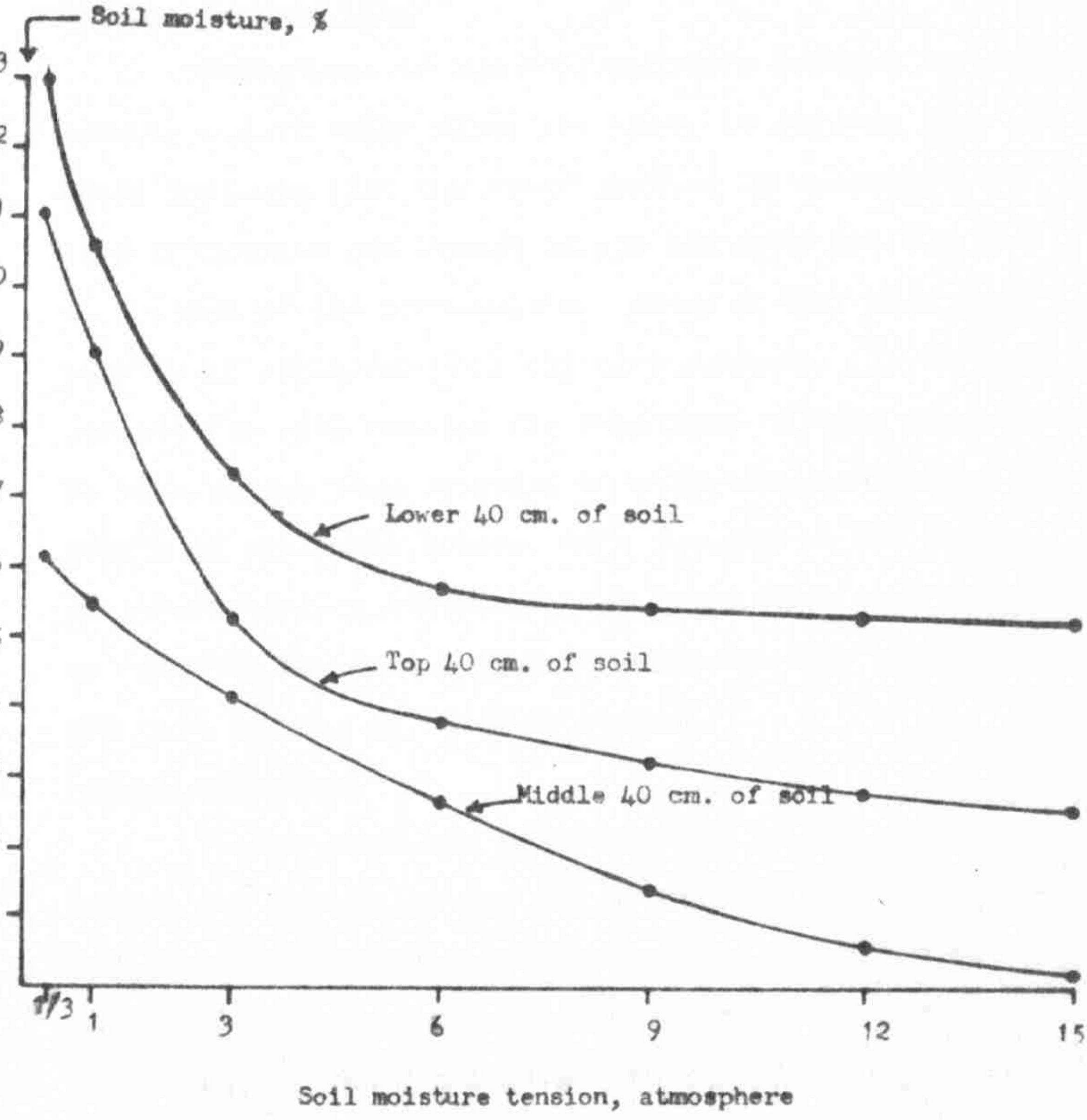

Figure 2. Relation of moisture content to soil moisture tension in the top middle and lower 40 centimeters of soil. Apple orchard, Dahr-al-Baydar, Lebanon. 1963.

The daily climatological records from which the above were obtained are shown in Tables 13 and 14 of the appendix.

<u>Irrigation practices</u>

Variations in the soil moisture content throughout growing season under study are shown in Figures (3,4 and 5). These indicate that the water applied by sprinklers in each irrigation was enough to wet the soil profile down to a depth of 120 centimeters. However they also show periods of deficient soil moisture content. In these periods the soil reached the permanent wilting percentage or even below, thus creating unfavourable conditions for growth of the apple trees. This was due to the length of the irrigation intervals, and could have been averted by reducing the time between irrigations but still using the same volumes of water as before.

<u>Actual water use</u>

Total water use as determined by the gravimetric method for the period May 9th to October 15th 1963, was 497.6 millimeters as is shown in Table 2. The range of daily rate of water use was between 0.89 and 7.63 millimeters. The total water use as determined by the gravimetric method (497.6 mm.) was higher than the sum of the water applied by sprinklers (313.6 mm.) and by precipitation (27.4 mm.) by 156.6 millimeters. This difference (156.6 mm.) may be accounted for by two considerations. The first is by considering the difference

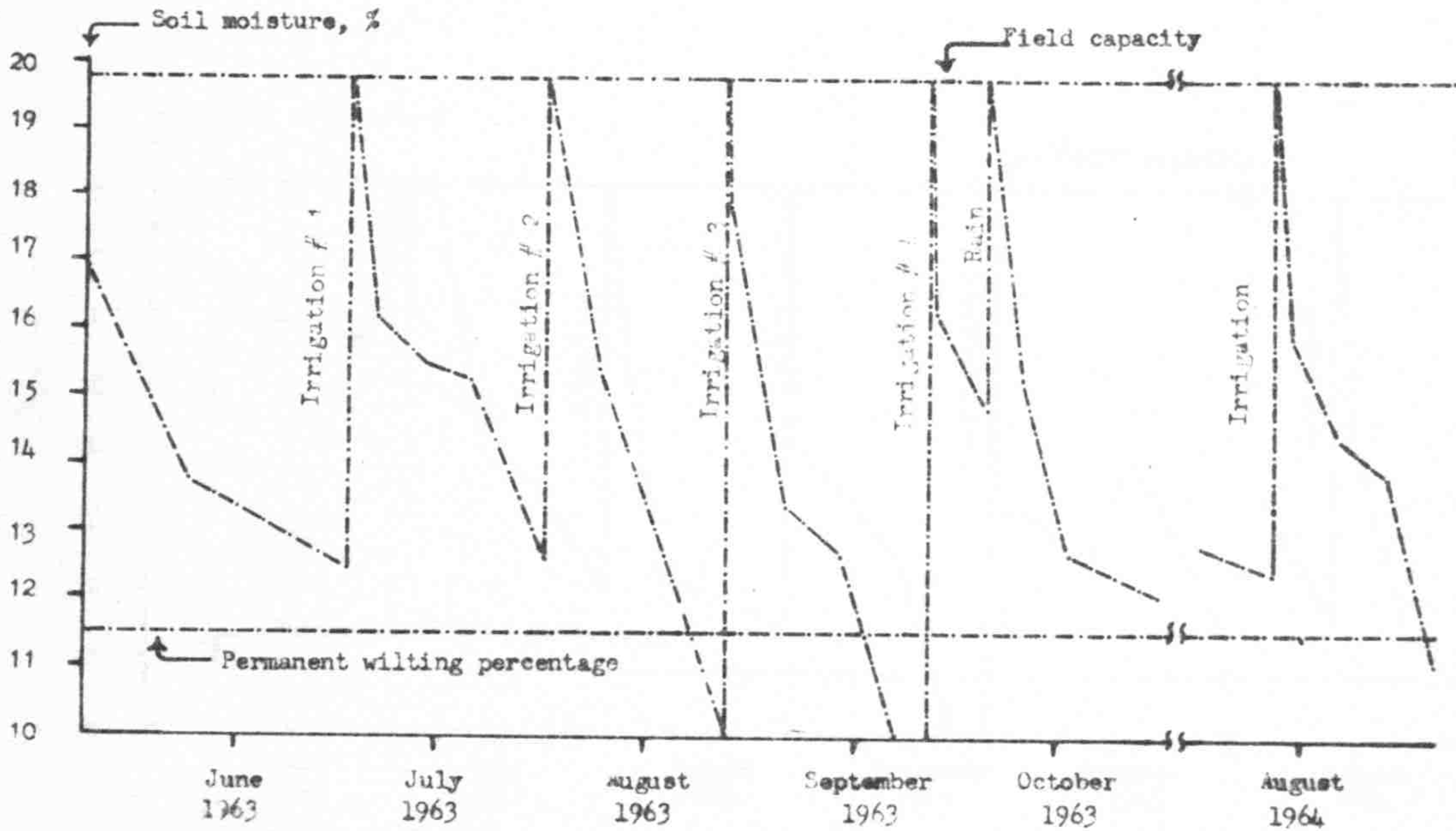

Figure 3. Variations in soil moisture content throughout the growing season in the top 40 centimeters of soil. Apple orchard, Dahr-al-Baydar, Lebanon 1963, 64.

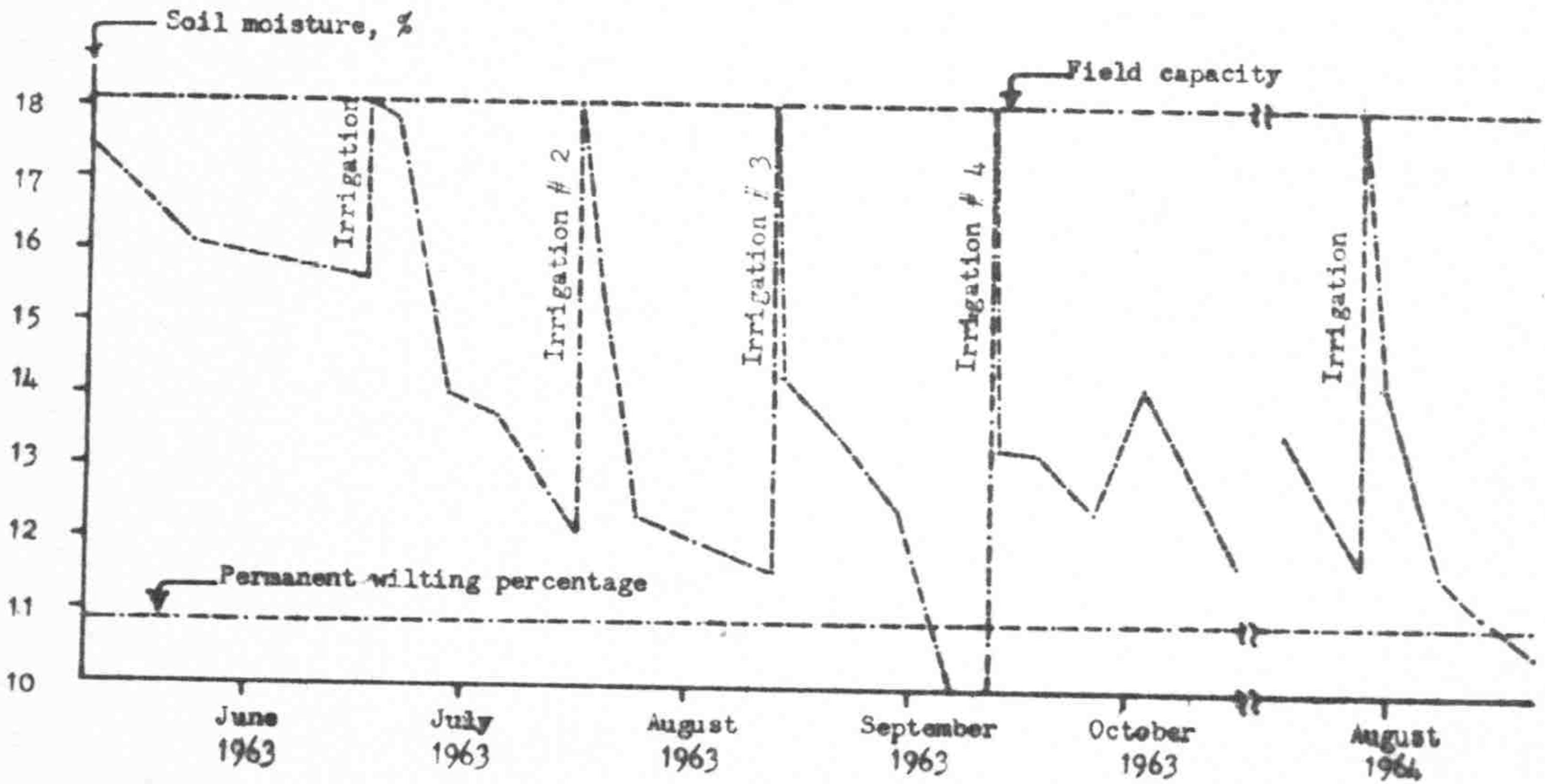

Figure 4. Variations in soil moisture content throughout the growing season in the middle 40 centimeters of soil. Apple orchard, Dahr-al-Baydar, Lebanon 1963, 64.

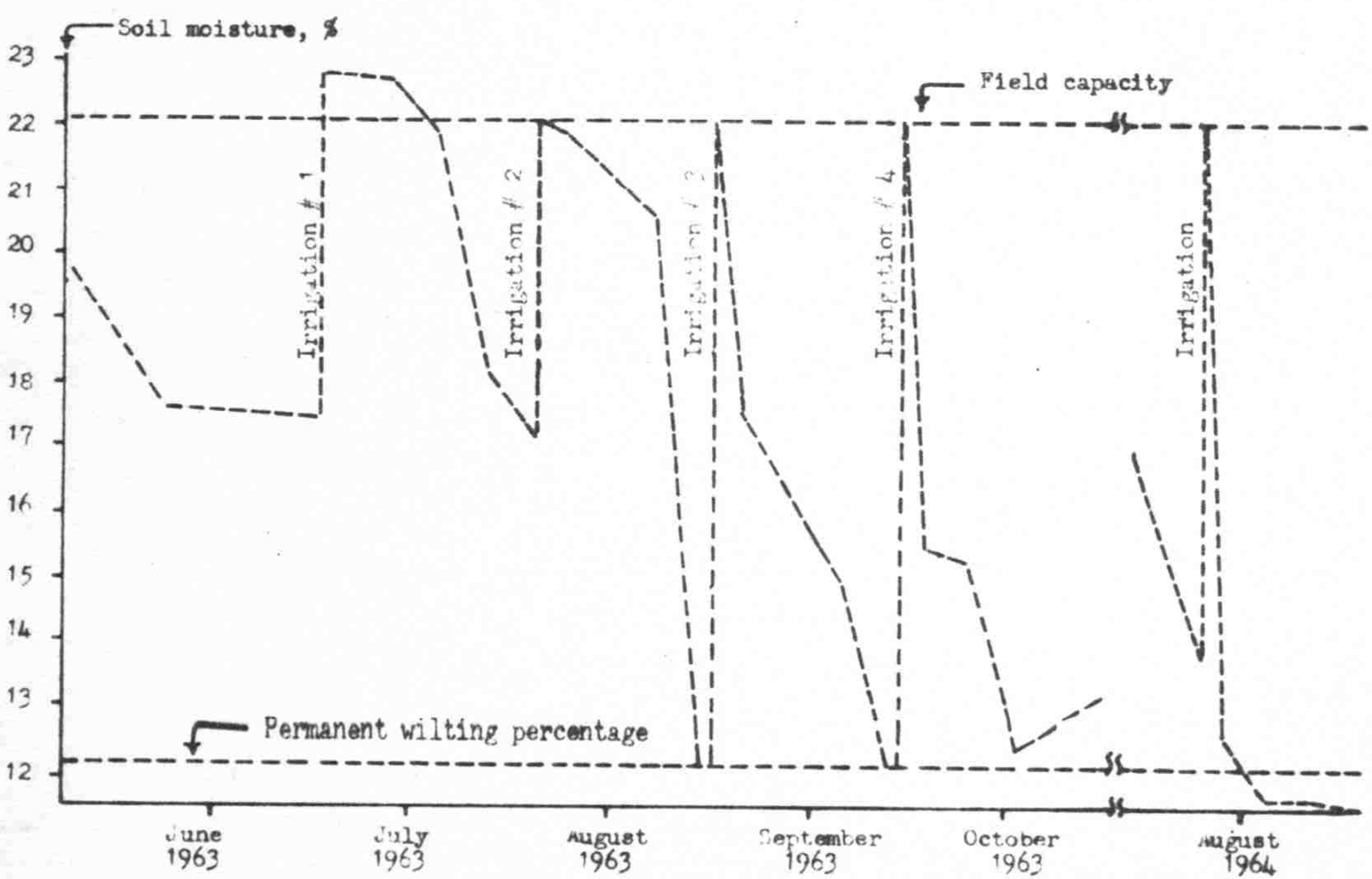

Figure 5. Variations in soil moisture content throughout the growing season in the lower 40 centimeters of soil. Apple orchard, Dahr-al-Baydar, Lebanon 1963, 64.

in the available soil moisture between the beginning and end of the growing season. By referring to Table 15 in the appendix it is possible to calculate this value from storage as 91.80 millimeters. The second consideration is that of the total horizontal projection of the area of each terrace, considering a depth of one meter, 20 percent is made up of stone walls. This part of the surface does not consume all the water it receives but contributes a large part of it to the adjoining soil.

The total water use was less than that found by Jensen *et al*. (34) and that reported by Israelson and Hansen (31) which might be due to different climatic environments. But assuming similar general climatic conditions this may further be attributed to the fact that the irrigation interval was too long and in such cases the plant might limit its transpiration (32 , 56). Available moisture content in the Jensen *et al*. experiment was kept at 75 percent throughout the growing season.

The average daily rates of water use in millimeters were 4.51, 3.86, 3.78, 1.95 and 1.88 during the months of August, July, September, May and June respectively. Maximum rate of water use was observed during a 6-days irrigation interval in August and it was 7.63 millimeters per day (Table 2).

The average daily rate of water use for the months of July, August, and September was in agreement with the

Table 2. Soil moisture use by direct soil sampling. Apple orchard, Dahr-al-Baydar, Lebanon, 1963.

Date of irrigation	Date of soil sampling	Interval (days)	% Change in soil moisture content (Average of 4 samples): Top 40 cms.	Middle 40 cms.	Lower 40 cms.	Water use from three layers: Total per interval (mm.)	Rate (mm/day)
	May 9						
(Rain) 0.8 mm.		15	3.14	1.42	2.21	36.00[x]	2.45
	May 24						
(Rain) 10.0 mm.		22	1.22	0.43	0.13	9.58[x]	0.89
	June 15						
June 17		6	0.51	2.25	0.05	15.44	2.57
	June 21						
		7	0.70	3.87	0.07	25.47	3.64
	June 28						
		7	0.25	0.34	0.82	7.42	1.06
	July 5						
		7	1.65	1.03	3.47	32.30	4.61
	July 12						
July 16		7	2.52	2.41	1.11	32.48	4.64
	July 19						
		5	2.63	3.03	0.63	34.05	6.81
	July 24						
		14	4.03	0.53	1.31	31.23	2.23
	Aug. 7						
Aug.12		6	1.98	0.29	6.55	45.77	7.63
	Aug. 13						
		8	4.34	0.82	5.00	53.40	6.68
	Aug. 21						
		8	0.76	1.02	1.27	16.21	2.03
	Aug. 29						
		7	2.33	2.21	1.15	30.58	4.37
	Sept. 5						
Sept.11		7	2.21	1.92	2.62	35.80	5.12
	Sept.12						
		6	1.27	0.11	1.23	13.71	2.29
	Sept.18						
(Rain) 16.6 mm.		7	----	0.72	0.25	5.25[x]	3.12
	Sept.25						
		7	2.60	----	2.76	28.28	4.01
	Oct. 2						
		13	0.64	2.49	----	17.18	1.32
	Oct. 15						
Total						497.55[xx]	

[x] Exclusive of rain, which was included in calculation of daily rate.

[xx] Includes 27.4 millimeters of precipitation.

maximum rate of water use for a 40-day period found by Wilcox et al. (75) in Canada, but less than that found by Jensen et al. (34), probably because of the relatively high soil moisture content maintained by them throughout their experiment.

Total water use from each of the three soil layers did not vary significantly. It was 175.7, 137.4 and 156.8 millimeters from the top, middle and lower 40 centimeter layers. This is probably due to the combination of several factors namely deficiency in available soil moisture, variations in soil texture and fluctuations in air temperatures..

Early in the season, when there was enough available moisture throughout the soil profile, it was found that the rate of depletion in soil moisture was highest in the top 40 centimeters followed respectively by the middle and lower 40 centimeters. (Figures 3, 4 and 5). These results were in agreement with Wilcox and Mason (74) and Aldrish et al. (2) who found that the rate of consumptive use was fastest in the top foot and decreased progressively with increases in depth. This was probably due to a higher concentration of fibrous roots (2, 29) better aeration (21) and warmer soil temperature (44) in the top 40 centimeters. Kramer (37) reported that lower temperatures and unfavorable CO_2/O_2 ratio reduce the rate of water absorption by plant roots.

As the soil in the top 80 centimeters dried out, the plant adjusted itself by getting more water from below the top 80 centimeters. (Figures 3, 4, and 5). Thus a reduction in the consumptive use due to the lack of available soil moisture in the top 80 centimeters of soil was accompanied by an increase in the consumptive use from the lower 40 centimeters. These results are in agreement with the findings of Wilcox and Mason (74).

The rate of soil moisture depletion from the top layer measured immediately after irrigation in July and August was faster than that in June and September (Table 2, Figures 3, 4, and 5). This was due to the high temperatures that prevailed in July and August which produced higher evaporation rates from the top soil layer. Moreover, higher temperatures increase the rate of water absorption (37).

The total water use from the lower 40 centimeters was more than that from the middle 40 centimeters (Table 2). This was due to the heavier texture of the lower 40 centimeters and subsequent increased water holding capacity. In addition to this there may be a higher concentration of fibrous roots in the lower layer (74).

Bouyoucos resistance units

Changes in the available soil moisture as measured by the Bouyoucos gypsum resistance units are shown in Figure 6 and Table 3. In general these were in agreement with the changes in soil moisture content as determined by

Table 3. Actual soil moisture, estimated available moisture by resistance units and soil moisture tension, at 3 different depths. Apple orchard, Dahr-al-Baydar, Lebanon, 1963.

Date	Top 40 cms.			Middle 40 cms.			Lower 40 cms.		
	% Soil moisture content[1]	% Available soil moisture[2]	Soil moisture tension[3] atm.	% Soil moisture content	% Available soil moisture	Soil moisture tension atm.	% Soil moisture content	% Available soil moisture	Soil moisture tension atm.
May 9	16.95	99	1.9	17.56	94	<0.33	19.8	93.75	1.33
May 24	13.81	97.5	6.0	16.14	100	0.33	17.59	97.75	2.80
June 15	12.59	16.25	14	15.71	83.75	0.70	17.46	100	2.90
June 21	16.19	88.25	2.4	17.95	80.25	<0.33	22.73	95.5	0.33
June 28	15.49	71.75	2.80	14.08	78.5	3.10	22.66	67.25	0.40
July 5	15.24	14.00	3.00	13.74	69.5	3.80	21.84	55.5	0.60
July 12	13.59	1.75	7.50	12.71	33.5	5.8	18.37	43.0	2.20
July 19	18.04	76.25	1.40	15.38	29.75	1.1	17.26	80.5	3.20
July 24	15.41	47.25	2.90	12.35	26.5	6.70	21.84	40.5	0.50
Aug. 7	11.38	0	>15	11.82	0	8.00	20.53	50.0	1.00
Aug. 13	17.75	75	1.50	14.31	75	2.70	13.98	42.5	>15.00
Aug. 21	13.41	52.75	8.00	13.49	68.75	4.20	17.36	16.0	3.07
Aug. 29	12.65	2.25	13.00	12.47	11.75	6.40	16.09	4	4.70
Sept. 5	10.32	0	>15	10.26	2.5	14.20	14.94	25	>15.00
Sept. 12	16.41	75	2.3	13.32	50	4.6	12.32	34	>15.00
Sept. 18	15.14	75	3.10	13.21	50	4.80	15.49	26.75	7.70
Sept. 25	15.33	67	3	12.49	47.5	6.40	15.24	10.5	13.67
Oct. 2	12.73	0	12.20	14.23	5.5	2.90	12.48	0	>15
Oct. 15	12.09	0	15.00	11.74	0	8.10	13.23	0	>15

1. Actual soil moisture content determined by oven drying.
2. Reading of Bouyoucos Moisture Meter.
3. Interpolated reading from Sorption Curve.

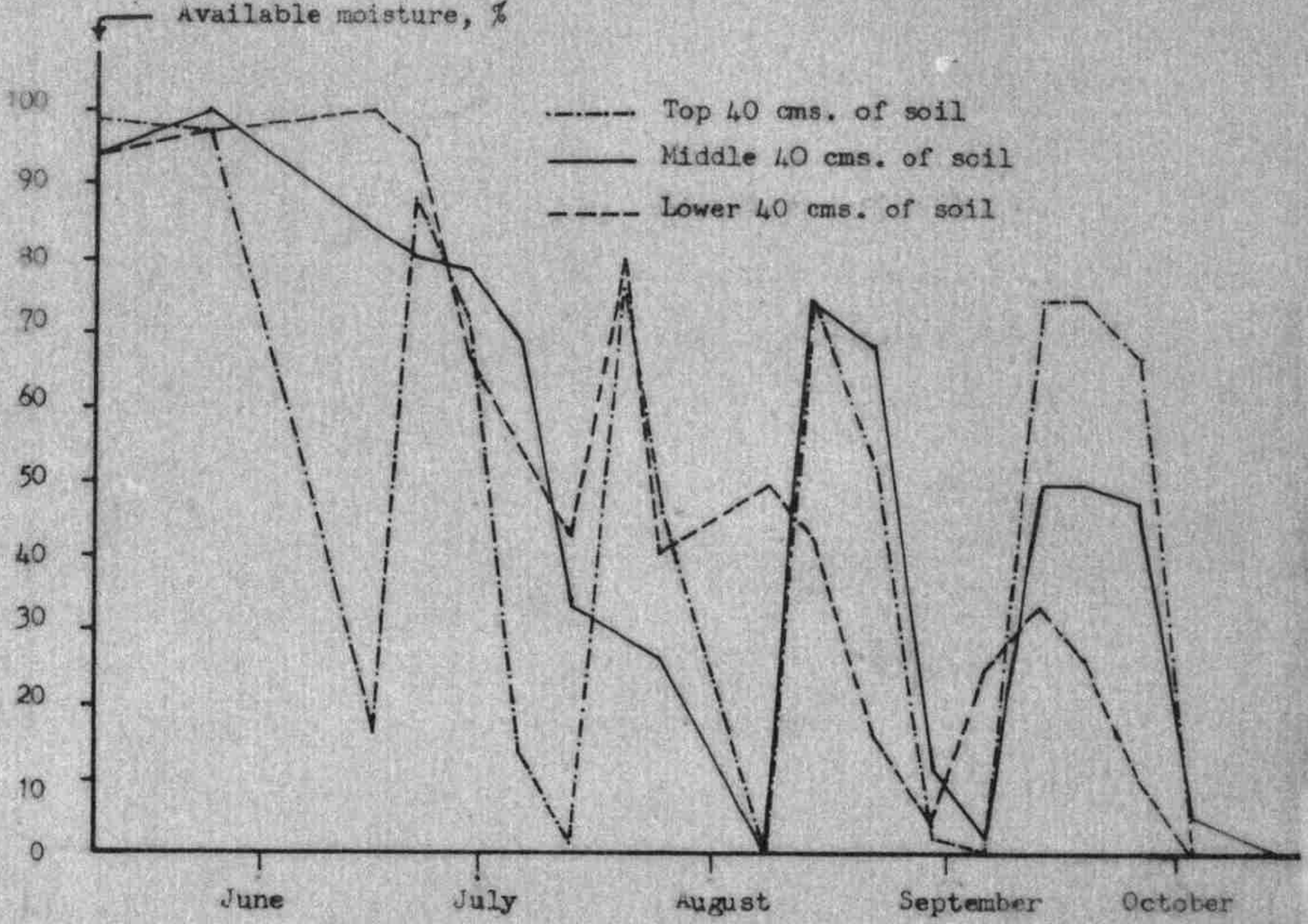

Figure 6. Variations in the available soil moisture throughout the growing season in the top, middle and lower 40 cms. of soil as measured by Bouyoucus resistance units, Apple orchard , Dahr-al-Baydar, Lebanon 1963.

the gravimetric method (Table 3).

The correlation between available soil moisture as determined by the resistance units and soil moisture content as determined by the gravimetric method was significant for the top, middle and lower 40 centimeter layers (Table 4). This result is in agreement with the findings of Colman and Hendrix (14) who found that in direct calibration, the electrical resistance of the cell is directly correlated to the moisture percentage of the surrounding soil.

Table 4. Correlation between percentage soil moisture determined by the gravimetric method and the percentage available soil moisture estimated by Bouyoucos resistance units. Apple orchard, Dahr-al-Baydar, Lebanon, 1963.

	r	t value	p value
Top 40 centimeters of soil	.78	5.14 xx	.001
Middle 40 centimeters of soil	.75	4.73 xx	.001
Lower 40 centimeters of soil	.59	3.01 xx	.001-.01

xx Statistically significant at 1% level.

Regression lines relating available soil moisture and the soil moisture content for the top, middle and lower 40 centimeter layers are shown in Figure 7. By knowing the depletion in the available soil moisture in a given interval, the depletion in soil moisture content can be found. Water use can be found by multiplying the depletion

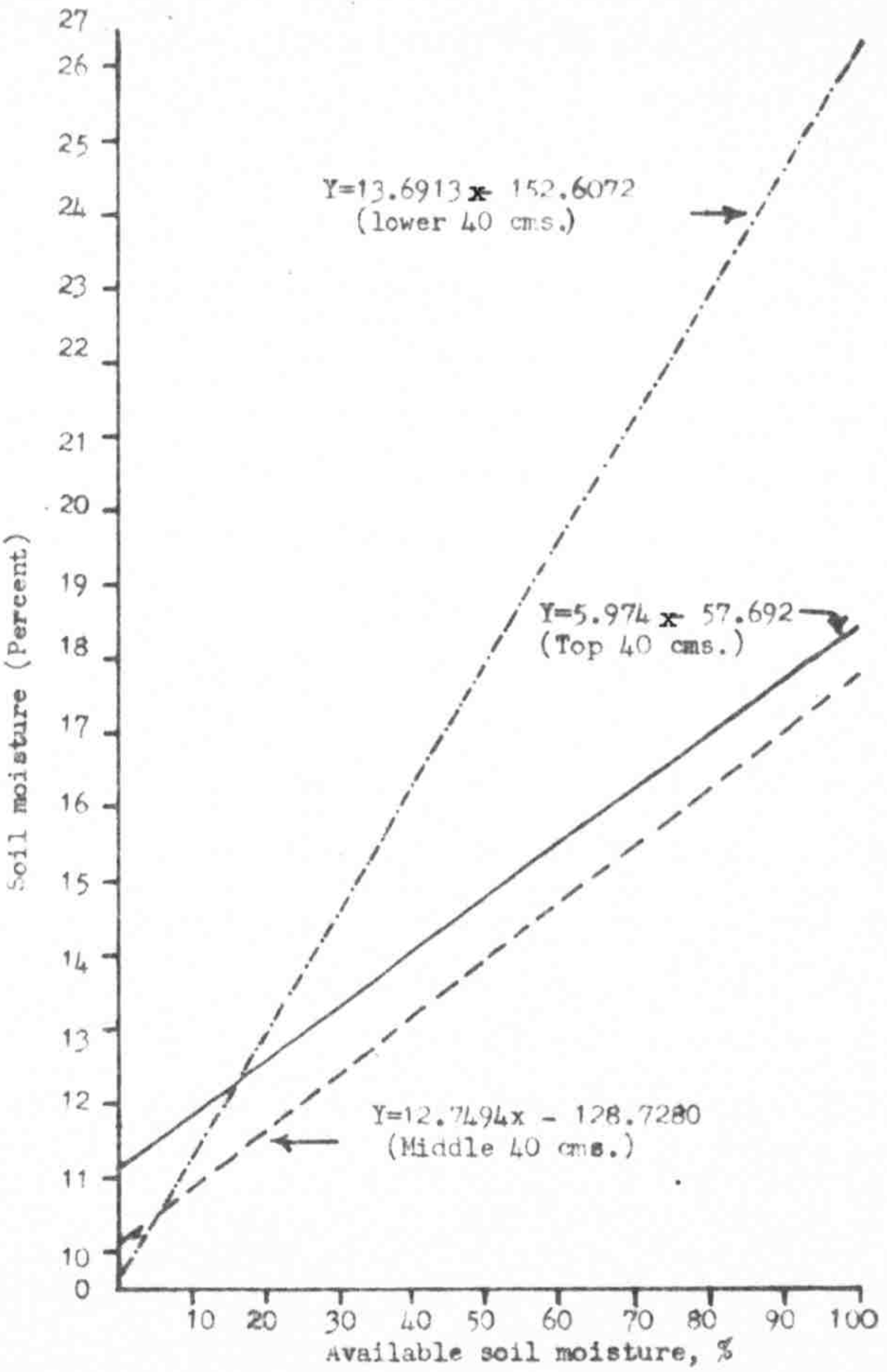

Figure 7. Relationship between soil moisture content and estimated available moisture by resistance units. Apple orchard, Dahr-al-Baydar, Lebanon 1963.

in the soil moisture content by the product of bulk density and depth. It appears from this study that the Bouyoucos resistance units may be used in determining water use and consequently the time of irrigation.

Estimated available soil moisture by soil moisture tension

Data in Table (3) show that, in general, soil moisture tension was more than one atmosphere. Therefore under such conditions tensiometers are not a suitable device for measuring the available soil moisture.

Water use by the neutron scattering method

Table 5 gives the determined rates of water use using the neutron scattering method, for five weekly intervals from July 16th to August 20th, 1964. These range from 2.10 to 4.57 millimeters with an average, for the whole period, of 3.17 millimeters per day. Water use, as determined by the gravimetric method for the same period ranged from 1.07 to 3.76 millimeters with an average of 2.72 millimeters per day for the whole period.

Table 5. Water use as determined by the neutron scattering method. Apple orchard, Dahr-al-Baydar, Lebanon, 1964.

Irrigation date	Soil moisture measuring date	Interval (day)	% Change in soil moisture content: Top 40 cms. (Average of 4 samples)	Middle 40 cms.	Lower 40 cms.	Water use: Total per interval mm.	Average daily rate mm.
June 21							
	July 16						
		7	1.1007	0.6159	1.0547	14.70	2.10
	July 23						
July 27		7	2.0224	1.2659	1.4766	25.41	3.63
	July 30						
		7	1.0075	1.4493	1.8750	23.00	3.29
	Aug. 6						
		7	2.500	1.8659	1.6211	32.00	4.57
	Aug. 13						
		7	1.3993	0.7609	0.8203	15.90	2.27
	Aug. 20						

Table 6 shows a comparison of both water use rates together with the differences in evaporation from black and white atmometers. Except for the interval from August 6 to 13, there seems to be close agreement in the values obtained by the two methods and the ratio between the total use as determined by each method is 1.11. The lack of agreement during this particular interval (August 6 to 13) is probably due to faulty operation of the neutron probe, since the climatic data, and the atmometers, indicate that it was a period of lower potential evapotranspiration than all other intervals, while the rate as determined by the neutron probe is the highest.

Table 6. Comparison of water use by gravimetric and neutron scattering method and differences in evaporation from black and white atmometers. Apple orchard, Dahr-al-Baydar, Lebanon, 1964.

Period	Water use		Ratio of gravimetric to neutron scattering	Difference in evaporation from black & white atmometers
	Gravimetric mm/day	Neutron scattering mm/day		cc/day
July 16 - 23	2.64	2.10	1.26	17.70
July 23 - 30	3.57	3.63	0.98	15.74
July 30-Aug.6	3.76	3.29	1.15	14.33
Aug. 6 - 13	1.07	4.57	0.23	13.46
Aug. 13 - 20	2.57	2.27	1.13	14.66

The total water use for this period as determined by the neutron scattering method for the top, middle and lower 40 centimeter layers was 43.04, 32.89 and 35.06 millimeters, respectively. These results do not differ significantly from those found by the gravimetric method which were 31.75, 36.24 and 27.30 millimeters for the top, middle and lower 40 centimeter layers. However correlations between rates of water use (excluding the August 6 to 13 interval) as determined by both methods were not significant while those between water use by the gravimetric method and the counting rate of neutrons were significant for the top 80 centimeters of the soil but again not significant for the lower 40 centimeters. Since in the neutron scattering method water use was determined by using the special laboratory calibration curve established for another soil and the neutron counting rate, it is reasonable to assume that the calibration curve is faulty. This however does not explain the lack of correlation for the lower 40 centimeter layer. The result in the top 80 centimeter layer were in agreement with those of Gardner and Kirkham (22) and Mc Guinness *et al*. (45).

Estimated water use by empirical equations

Table 7 gives the estimated potential evapotranspiration for the 1963 season as determined by the Penman and Blaney-Criddle equations. It also gives the actual evapotranspiration as determined by the gravimetric method

Table 7. Actual evapotranspiration and estimated potential evapotranspiration. Apple orchard, Dahr-al-Baydar, Lebanon, 1963.

Period	Actual evapo-trans-piration (mm/day)	Estimated potential evapotranspiration				Difference in evaporation from black & white atmometers	
		Penman		Blaney-Criddle			
		E_o [x] (mm/day)	Actual/Estimated	$(\frac{tP}{100})$ [xx] (mm/day)	Actual/Estimated	(cm^3/day)	C [xxx]
May 9-24	2.45	4.26	0.57	4.15	0.59	12.19	0.20
May 24-June 15	0.89	5.83	0.15	4.70	0.19	15.18	0.06
June 15-21	2.57	7.67	0.34	5.12	0.50	15.54	0.17
21-28	3.64	7.44	0.49	5.42	0.67	20.09	0.18
28-July 5	1.06	7.00	0.15	5.30	0.20	17.26	0.06
July 5-12	4.61	6.42	0.72	5.09	0.91	18.46	0.25
12-19	4.64	7.62	0.61	5.47	0.85	19.33	0.24
19-24	6.81	7.33	0.93	5.31	1.28	17.18	0.40
July 24-Aug. 7	2.23	7.38	0.22	5.26	0.42	18.02	0.12
Aug. 7-13	7.63	7.44	1.03	5.14	1.48	16.97	0.45
13-21	6.68	7.58	0.88	5.53	1.21	17.38	0.38
21-29	2.03	6.73	0.30	5.29	0.38	16.81	0.12
Aug. 29-Sept.5	4.37	6.10	0.72	4.81	0.91	16.38	0.27
Sept. 5-12	5.12	5.83	0.88	4.80	1.07	16.00	0.32
12-18	2.29	4.95	0.46	4.56	0.50	11.65	0.20
18-25	3.12	3.51	0.89	4.16	0.75	11.07	0.28
Sept.25-Oct. 2	4.01	4.25	0.94	4.69	0.86	11.62	0.35
Oct. 2-15	1.32	4.04	0.33	4.26	0.31	12.22	0.11

x E_o is the estimated evaporation from a free water surface per day according to Penman equation.

xx tP/100 is the estimated potential evapotranspiration according to Blaney-Criddle formula.

xxx C is the ratio between water use in millimeters per day and the difference in evaporation from black and white atmometers in cubic centimeters per day.

and the average daily difference in evaporation from black and white atmometers. This latter figure, though not given in comparable figures, might be used as an indicator of potential evapotranspiration and will be treated as the figures obtained by Penman and Blaney-Criddle. These estimates are expressed on a daily basis for each period. Figure 8 shows the same data in a continuous graph form.

The data in Table 8 and Figure 9 indicate a highly significant correlation between potential evapotranspiration as measured by the three methods, although generally they give different results (47, 69). This may be due to the low variability of the radiation and mean temperatures for all periods during the growing season in this special situation. Moreover, the lag of temperature behind radiation (which arises from the thermal storage of the soil) which causes great error on monthly estimates of evapotranspiration may be very low (47).

Table 8. Correlation between estimated potential evapotranspiration as measured by Penman, Blaney-Criddle and the difference in evaporation from black and white atmometers throughout the growing season, Apple orchard, Dahr-al-Baydar, Lebanon, 1963.

Methods	r	t value	p value
Atmometers vs Penman	0.8964	8.0884 xx	.001
Atmometers vs Blaney-Criddle	0.8893	7.778 xx	.001
Penman vs Blaney-Criddle	0.9416	11.1829 xx	.001

xx Statistically significant at 1% level.

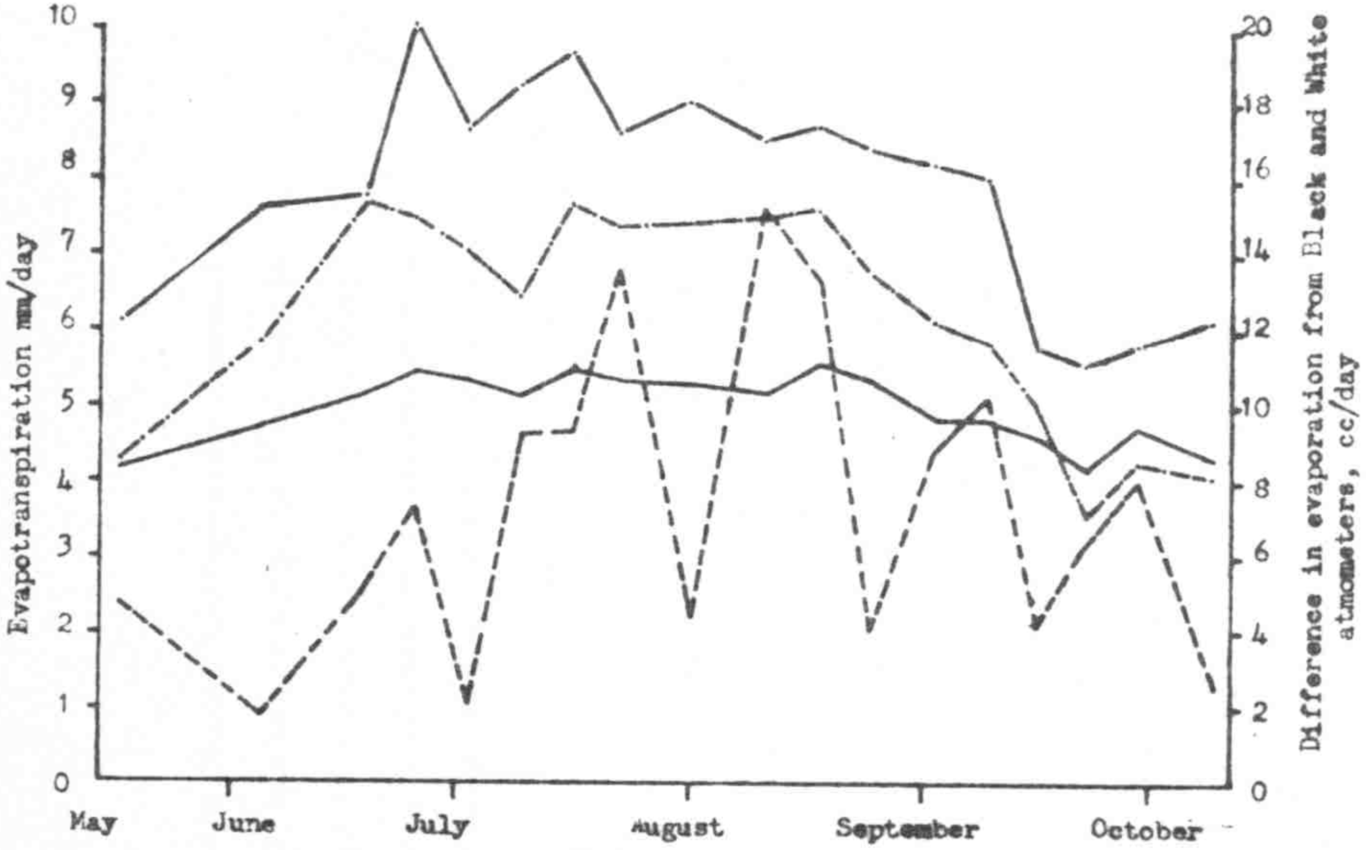

Figure 8. Actual evapotranspiration and estimated potential evapotranspiration. Apple orchard, Dahr-al-Baydar. Lebanon 1963.

- - - Actual water use — — Atmometer difference
—— P.E.T. by Blaney Criddle -·-·- P.E.T. by Penman

Correlation between actual and estimated water use

Table (9) shows that the correlations between actual evapotranspiration as determined by direct soil sampling and potential evapotranspiration calculated by the three methods were not significant. These relationships are also shown in figure 10. Since the orchard went through periods of deficient soil moisture it was assumed that this lack of correlation was due to the reduced rates of water use during these periods of water shortage.

Table 9. Correlation between actual evapotranspiration and estimated potential evapotranspiration throughout the growing season. Apple orchard, Dahr-al-Baydar, Lebanon, 1963.

Methods	r	t value	p value
Actual vs Penman	0.3295	1.3955	.1-.2
Actual vs Blaney-Criddle	0.3923	1.7060	.1-.2
Actual vs Atmometers	0.3878	1.6829	.1-.2

However Table 10 shows that the correlations between actual and estimated water use during the intervals when the plants were not short of water, again were not significant.

The lack of correlation between actual evapotranspiration and estimated potential evapotranspiration as determined by the difference in atmometers is in agreement with the results of Stork in Iraq (62), but not in

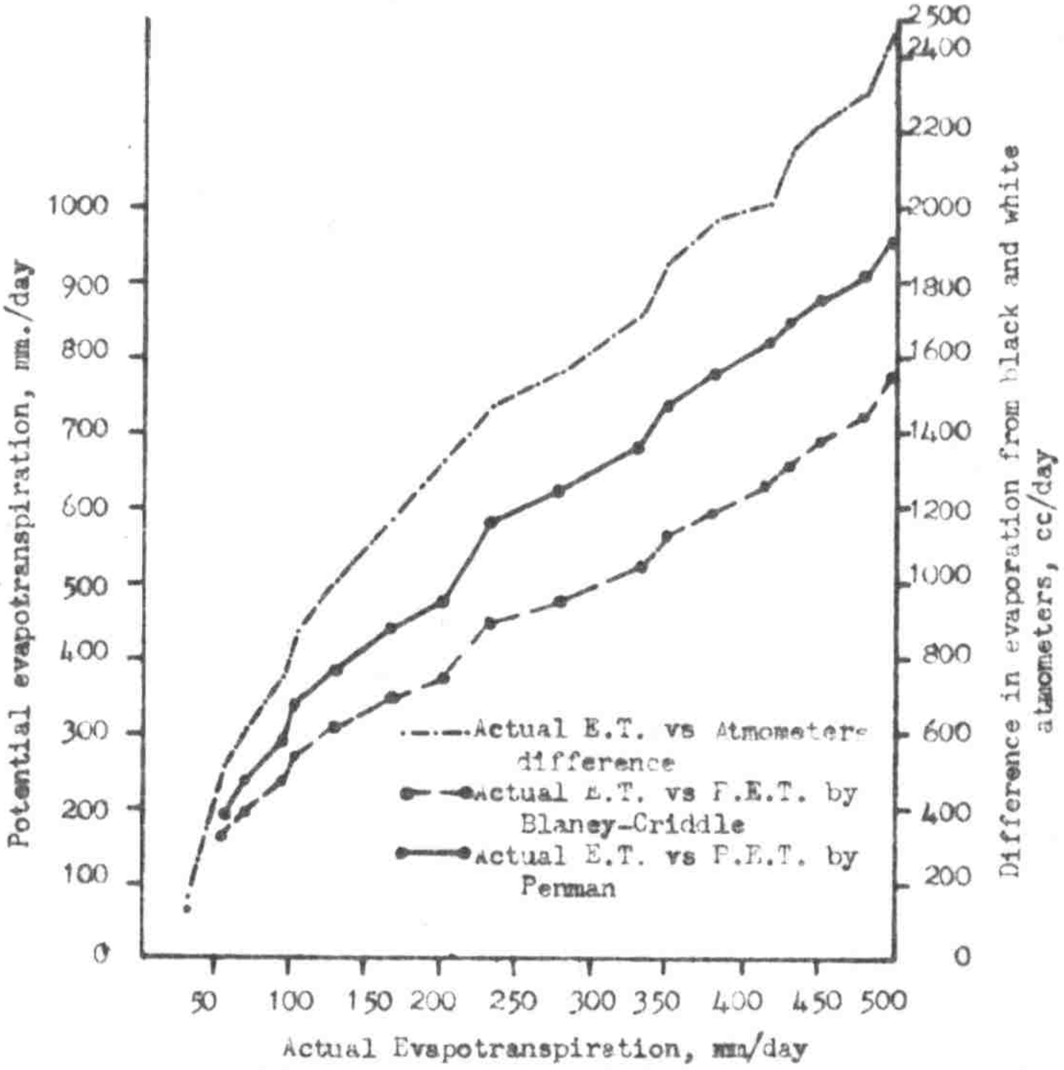

Figure 10. Relationship between actual and estimated potential evapotranspiration, Apple orchard, Dahr-al-Baydar, Lebanon 1963

agreement with those of Halkias _et al_.(26).

The lack of correlation between actual evapotranspiration and that estimated by Blaney-Criddle does not agree with the work of Pruit (53).

Table 10. Correlation between actual evapotranspiration and estimated potential evapotranspiration during period of high soil moisture content. Apple orchard, Dahr-al-Baydar, Lebanon, 1963.

Period	Actual water use	Estimated potential evapotranspiration		Difference in atmometers
		Penman	Blaney-Criddle	
	Millimeters per day			cc/day
May 9 to 24	2.40	4.26	5.06	12.19
June 21 to 28	3.64	7.44	6.40	20.09
July 19 to 24	6.81	7.33	6.48	17.18
Aug. 13 to 21	6.67	7.58	6.75	17.38
Sep. 12 to 18	2.29	4.95	5.38	11.65
Correlation Factor (r)		0.8108	0.8627	0.6025
t value		2.40	3.15	1.31
p value		0.1-.05	0.1-.05	.2-.3

The ratio of actual evapotranspiration to estimated potential evapotranspiration for each interval during the growing season is shown in Table (7). In the case of Penman's equation it varies from 0.15 to 1.03 with an average of 0.52 for the whole growing season. According to Penman (49) this ratio is 0.8 in the months of May to August and 0.7 in September and October, with 0.75 for the whole growing season. The ratio varies from 0.19 to 1.48 in the case of Blaney-Criddle equation with an average of 0.64 for the whole growing season. This ratio for the whole growing season is in agreement with Blaney (6) who reported that the ratio was 0.65 all through the growing season. The ratio varies from 0.06 to 0.45 with an average of 0.20 for the whole growing season in the case of differences in evaporation from black and white atmometers. According to Halkais <u>et al</u>. (26) this ratio was 0.26 throughout the growing season.

SUMMARY AND CONCLUSIONS

The immediate objective of this investigation was to evaluate a certain irrigation practice and to determine the rate of water use by apple trees through direct methods and climatic data. The ultimate objective is to establish a field technique for evaluating irrigation practices, mainly in apple orchards and to recommend measures for their improvements.

Changes in the soil moisture content throughout the growing season were determined by regular periodic sampling of the soil, by the use of Bouyoucos gypsum resistance units and the neutron scattering method. The Blaney-Criddle formula, the Penman equation and the difference in evaporation between black and white atmometers were used to estimate water use.

In general, the irrigation of the orchard was unsatisfactory, because the soil moisture was allowed to reach the permanent wilting percentage and even below it during the growing period of the crop. The quantities applied in each irrigation were adequate, but the interval between irrigations was too long. More frequent irrigations would have resulted in a satisfactory irrigation practice.

In 1963, the daily average rate of actual water use as determined by the gravimetric method ranged from 0.89 to 7.63 millimeters with an average of 3.12 millimeters for the whole growing season. Maximum daily rate of water use was 7.63 millimeters. The total seasonal use was 49.76 centimeters or 497.6 cubic meter per dunum of orchard. Since the orchard was underirrigated, it would seem advisable to recommend a larger value of water for proper irrigation of apple orchards. The exact increase over this figure would require further research for its determination.

Early in the season the rate of water use was greatest from the shallow depths of the root zone and decreased with increase in depth. As the top 40 centimeters of the soil became deficient in available moisture, the rate of water use increased in the lower layers and by the end of growing season almost all of the soil down to 120 centimeters had reached the permanent wilting percentage.

A highly significant positive correlation was obtained between percentage soil moisture as determined by the gravimetric method and the available soil moisture as measured by resistance gypsum units for the whole soil profile down to 120 centimeters of soil.

Correlations between rates of potential evapotranspiration as estimated by the Blaney-Criddle formula, Penman equation, and difference in evaporation from black and white atmometers were highly significant, but the correlations between rates of actual water use and estimated potential evapotranspiration rates were not significant.

In the period July 16th to August 20th, 1964, the average daily rate of actual water use as determined by the gravimetric method was compared with that determined by the use of neutron scattering method. The ratios between these rates, excluding a period of suspected malfunctioning of the neutron probe, ranged from 0.98 to 1.26 with an average of 1.11.

The correlation between percentage soil moisture content as determined by the gravimetric method and the counting rate of neutrons was significant for the top 80 centimeters of soil but not significant for the lower 40 centimeters.

On the basis of the results of this study it appears that the irrigation practice was not satisfactory. Bouyoucos gypsum resistance units proved to be a reliable device for measuring water use indirectly and consequently for indicating the time of irrigation. The Blaney-Criddle method gave closer estimates of the total water use than either the Penman equation or the difference in evaporation from black and white atmometers. The neutron scattering method if used with field calibration curves would probably give satisfactory results with the added advantage of reduced field work and effort. However, the high cost of such equipment places it beyond the reach of the average apple producer.

This work should be repeated for many more years and in several other areas. Then it would be possible to embark on the ultimate objective which is predicting the time of irrigation and the water quantities required.

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Table 11. Relation between bulk density in the top, middle and lower 40 centimeter layers. Dahr-al-Baydar, Lebanon, 1963.

Difference between means of bulk density	t value	p value
Top 40 cms. vs Middle 40 cms.	1.3795	0.2-0.4
Top 40 cms. vs Lower 40 cms.	0.8269	0.4-0.5
Middle 40 cms. vs Lower 40 cms.	2.2762	0.05-0.10

Table 12. Relation between field capacity in the top, middle and lower 40 centimeter layers. Dahr-al-Baydar, Lebanon, 1963.

Difference between means of F.C.	t value	p value
Top 40 cms. vs Middle 40 cms.	1.9683	0.100-0.200
Top 40 cms. vs Lower 40 cms.	2.7798	0.02 -0.05
Middle 40 cms. vs Lower 40 cms.	3.9603	0.02 -0.05

x Statistically significant at 5% level.

Table 13. Daily maximum, minimum, and average temperature during themonths of May to October, 1963. Apple orchard, Dahr-al-Baydar, Lebanon.

Day	May			June			July		
	Max.	Min.	Aver.	Max.	Min.	Aver.	Max.	Min.	Aver.
1	6.2	2.8	4.5	14.2	9.8	12.0	20.7	14.6	17.6
2	9.8	3.8	6.8	14.7	7.6	11.2	17.6	11.8	14.7
3	12.2	4.2	8.2	17.1	7.6	12.4	19.1	11.8	15.4
4	12.5	7.8	10.2	21.8	10.3	16.0	21.8	13.5	17.6
5	13.0	5.8	9.4	24.8	15.3	20.0	19.9	13.7	16.8
6	13.0	7.8	10.4	21.2	15.3	18.2	18.3	12.4	15.4
7	14.8	7.8	11.3	27.7	15.8	21.8	20.0	13.4	16.7
8	15.8	8.0	11.9	20.0	13.2	16.6	20.0	14.8	17.4
9	14.0	9.0	11.5	16.0	8.2	12.1	20.2	14.5	17.4
10	9.2	5.5	7.4	13.4	7.8	10.6	22.0	15.0	18.5
11	9.2	5.7	7.5	14.6	7.3	11.0	22.0	15.0	18.5
12	15.0	5.0	10.0	20.8	10.0	15.4	23.7	16.1	19.9
13	21.2	11.6	16.4	23.0	14.2	18.6	23.6	18.0	20.8
14	13.8	9.6	11.7	21.4	14.3	17.8	23.8	17.3	20.6
15	12.0	5.0	8.5	17.2	10.3	13.8	22.8	16.8	19.8
16	12.0	5.8	8.9	18.8	12.8	15.8	22.6	15.3	19.0
17	14.7	4.4	9.6	22.0	14.5	18.2	23.2	16.0	19.6
18	20.0	10.0	15.0	26.8	19.3	23.0	22.7	15.8	19.2
19	20.0	8.0	14.0	23.0	13.0	18.0	20.8	14.0	17.4
20	10.4	5.8	8.1	15.8	9.2	12.5	23.0	13.3	16.8
21	15.0	5.7	10.4	17.8	11.6	14.7	21.7	16.0	18.8
22	23.4	11.2	17.3	21.6	11.8	16.7	22.2	18.0	20.1
23	13.8	8.5	11.2	23.8	15.6	19.7	23.4	17.0	20.2
24	13.0	4.8	8.9	24.8	18.4	21.6	23.0	16.7	19.8
25	21.8	8.2	15.0	21.8	15.2	18.5	20.8	14.0	17.4
26	15.8	8.9	12.4	23.2	15.0	19.1	22.3	14.0	18.2
27	12.8	6.3	9.6	26.3	17.1	21.7	21.8	15.3	18.6
28	11.0	7.0	9.0	27.2	19.7	23.4	21.8	15.8	18.8
29	13.7	6.0	9.9	25.0	18.3	21.0	21.8	16.0	18.9
30	22.2	10.8	16.5	23.8	14.8	19.3	23.8	18.1	21.0
31	22.6	14.8	18.7				23.2	15.8	19.5

Table 13 continued.

Day	Months								
	August			September			October		
	Max.	Min.	Aver.	Max.	Min.	Aver.	Max.	Min.	Aver.
1	23.8	18.1	21.0	24.4	17.7	21.0	23.9	17.4	20.6
2	23.7	16.0	19.8	21.8	15.6	18.7	24.3	17.1	20.3
3	23.2	15.5	19.4	22.1	13.0	17.6	23.0	14.6	18.8
4	23.0	15.9	19.4	21.8	15.0	18.4	19.4	12.5	16.0
5	22.0	17.0	19.5	24.0	16.1	20.0	19.6	13.4	16.5
6	22.7	17.0	19.8	23.4	16.7	20.0	21.3	14.5	17.9
7	23.0	16.5	19.8	24.0	17.0	20.5	24.0	15.3	19.6
8	23.3	17.0	20.2	27.0	15.4	21.2	25.5	16.2	20.8
9	23.9	13.9	18.9	24.2	16.2	20.2	26.1	18.1	22.1
10	22.9	16.7	19.8	23.0	16.7	19.8	24.5	19.0	21.8
11	23.3	16.8	20.0	22.3	13.2	17.8	22.4	14.6	18.5
12	23.0	15.0	19.0	25.3	15.6	20.4	21.4	14.3	17.8
13	22.7	17.0	19.8	24.0	16.0	20.0	22.3	14.6	18.4
14	23.3	16.3	19.8	19.6	15.0	17.3	19.1	13.0	16.0
15	25.0	17.8	21.4	21.4	12.8	17.1	17.9	9.7	13.8
16	27.3	18.2	22.8	22.6	12.7	17.6	20.8	11.3	16.0
17	27.7	19.4	23.6	19.1	12.0	15.6	25.1	15.9	20.5
18	27.8	19.0	23.4	18.3	11.0	14.6	24.5	17.2	20.8
19	29.1	20.5	24.8	17.3	10.0	13.6	16.7	12.5	14.6
20	27.0	19.6	23.3	16.1	11.0	13.6	14.8	10.9	12.8
21	29.2	20.0	24.6	16.6	11.2	13.9	12.0	8.7	10.4
22	26.9	17.0	22.0	19.9	11.4	15.6	8.3	5.0	6.6
23	20.7	13.0	16.8	23.4	11.8	17.6	10.0	4.9	7.5
24	25.0	15.0	20.0	19.7	11.4	15.6	10.0	4.1	7.0
25	25.7	19.0	22.4	20.0	13.7	16.8	11.7	4.0	7.8
26	23.9	17.9	20.9	20.4	10.5	15.4	12.6	6.7	9.6
27	22.8	15.0	18.9	25.5	15.0	20.2	14.0	6.3	10.2
28	22.5	17.7	20.1	27.5	19.0	23.2	15.8	8.0	11.9
29	22.1	16.5	19.3	28.2	18.2	23.2	17.7	9.4	13.6
30	21.8	14.4	18.1	24.3	17.3	20.8	17.9	11.0	14.4
31	24.8	15.8	20.3				15.2	6.9	11.0

Table 14. Daily relative humidity, wind velocity, fraction of sky covered with clouds and precipitation during the months of May to October, 1963. Apple orchard, Dahr-al-Baydar, Lebanon.

Month	May				June			July		
Day	R.H.	u	m/10	ppt. mm.	R.H.	u	m/10	R.H.	u	m/10
1	96	362	0.96	6.2	65	436	0.50	47	222	0.13
2	90	389	0.67		82	181	0.33	67	295	0.38
3	75	107	0.54		50	128	0.13	85	369	0.29
4	64	121	0.67		57	168	0.25	69	242	0.17
5	80	114	0.25		35	128	0.42	66	262	0.21
6	88	130	0.58		46	161	0.25	92	268	0.50
7	69	141	0.62		27	262	0.38	77	228	0.08
8	74	201	0.67		50	376	0.21	57	329	0.08
9	85	87	0.62	0.4	80	349	0.33	63	322	0.08
10	96	342	0.83		69	403	0.42	54	322	0.00
11	98	382	0.83		77	376	0.50	50	322	0.00
12	76	222	0.17	0.8	62	141	0.00	53	282	0.00
13	52	215	0.62		36	275	0.00	50	396	0.00
14	82	322	0.50		56	497	0.00	54	336	0.00
15	78	309	0.38		52	349	0.25	60	235	0.13
16	72	295	0.38		29	376	0.00	52	242	0.08
17	86	154	0.17		37	349	0.00	56	161	0.21
18	38	128	0.21		34	201	0.00	43	289	0.00
19	71	309	0.71		47	396	0.04	68	289	0.17
20	97	389	0.88		58	342	0.50	68	383	0.29
21	71	161	0.50		66	188	0.13	50	383	0.42
22	40	201	0.08		62	208	0.04	56	450	0.00
23	81	201	0.50		55	114	0.00	55	383	0.08
24	57	208	0.38		54	195	0.00	56	275	0.04
25	38	188	0.46		57	309	0.00	60	181	0.17
26	68	383	0.21		47	228	0.00	54	228	0.08
27	82	349	0.71		40	208	0.00	66	329	0.08
28	95	302	1.00	10.0	38	128	0.00	58	322	0.04
29	87	222	0.38		38	242	0.00	54	329	0.17
30	56	47	0.50		55	302	0.00	45	329	0.04
31	33	295	0.00					46	282	0.13

Table 14 continued.

August			September				October			
R.H.	u	m/10	R.H.	u	m/10	ppt. mm.	R.H.	u	m/10	ppt. mm.
50	369	0.04	49	222	0.08		45	134	0.21	
55	336	0.04	72	389	0.18		38	94	0.08	
50	255	0.04	60	154	0.13		42	222	0.17	
46	309	0.04	66	221	0.04		64	287	0.21	
54	309	0.04	60	181	0.00		60	128	0.00	
48	302	0.00	58	221	0.00		59	87	0.00	
46	295	0.04	48	201	0.00		45	94	0.00	
50	564	0.00	47	161	0.00		37	141	0.17	
54	436	0.17	38	228	0.00		36	94	0.08	
54	329	0.13	56	208	0.08		44	101	0.04	
57	436	0.25	41	161	0.08		52	161	0.08	
61	362	0.25	28	101	0.00		37	208	0.17	
55	383	0.25	51	242	0.08		45	228	0.13	
48	416	0.04	65	221	0.21		59	228	0.33	
39	295	0.04	55	235	0.17		87	356	0.54	
40	168	0.04	66	161	0.17		43	161	0.50	
43	208	0.00	81	215	0.25		37	67	0.50	
40	201	0.00	84	195	0.29		38	168	0.83	5.5
51	201	0.00	85	195	0.25		70	255	0.96	3.1
30	396	0.00	84	262	0.75	11.9	86	403	1.00	7.9
36	208	0.00	90	242	0.62	1.5	96	456	0.83	14.5
42	161	0.29	66	121	0.13		97	456	1.00	32.2
64	315	0.50	58	362	0.67	3.2	89	315	0.75	9.6
56	369	0.21	66	107	0.21		90	175	0.54	6.4
38	329	0.04	71	121	0.42		84	13	0.79	
49	322	0.04	70	148	0.00		81	67	0.46	
42	309	0.13	41	87	0.00		69	47	0.33	
36	322	0.08	36	101	0.08		78	20	0.08	
41	396	0.13	34	141	0.13		61	87	0.17	
53	302	0.04	36	222	0.58		62	94	0.25	
62	148	0.00					77	248	0.46	18.0

Table 15. Water use by apple trees. Apple orchard, Dahr-al-Baydar, Lebanon, 1963.

Irrigation date	Sampling date	Top 40 cm. layer – Soil Moisture, % – Sample 1	Top – Sample 2	Top – Sample 3	Top – Sample 4	Top – Average of four samples	Water use – top 40 cm. layer – Actual – Per interval %	Top – Per interval cm.[x]	Top – Daily rate cm.[xx]	Top – Calculated[xx] daily rate cm.	Middle 40 cm. layer – Soil Moisture, % – Sample 1	Middle – Sample 2	Middle – Sample 3	Middle – Sample 4	Middle – Average of four samples	Water Use-Middle 40 cm. layer – Actual – Per interval %	Middle – Per interval cm.[x]	Middle – Daily rate cm.	Middle – Calculated daily rate cm.	Lower 40 cm. layer – Soil Moisture, % – Sample 1	Lower – Sample 2	Lower – Sample 3	Lower – Sample 4	Lower – Average of four samples	Water Use-Lower 40 cm. layer – Actual – Per interval %	Lower – Per interval cm.	Lower – Daily rate cm.	Lower – Calculated daily rate cm.	Daily rate of water use cm.[xxx]
	May 9	16.94	15.48	20.87	14.51	16.95					17.57	17.49	17.06	18.12	17.56					19.79	18.43	17.37	23.61	19.80					
							3.14	1.6830	0.1122							1.42	0.7838	0.0523							2.21	1.1315	0.0754		0.2399
	May 24	12.52	13.16	9.97	19.6	13.81					16.8	15.34	15.45	16.97	16.14					19.82	16.88	15.76	17.90	17.59					
							1.22	0.6539	0.0297							0.43	0.2374	0.0112							0.13	0.0666	0.0032		0.0441
	June 15	15.80	12.58	10.6	11.38	12.59					14.24	13.0	20.17	15.44	15.71					20.60	17.35	15.69	17.36	17.46					
June 17										0.0456									0.2072									0.0045	0.2573
	June 21	19.86	19.27	14.59	11.04	16.19					16.34	18.29	18.64	18.70	17.95					22.80	23.10	22.08	22.93	22.73					
							0.70	0.3752	0.0536							3.87	2.1362	0.3052							0.07	0.0358	0.0051		0.3639
	June 28	17.23	18.07	13.55	13.12	15.49					14.97	13.62	13.79	13.95	14.08					27.90	15.03	25.00	22.72	22.66					
							0.25	0.134	0.0191							0.34	0.1877	0.0268							0.82	0.4198	0.0600		0.1059
	July 7	20.20	16.00	12.79	11.95	15.24					13.26	14.4	11.35	15.95	13.74					24.25	22.77	19.01	21.34	21.84					
							1.65	0.8844	0.1263							1.03	0.5686	0.0812							3.47	1.7766	0.2538		0.4613
	July 12	15.86	13.37	12.2	12.93	13.59					12.24	12.14	11.76	14.68	12.71					14.64	15.45	21.20	22.18	18.37					
July 16										0.1930									0.1898						1.11	0.5683	0.0812		0.4640
	July 19	19.00	18.56	19.5	15.11	18.04					19.14	14.88	15.60	11.92	15.38					20.62	12.26	18.90	17.28	17.26					
							2.63	1.4097	0.2819							3.03	1.6726	0.3345										0.0646	0.6810
	July 24	14.78	18.18	17.08	11.6	15.41					13.31	13.22	11.36	11.52	12.35					23.01	21.84	20.16	22.35	21.84					
							4.03	2.1601	0.1543							0.53	0.2926	0.0209							1.31	0.6707	0.0479		0.2231
	Aug. 7	14.10	13.27	9.06	9.07	11.38					11.97	12.12	11.42	11.76	11.82					19.51	20.84	21.24	20.54	20.53					
Aug. 12										0.1770									0.0268						6.55	3.3536	0.5589		0.7627
	Aug. 13	18.19	20.14	15.87	16.79	17.75					11.27	15.59	14.77	15.61	14.31					19.02	11.92	9.44	15.54	13.98					
							4.34	2.3262	0.2908							0.82	0.4526	0.0566										0.3201	0.6675
	Aug. 21	17.14	17.13	10.80	8.55	13.41					14.24	14.22	11.83	13.66	13.49					16.16	19.17	17.27	16.82	17.36					
							0.76	0.4074	0.0509							1.02	0.563	0.0704							1.27	0.6502	0.0813		0.2026
	Aug. 29	14.03	13.43	10.50	12.64	12.65					15.37	9.98	12.07	12.01	12.47					18.65	13.82	15.79	16.11	16.09					
							2.33	1.2489	0.1784							2.21	1.2199	0.1743							1.15	0.5888	0.0841		0.4368
	Sept. 5	11.16	11.97	10.16	8.00	10.32					9.25	11.64	10.41	9.74	10.26					13.61	13.67	15.39	17.08	14.94					
Sept. 11										0.1691									0.1508						2.62	1.3414	0.1916		0.5115
	Sept. 12	18.35	20.81	14.24	12.24	16.41					17.42	12.07	10.89	12.91	13.32					17.19	10.11	9.66	12.33	12.32					
							1.27	0.6807	0.1134							0.11	0.0607	0.0101										0.1050	0.2285
	Sept. 18	18.21	20.32	9.20	12.81	15.14					14.75	13.44	10.68	13.98	13.21					23.48	10.29	12.69	15.51	15.49					
																0.72	0.3974	0.0568							0.25	0.1280	0.0183		0.0751
	Sept. 25	18.38	16.48	12.35	14.1	15.33					15.99	11.26	10.48	12.24	12.49					21.18	12.70	15.20	11.85	15.24					
							2.60	1.3936	0.1991																2.76	1.4131	0.2019		0.4010
	Oct. 2	15.76	14.69	8.88	11.58	12.73					16.94	11.08	14.66	14.24	14.23					13.18	10.69	12.47	13.57	12.48					
							0.64	0.3430	0.0264							2.49	1.3745	0.1057											0.1321
	Oct. 15	12.00	13.74	10.6	12.56	12.09					12.63	11.77	8.49	14.07	11.74					17.59	13.24	11.70	10.39	13.23					

x Water use % X depth X apparent weight of the soil

xx The average of two adjacent actual daily rate of water use figures.

xxx Total daily rate of actual and calculated water use from top, middle and lower 40 centimeter layers.

Table 16. Daily rate of potential evapotranspiration estimated by Penman equation and Blaney-Criddle formula. Apple Orchard, Dahr-al-Baydar, Lebanon, 1963.

Period	Temperature °C	Temperature °F	Relative Humidity	u wind velocity mile/day	Fraction of sky covered with cloud. m/10	Saturation vapour pressure e_a m.m.Hg	σTa^4 mm/day	R_A mm/day	E_a mm/day	R_c	$°R_B$xx	H = $R_c - R_B$	Δ m.m.Hg	Penman's E_o mm/day	Blaney-Criddle P	Blaney-Criddle P.E.T.
May 9-24	11.2	52.16	75	248	0.49	9.973	12.95	16.05	3.03	7.014	2.24812	4.77	0.66	4.26	9.71	4.15
May 24-June 15	14.3	57.74	59	267	0.33	12.22	13.52	16.55	6.44	8.647	3.02848	5.62	0.79	5.83	9.70	4.70
June 15-21	16.9	62.42	43	336	0.13	14.44	14.02	16.62	12.56	10.421	4.19478	6.23	0.92	7.67	9.69	5.12
21-28	18.9	66.02	54	207	0.02	16.37	14.41	16.61	8.09	11.361	4.095322	7.27	1.02	7.44	9.69	5.42
June 28-July 5	18.5	65.30	57	256	0.14	15.97	14.33	16.51	8.56	10.1949	3.61546	6.58	1.00	7.00	9.82	5.30
July 5-12	17.2	62.96	66	205	0.14	14.71	14.08	16.45	5.34	10.158	3.429888	6.73	0.93	6.42	9.87	5.09
12-19	19.8	67.64	53	277	0.06	17.32	14.59	16.32	10.74	10.853	4.019545	6.83	1.07	7.62	9.87	5.47
19-24	18.7	65.66	59	378	0.19	16.17	14.37	16.15	11.09	9.666	3.339588	6.33	1.01	7.33	9.87	5.31
July 24-Aug. 7	19.4	66.92	53	297	0.07	16.89	14.51	15.85	11.03	10.390	3.95543	6.435	1.04	7.38	9.60	5.26
Aug. 7-13	19.6	67.28	54	404	0.17	17.10	14.55	15.44	13.88	9.388	3.5866	5.80	1.06	7.44	9.33	5.14
13-21	22.4	72.32	43	284	0.05	20.31	15.09	15.10	15.56	10.04	4.2011	5.84	1.24	7.58	9.33	5.53
21-29	20.7	69.26	45	292	0.16	18.31	14.77	14.55	13.82	8.846	3.811	5.04	1.13	6.73	9.33	5.29
Aug. 29-Sept.5	19.1	66.38	58	262	0.08	16.58	14.45	13.97	8.82	9.157	3.763	5.39	1.03	6.10	8.64	4.81
Sept. 5-12	19.9	67.82	50	194	0.02	17.42	14.61	13.45	8.96	9.20	4.1522	5.05	1.08	5.83	8.36	4.80
12-18	18.0	64.4	58	196	0.15	15.47	14.23	12.97	6.73	8.01	3.549	4.46	0.97	4.95	8.36	4.56
18-25	14.9	58.82	76	212	0.42	12.70	13.64	12.50	3.33	5.94	2.368	3.57	0.82	3.51	8.36	4.16
Sept.25-Oct. 2	20.0	68.00	48	136	0.20	17.53	14.63	11.95	7.53	7.04	3.599	3.44	1.09	4.25	8.23	4.69
Oct. 2-15	18.8	65.84	48	159	0.11	16.27	14.40	11.15	7.67	7.10	4.018	3.08	1.02	4.04	7.90	4.26
May 1-May 31	10.96	51.73	73	238	0.51	9.838	12.91	16.00	3.15	6.84	2.231	4.61	0.65	4.18	9.71	4.10
June 1-June 30	17.05	62.69	52	267	0.16	14.532	14.04	16.54	8.95	10.06	3.743	6.32	0.92	6.92	9.69	5.14
July 1-July 31	18.4	65.12	59	300	0.13	15.865	14.32	16.32	9.10	10.02	3.528	6.49	1.00	7.04	9.87	5.27
Aug. 1-Aug. 31	20.61	69.10	48	315	0.09	18.206	14.75	15.15	13.76	9.79	3.935	5.85	1.12	7.39	9.33	5.28
Sept.1-Sept.30	18.24	64.83	59	194	0.19	15.71	14.28	13.00	6.63	7.78	3.437	4.34	0.98	4.83	8.36	4.59
Oct. 1-Oct. 31	15.29	59.52	62	180	0.38	13.025	13.71	10.57	4.85	6.63	2.716	3.91	0.84	4.14	7.90	3.85

$$E_a = 0.35\ (1 + \frac{u}{100})\ (e_a - e_d)$$

$$R_c = 0.95\ R_A\ (0.18 + 0.55\ n/N)$$

$$°R_B = \sigma Ta^4\ (0.56 - 0.09\sqrt{e_d})\ (0.1 + 0.90\ n/N)$$

Table 16. Daily rate of potential evapotranspiration estimated by Penman equation and Blaney-Criddle formula. Apple Orchard, Dahr-al-Baydar, Lebanon, 1963.

Period	Temperature		Relative	u wind velocity	Fraction of sky covered with cloud.	Saturation vapour pressure e_a	σT_a^4	R_A	E_a	R_c	σR_Bxx	H = $R_c - R_B$	Δ	Penman's E_o	Blaney-Criddle	
	°C	°F	Humidity	mile/day	m/10	m.m.Hg	mm/day	mm/day	mm/day				m.m.Hg	mm/day	P	P.E.T.
May 9-24	11.2	52.16	75	248	0.49	9.973	12.95	16.05	3.03	7.014	2.24812	4.77	0.66	4.26	9.71	4.15
May 24-June 15	14.3	57.74	59	267	0.33	12.22	13.52	16.55	6.44	8.647	3.02848	5.62	0.79	5.83	9.70	4.70
June 15-21	16.9	62.42	43	336	0.13	14.44	14.02	16.62	12.56	10.421	4.19478	6.23	0.92	7.67	9.69	5.12
21-28	18.9	66.02	54	207	0.02	16.37	14.41	16.61	8.09	11.361	4.095322	7.27	1.02	7.44	9.69	5.42
June 28-July 5	18.5	65.30	57	256	0.14	15.97	14.33	16.51	8.56	10.1949	3.61546	6.58	1.00	7.00	9.82	5.30
July 5-12	17.2	62.96	66	205	0.14	14.71	14.08	16.45	5.34	10.158	3.429888	6.73	0.93	6.42	9.87	5.09
12-19	19.8	67.64	53	277	0.06	17.32	14.59	16.32	10.74	10.853	4.019545	6.83	1.07	7.62	9.87	5.47
19-24	18.7	65.66	59	378	0.19	16.17	14.37	16.15	11.09	9.666	3.339588	6.33	1.01	7.33	9.87	5.31
July 24-Aug. 7	19.4	66.92	53	297	0.07	16.89	14.51	15.85	11.03	10.390	3.95543	6.435	1.04	7.38	9.60	5.26
Aug. 7-13	19.6	67.28	54	404	0.17	17.10	14.55	15.44	13.88	9.388	3.5866	5.80	1.06	7.44	9.33	5.14
13-21	22.4	72.32	43	284	0.05	20.31	15.09	15.10	15.56	10.04	4.2011	5.84	1.24	7.58	9.33	5.53
21-29	20.7	69.26	45	292	0.16	18.31	14.77	14.55	13.82	8.846	3.811	5.04	1.13	6.73	9.33	5.29
Aug. 29-Sept.5	19.1	66.38	58	262	0.08	16.58	14.45	13.97	8.82	9.157	3.763	5.39	1.03	6.10	8.64	4.81
Sept. 5-12	19.9	67.82	50	194	0.02	17.42	14.61	13.45	8.96	9.20	4.1522	5.05	1.08	5.83	8.36	4.80
12-18	18.0	64.4	58	196	0.15	15.47	14.23	12.97	6.73	8.01	3.549	4.46	0.97	4.95	8.36	4.56
18-25	14.9	58.82	76	212	0.42	12.70	13.64	12.50	3.33	5.94	2.368	3.57	0.82	3.51	8.36	4.16
Sept.25-Oct. 2	20.0	68.00	48	136	0.20	17.53	14.63	11.95	7.53	7.04	3.599	3.44	1.09	4.25	8.23	4.69
Oct. 2-15	18.8	65.84	48	159	0.11	16.27	14.40	11.15	7.67	7.10	4.018	3.08	1.02	4.04	7.90	4.26
May 1-May 31	10.96	51.73	73	238	0.51	9.838	12.91	16.00	3.15	6.84	2.231	4.61	0.65	4.18	9.71	4.10
June 1-June 30	17.05	62.69	52	267	0.16	14.532	14.04	16.54	8.95	10.06	3.743	6.32	0.92	6.92	9.69	5.14
July 1-July 31	18.4	65.12	59	300	0.13	15.865	14.32	16.32	9.10	10.02	3.528	6.49	1.00	7.04	9.87	5.27
Aug. 1-Aug. 31	20.61	69.10	48	315	0.09	18.206	14.75	15.15	13.76	9.79	3.935	5.85	1.12	7.39	9.33	5.28
Sept.1-Sept.30	18.24	64.83	59	194	0.19	15.71	14.28	13.00	6.63	7.78	3.437	4.34	0.98	4.83	8.36	4.59
Oct. 1-Oct. 31	15.29	59.52	62	180	0.38	13.025	13.71	10.57	4.85	6.63	2.716	3.91	0.84	4.14	7.90	3.85

$$E_a = 0.35\left(1 + \frac{u}{100}\right)(e_a - e_d)$$

$$R_c = 0.95\, R_A\, (0.18 + 0.55\, n/N)$$

$$\sigma R_B = \sigma T_a^4\,(0.56 - 0.09\sqrt{e_d})\,(0.1 + 0.90\, n/N)$$

TABLE 17

Daytime Hour Percentages for Each Month of the Year for Latitudes 26 to 48 Degrees North of Equator*

Month	Latitudes in Degrees North of Equator											
	26	28	30	32	34	36	38	40	42	44	46	48
	%	%	%	%	%	%	%	%	%	%	%	%
Jan.	7.49	7.40	7.30	7.20	7.10	6.99	6.87	6.76	6.62	6.49	6.33	6.17
Feb.	7.12	7.07	7.03	6.97	6.91	6.86	6.79	6.73	6.65	6.58	6.50	6.42
March	8.40	8.39	8.38	8.37	8.36	8.35	8.34	8.33	8.31	8.30	8.29	8.27
April	8.64	8.68	8.72	8.75	8.80	8.85	8.90	8.95	9.00	9.05	9.12	9.18
May	9.38	9.46	9.53	9.63	9.72	9.81	9.92	10.02	10.14	10.26	10.39	10.53
June	9.30	9.38	9.49	9.60	9.70	9.83	9.95	10.08	10.21	10.38	10.54	10.71
July	9.49	9.58	9.67	9.77	9.88	9.99	10.10	10.22	10.35	10.49	10.64	10.80
Aug.	9.10	9.16	9.22	9.28	9.33	9.40	9.47	9.54	9.62	9.70	9.79	9.89
Sep.	8.31	8.32	8.34	8.34	8.36	8.36	8.38	8.38	8.40	8.41	8.42	8.44
Oct.	8.06	8.02	7.99	7.93	7.90	7.85	7.80	7.75	7.70	7.63	7.58	7.51
Nov.	7.36	7.27	7.19	7.11	7.02	6.92	6.82	6.72	6.62	6.49	6.36	6.22
Dec.	7.35	7.27	7.14	7.05	6.92	6.79	6.66	6.52	6.38	6.22	6.04	5.86
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

*From "Sunshine Tables," United States Weather Bureau Bulletin 805, Edition of 1905.