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Effect of Irrigation Frequency on the Average Evapotranspiration for Various Crop-Climate-Soil Systems

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NUMEROUS formulas have been developed to predict evapotranspiration based on climatic data (ASAE, 1966; ASCE, 1966). Most of these formulas can be successfully applied to conditions where there is a continuous and abundant supply of soil water. For economical and technical reasons, however, an abundance of soil water cannot be maintained continuously and a drying cycle of the soil is almost unavoidable even under conditions of good irrigation. Hence, many of the formulas based solely on climatic variables are of limited application since they do not take into account the soil moisture or the nature and condition of the plants.

The soil, the plant, and the atmosphere form a single continuous system for the movement of water. The evaporation of water from plants is the result of interactions of all three components of the system, and it cannot be characterized by any single component. Better decisions will be possible in practical plant-water problems when the quantitative limits imposed by these three interacting components are better understood. Working mathematical models will play an important role in achieving this.

Several models have been advocated for the relation between soil water and the ratio of actual evapotranspiration, ET, to potential or maximum evapotranspiration, ET_x. Thus, ET, can be estimated from empirical calculations of ET_x. Tanner (1967) has reviewed these methods. The major proposals for empirically relating the ET/ET_x ratio to soil moisture are: (a) A ratio of unity (equal availability) in the whole range of soil water between field capacity, FC, and permanent wilting point, PWP (Veihmeyer and Hendrickson, 1955; Glover and Forsgate, 1964); (b) a linear decrease of the ET/ET_x ratio between FC and PWP, (Thornthwaite and Mather, (1955); Wu, (1967); (c) a linear decrease in availability between FC and oven-dryness (Havens, 1956); and (d) various curvilinear relationships (Pierce, 1958; Engleman and Decker, 1965; West and Perkman, 1953; Butler and Prescott, 1955).

It has been customary in irrigation practices to asusme equal availability between FC and PWP, although experimental evidence indicates that this is not a correct assumption in many cases. Gardner and Ehlig (1963) have also demonstrated that the lower limit of available water can be less than the 15 atmospheres percentage (PWP), being more nearly in the 30-50 atmosphere range.

The experiments of Denmead and Shaw (1962), Holmes (1961), Zahner (1967), and of Holmes and Robertson (1959) have done much to resolve the controversy about the relation between soil moisture and the ratio ET/ET_x. They have demonstrated how the evaporation intensity of the atmosphere, moisture retaining property of the soil, and extent of the root system influence the relation between soil water and evapotranspiration. Shaw (1963) included the effect of evaporative demands of the environment in his ET/ET_x model. In similar models Holmes (1961) and Zahner (1967) include the influence of soil types. The model of Holmes and Robertson (1959) takes into account the influence of root systems. Their experiments demonstrate the influence that the interactions between the soil, plant, and atmospheric factors have on the relationship between soil moisture and water consumption by crops.

THEORY

Norero (1969) has developed Equation [1] to express evapotranspiration as a function of soil moisture and evaporative demands of the atmosphere.

$$\frac{d\,ET}{d\,\psi} = k\left(\frac{ET}{\psi}\right)(1 - ET/ET_x) \quad ..[1]$$

in which

- ET = the actual evapotranspiration
- ψ = the total soil moisture potential
- k = a proportionality coefficient
- ET_x = the evapotranspiration that would occur from a particular crop-soil unit when soil moisture was not limiting.

Equation [1] provides a good fit for the evapotranspiration–soil moisture relationship under widely differing conditions. If proper values are chosen for its coefficients, the formula yields relations that are similar to several of the models taken from the literature.

The following expression may be derived from Equation [1].

$$ET = \left(\frac{C}{C + \psi^k}\right) ET_x \quad .....[2]$$

in which

C = a constant of integration.

By utilizing the relationship $\psi = a\,\theta^{-b}$ and consolidating the constants, equation [2] can be stated in terms of soil moisture content, θ, as

$$ET = \left(\frac{n}{n + \theta^{-m}}\right) ET_x \quad .....[3]$$

in which

- θ = the average volumetric soil moisture content in the root zone
- n & m = consolidated constants.

These models (equations [2] and [3]) express the following three ideas. First when the soil moisture is plentiful (very small ψ^k or θ^{-m}) evapotranspiration from a crop-soil unit is at a maximum, ET_x, and is primarily a function of the amount of energy available to evaporate water. Under wet conditions, equations [2] and [3] simplify to:

$$ET = p\,ET_x = f(ED) = g\,E_o \quad ...[4]$$

in which

- p = a variable which is approximately equal to 1.0 when the soil is wet

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ED = the evaporative demands of the atmosphere, as measured, for example, in terms of evaporation from a free water surface (evaporation pan)

E_o = a measure of the evaporative intensity of the atmosphere

g = a proportionality coefficient expressing the ratio ET_x/E_o.

Second, when the soil begins to dry, water may not be conducted to the evaporating surfaces fast enough to meet the atmospheric demand. Then the actual evapotranspiration falls behind the maximum rate, and the level of soil moisture becomes a controlling factor. In equation [4], p, which represents the terms in the brackets in equations [2] and [3], becomes increasingly less than 1.0. The term p then expresses the degree of inhibition of ET_x that is imposed by limiting soil moisture.

Third, the general shape of the variable function p is sigmoidal having a degree of curvature which is determined by interactions between atmospheric factors, the nature of the soil, and the conditions of the vegetation. These interactions determine the capacity of the soil-plant-system to conduct and transpire water and are expressed by the value of the coefficients c and k of equation [2] or n and m of equation [3].

The term ET_x is considered as the maximum possible evapotranspiration in response to the evaporative demands of the atmosphere. It may differ from "potential evapotranspiration" (Penman, 1956) because it does not involve the stringent conditions specifice for the latter. For most practical situations ET_x equals the evapotranspiration at field capacity, ET_{fc}. However, there may be exceptions in which ET_x may not be obtained even when the soil is at field capacity (Godard, 1964).

Equation [3] may be used to analyze the effects that the irrigation frequency has on evapotranspiration under different environmental conditions. To simplify the computations it is necessary to derive the relation between evapotranspiration and time. This may be accomplished by rearranging equation [3] to produce

$$ET = \left[\frac{1}{1 + (\frac{1}{n})\,\theta^{-m}} \right] ET_x \quad \ldots [5]$$

and then introducing

$$ET = -h\frac{d\theta}{dt} \quad \ldots\ldots\ldots\ldots [6]$$

in which

h = the effective rooting depth or water extraction depth

t = time, and

$$\left(\frac{1}{n}\right) = \theta_c^m \quad \ldots\ldots\ldots\ldots [7]$$

in which

θ_c = the volumetric water content at which ET = 0.5 ET_x (Norero, 1969).

Substituting equations [6] and [7] into equation [5] yields

$$\frac{d\theta}{dt} = -\left\{ \frac{1}{h\left[1 + (\frac{\theta_c}{\theta})^m\right]} \right\} ET_x \quad \ldots\ldots\ldots\ldots [8]$$

Separating variables and integrating equation [8] gives

$$\left[1 - \left(\frac{1}{m-1}\right)\left(\frac{\theta_c}{\theta}\right)^m\right]\theta = C - \left(\frac{ET_x}{h}\right)t \quad \ldots\ldots\ldots\ldots [9]$$

Letting t = 0 when the water content ratio is at field capacity, $\theta = \theta_{fc}$, the value of the constant of integration C, is

$$C = \theta_{fc} - \left(\frac{1}{m-1}\right)\left(\frac{\theta_c}{\theta_{fc}}\right)^m \theta_{fc} \quad \ldots\ldots\ldots\ldots [10]$$

in which

θ_{fc} = the volumetric moisture content at field capacity.

The second term on the right hand side of equation [10] is negligible, therefore, C in equation [9] can be replaced by θ_{fc}. Upon rearranging and solving for t, equation [9] becomes

$$t = \frac{h}{ET_x}\left\{\theta_{fc} - \left[1 - \left(\frac{1}{m-1}\right)\left(\frac{\theta_c}{\theta}\right)^m\right]\theta\right\} \quad \ldots\ldots\ldots\ldots [11]$$

Equation [11] can be used to convert the data expressed by equation [3] to a time basis. The necessary parameters h, ET_x, and θ_{fc} are known from the experimental conditions and θ_c, and m can be obtained by fitting equation [3] to the experimental evapotranspiration data. Note that equation [11] is dimensionally consistent; therefore, h and ET_x must be in the same length units and t will be in the same time units as ET_x. Furthermore, the volumetric moisture content values, θ, should be in the decimal form.

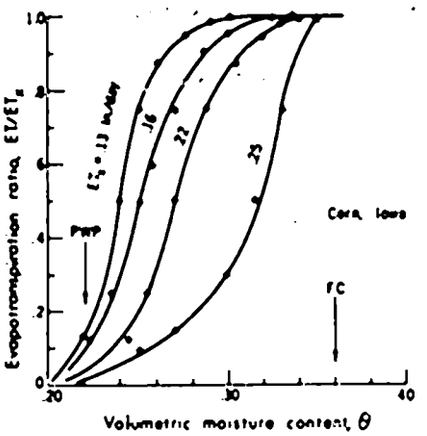

FIG. 1 Actual evapotranspiration versus moisture content curves for various ET_x intensities taken from Denmead and Shaw (1962).

PROCEDURE

The following two sources of field data were selected to study the effect of irrigation frequency on evapotranspiration.

1 Data from Denmead and Shaw (1962), concerning the influence of atmospheric evaporative demands on the evapotranspiration of corn in Iowa, was evaluated. The corn plants were grown in 24 in. deep, 20-gal. field lysimeters filled with Colo silty clay loam.

2 Experimental data from Bahrani and Taylor (1961) concerning the evapotranspiration of an established crop of alfalfa, with an extensive 9 ft deep root system, as a function of soil moisture potential was also analyzed. The experiment was conducted in Utah on a Millville silt loam soil, and measurements were taken during a period of high atmospheric evaporative intensities.

Fig. 1 shows the relation between ET/ET_x and θ for four of the five ET_x intensities investigated in the corn study. The plotted points are actual field data and the curves depict the functional relationship described by equation [3], which approximately fit the data.

The data available from the alfalfa study was in terms of ET/ET_x versus ψ for a single high value of ET_x = 0.46 in. per day. In order to utilize these data, the soil moisture ψ values were converted to θ values by utilizing the relation between ψ and θ presented by Ashcroft and Taylor (1953) for Milville

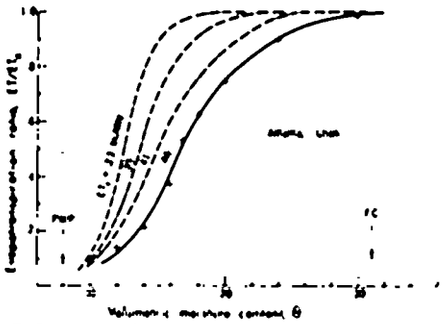

FIG. 2 Actual evapotranspiration versus moisture content curves for various ET_x intensities synthesized from ET versus ψ data for ET_x = 0.46 in. per day, data taken from Bahrani and Taylor (1961).

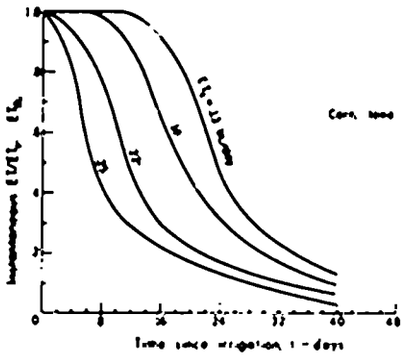

FIG. 3 Instanteous evapotranspiration ratio versus time since irrigation for various ET_x intensities, constructed from the data of Denmead and Shaw (1962).

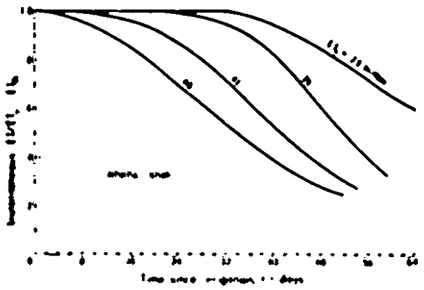

FIG. 4 Instantaneous evapotranspiration ratio versus time since irrigation for various ET_x intensities, constructed from the data of Bahrani and Taylor (1961).

silt loam. Fig. 2 shows a plot of ET/ET_x versus calculated θ data for a constant ET_x = 0.46 in. per day and the functional relationship described by equation [3] which approximately fits these data.

Fig. 2 also shows the synthesized relationship between ET/ET_x and θ for three lower ET_x intensities. The following procedure was utilized to develop these three curves.

The sum of the impedances, $I_p + I_s$, to water flow through the soil-plant system when the stomata first begin to close was considered to be the same under all four evaporative demands. This impedance was calculated from the experimental data for an ET_x of 0.46 in. per day using the equation presented by Norero (1969):

$$\psi_x = \text{crit}\,\psi_l - (I_p + I_s)(ET_x - E_s) \qquad [12]$$

in which

ψ_x = the value of ψ at Et = 0.95 Et_x

$\text{crit}\psi_l$ = the critical water potential at which the plant begins to close the stomata (a value of 4 atmospheres was assumed for the alfalfa)

I_p = the impedance to water flow through the plant

I_s = the impedance to water flow through the soil toward the plant roots

E_s = the evaporation from the soil surface which was assumed equal to zero for the dense stand of alfalfa.

The estimated $I_p + I_s$ was then used to compute ψ_x values for the three assumed ET_x intensities.

The minimum soil moisture potential at which evapotranspiration nearly ceases, Et = 0.05 Et_x, was also assumed to be the same under all 4 atmospheric evaporative demands. This minimum soil moisture potential, ψ_n, was obtained from the experimental data for Et_x = 0.46 in. per day and used for the three assumed ET_x intensities.

The estimated ψ_x and ψ_n values for the three assumed ET_x intensities were converted to θ_x and θ_n values. To obtain the general relationship between ET and θ a straight line was drawn between θ_x and θ_n on a logarithmic plot having θ as the abscissa and $ET/(ET_x - ET)$ as the ordinate. (By definition, when $\theta = \theta_x$, $ET/(ET_x - ET)$ = 19 and when $\theta = \theta_n$, $ET/(ET_x - ET)$ = 0.053.)

The primary relationships between ET/ET_x and θ presented in Figs. 1 and 2 were used in equation [11] to compute estimated ET values at various times, t, since the plant root zones were filled to field capacity. Each of these ET values was then converted to an instantaneous ET/ET_x ratio, ET_{Rt}. Figs. 3 and 4 show plots of the relationships between ET_{Rt} and t for four different ET_x intensities for the corn and alfalfa respectively.

The ET_{Rt} versus t curves presented in Figs. 3 and 4 were then graphically integrated (in 2-day steps) in order to obtain the relationships between the average ET/ET_x ratios, ET_{Ra}, and t. (The graphical method of integration was used because the integral is quite complex.) Figs. 5 and 6 show a plot of the relationship between ET_{Ra} and t for the four ET_{Ra} and t for the four ET_x intensities for the corn and alfalfa respectively.

DISCUSSION

In general ET/ET_x may be considered as a gauge of relative growth or plant productivity. In order to assure high productivity, this ratio must be maintained near 1.0, i.e., ET = ET_x, during the rapid growth, flowering, and/or fruiting stages of crop development. It is apparent from Figs. 1 and 2 that in order to accomplish this, the average soil moisture in the root zone must be maintained at a high level. In other words frequent irrigations are necessary in order to optimize production especially when ET_x is high.

The importance of irrigation frequency is readily apparent from the ET_{Rt} versus t curves shown in Figs. 3 and 4. For example, the following deductions can be made from Fig. 3. During the 7th day following an irrigation which brought the corn root zone

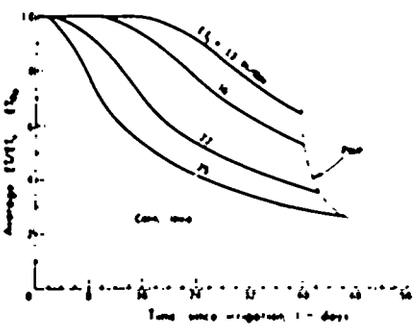

FIG. 5 Average evapotranspiration ratio versus days since irrigation for various ET_x intensities, constructed from the data of Denmead and Shaw (1962).

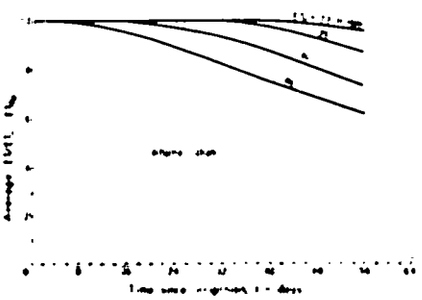

FIG. 6 Average evapotranspiration ratio versus days since irrigation for various ET_x intensities, constructed from the data of Bahrani and Taylor (1961).

to field capacity, ET_{R_I} = 0.5 for the maximum ET_x = 0.25 in. per day curve and depth of ET = (0.5) (0.25) = 0.125 in. instead of the potential 0.25. This reduction in ET results from partial closure of the stamata and it might be expected that the growth process are also progressing at less than the potential rate. On the other hand, from the minimum ET_x = 0.13 in. per day curve, ET_{R_I} = 1.0 on the 7th day and it takes 24 days before it decreases to 0.5.

The ET_{R_a} versus t curves presented in Figs. 5 and 6 can be used to predict actual moisture requirements and anticipated productivity under differing irrigation regimes and climatic conditions for the corn and alfalfa soil-crop systems. For example, in Fig. 5 for corn, if ET_x = 0.25 in. per day and the irrigation frequency, F, is 7 days, ET_{R_a} = 0.8, and the average evapotranspiration rate, ET_a during the 7 day period is (0.8 x 0.25) = 0.20 in. per day. At this average rate, the depth of water, D, consumed between irrigations would be (7 x 0.20) = 1.4 in. Furthermore, it might be expected that the crop productivity may only be 80 percent of optimum during this period. To obtain optimum crop production, daily irrigations would have been required so that ET_a = ET_x = 0.25 in. per day.

It is interesting to speculate on the productivity of the corn when ET_x = 0.25 in. per day and it is irrigated daily by a continuously moving sprinkler irrigation system, which has a capacity of only 0.20 in. per day. With daily applications, a great deal of superficial moisture would be present, and it seems reasonable to expect that the regulatory devices of the plant would not function in a usual manner. As long as sufficient soil moisture were present, the ET_a would approximate 0.25 in. per day and the 0.05 in. deficit would be taken from soil moisture storage. At some level of soil moisture depletion, the corn might begin to alternate between daily periods of rapid growth and wilting. This could cause serious growth problems and result in greatly reduced productivity. On the other hand, a system with a similar 0.20 in. per day capacity, but operated on a 7 day cycle as described earlier, may produce near optimum results. According to the above arguments, when short irrigation intervals are employed, it is important that the system capacity be sufficient to meet ET_x demands.

A broadly used irrigation design and scheduling practice is to assume that the average evapotranspiration, ET_a, is equal to ET_x. The irrigation frequency, F, is then determined by dividing approximately 50 percent of the available soil moisture holding capacity of the plant root zone by ET_x. The depth of water required per irrigation, D, is then assumed to be (F) (ET_x) or approximately 50 percent of the available moisture in the root zone. A more rational scheduling practice would be to select an irrigation frequency which would produce a given ET_{R_a} as determined from an ET_{R_a} versus t curve for the specific situation.

TABLE 1 FREQUENCY, F, AND DEPTH OF IRRIGATION, D, AS DETERMINED BY DIFFERENT SCHEDULING CRITERIA FOR THE CORN GROWN UNDER THE VARIOUS CLIMATIC CONDITIONS*

	50 percent method			Rational method					
				ET_{R_a} = 0.90			ET_{R_a} = 0.80		
ET_x, in. per day	ET_a, in. per day	F, days	D, in.	ET_a, in. per day	F, days	D, in.	ET_a, in. per day	F, days	D, in.
0.25	0.25	6	1.5	0.23	5	1.1	0.20	7	1.4
0.22	0.22	7	1.5	0.20	9	1.8	0.18	13	2.3
0.16	0.16	10	1.6	0.14	18	2.6	0.13	23	2.9
0.13	0.13	13	1.7	0.12	25	2.9	0.10	30	3.1

*Based on 3.36 in. of available moisture in the root zone and the information presented in Figure 5.

Table 1 shows a comparison between these two scheduling methods when applied to the corn grown in the 24 in. deep lysimeters which contain 3.36 in. of available moisture.

The same types of deductions which were developed from Fig. 5 for corn grown in shallow field lysimeters can be made from the deep rooted field alfalfa data presented in Fig. 6. However, it is more interesting to note the differences between the figures. Although the ET_x intensities for the alfalfa are considerably higher than those for the corn, the ET_{R_a} for alfalfa remains higher for a longer period. The shallow rooted corn requies very frequent irrigations to obtain maximum production when ET_x is high, however, little or no additional crop growth would be obtained by such frequent irrigations on the deep rooted alfalfa.

Much of the difference in the irrigation frequency requirements of the corn and alfalfa can be explained by the amount of available soil moisture in the root zones. While the corn had a 2 ft root zone with an available moisture supply of only 3.36 in., the alfalfa had a 9 ft root zone containing 24.8 in. of available moisture. When ET_x = 0.22 in. per day and the corn is irrigated every 7 days, ET_{R_a} = 0.95 (see Fig. 5). When ET_x = 0.23 in. per day and the alfalfa is irrigated every 56 days, ET_{R_a} = 0.95 (Fig. 6). The ratio of the irrigation frequencies (56/7) = 8, at which both crops having a similar ET_x have a similar ET_{R_a} = 0.95, is of the same magnitude as their respective root zone soil moisture holding capacities (24.8/3.36) = 7.4.

In order to use θ or ψ field records for irrigation scheduling purposes, a value of ET_{R_a}, which gives an indication of relative production, should first be selected. This value of ET_{R_a} can be related to an ET_{R_I} for the same irrigation frequency and then ET_{R_I} can be related to θ or ψ. For example, if an ET_x of 0.46 in. per day is anticipated and a value of ET_{R_a} = 0.90 is selected (approximately 90 percent relative production is desired) for the deep rooted alfalfa, from Fig. 6, a 24 day irrigation interval is indicated. From Fig. 4 approximately 24 days following an irrigation, ET_{R_I} = 0.7 and from Fig. 2 when ET_{R_I} = 0.7, θ = 19.2. This value of θ would be approximately equivalent to ψ = -1 atmosphere at a depth of between 2 and 3 feet in the alfalfa crop-soil system investigated.

SUMMARY AND CONCLUSIONS

The general relationship between ET_{R_a} and the time since the root zone soil moisture has been completely replenished (fully irrigated) was developed and discussed. The development of this relationship began with a knowledge of the relationship between ET/ET_x and either θ or ψ for at least one ET_x intensity. Methods were explained for expanding ET/ET_x versus θ or ψ data for a single value of ET_x to produce data for various other ET_x intensities.

Examples of the above manipulations were given and the final development of ET_{R_a} versus t curves were produced from field crop data found in the literature. The data selected were for corn grown in shallow field lysimeters and deep rooted field alfalfa to demonstrate rather extreme cases in terms of the irrigation frequency required to maintain a high ET_{R_a} or relative productivity. The usefulness of these curves for designing irrigation

systems and developing irrigation scheduling was discussed.

An ability to extend the data from a single ET_x experiment to other ET_x intensities plus knowledge of the relationships between θ and ψ for the soils in question should prove very useful. With this capability it is possible to take the crop data obtained from a few field experiments and extend it to other climatic zones and/or field sites. Furthermore, it may also be possible to group crops which have similar leaf-root development relationships and draw inferences for a whole crop group from experiments conducted on only one crop within the group.

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