METEOROLOGICAL APPROACHES TO IRRIGATION SCHEDULING[1]

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This paper briefly summarizes the recently developed, user-oriented USDA irrigation scheduling computer program that is being used in several states (3, 5, 6, 7)[3], the modifications that are underway, and the future refinements that are being considered.

Irrigation scheduling is a decision-making process that is repeated many times each year for each field. Instruments available for directly or indirectly measuring soil moisture or the plant-water status have not been used extensively by the irrigator because they require reguular servicing and frequent readings. Furthermore, these instruments provide only part of the information needed--they indicate the present status of soil moisture or the plant water status, not the expected date of the next irrigation or the amount of water needed.

Evapotranspiration accounts for most of the depletion of soil moisture. Tremendous scientific gains have been achieved in measuring and predicting daily evapotranspiration. However, these developments generally have not been in a form that the irrigated farm manager can use. The modern farm manager could use a service that will provide an estimate of the present soil moisture status, predicted irrigation dates, and amounts of water to apply for each field. This information will increase his management skills through better and more profitable irrigation decisions than he is now able to make.

USDA IRRIGATION SCHEDULING COMPUTER PROGRAM

The concept of irrigation scheduling using meteorological data is not new (1, 12, 14, 15, 16, 19, 20). The USDA computer program was developed cooperatively with farm managers and service groups, and requires limited input data. Rational equations are used so that each can be replaced as more accurate ones are developed. The principles and procedures involved are described in the following sections.

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[3] Numbers in parentheses refer to the appended references.

Soil Moisture Depletion

The major dependent variable is soil moisture depletion and the major components are:

$$D = \sum_{i=1}^{n} (E_t - R_e - I + W_d) \qquad [1]$$

where D = depletion of soil moisture (after a thorough irrigation $D = 0$); E_t = evapotranspiration; R_e = rainfall (excluding runoff); I = irrigation water applied; W_d = the drainage from the root zone; and $i = 1$ for the first day after a thorough irrigation when $D = 0$. The terms to the right of the equal sign are daily totals, expressed in inches, in the present computer program of this model.

Potential Evapotranspiration

The program first estimates daily potential evaporative flux, E^* (the evaporative flux from a well-watered reference crop like alfalfa with 12 to 18 inches of top growth). A combination equation (energy balance and aerodynamic) using daily values of a limited number of meteorological parameters provides adequate estimates of E^* for this purpose. The most common combination equation is that presented by Penman (13):

$$E^* = \frac{\Delta}{\Delta + \gamma} (R_n - G) + \frac{\gamma}{\Delta + \gamma} (15.36)(1.0 + 0.01W)(e_s - e_d) \qquad [2]$$

where Δ is the slope of the saturation vapor pressure-temperature curve (de/dT), γ is the psychrometric constant, e_s is the mean saturation vapor pressure in mb (mean of the saturation vapor pressures at maximum and minimum daily air temperature), and e_d is the estimated actual vapor pressure based on the saturation vapor pressure at mean dew point temperature in mb. The parameters $\Delta/(\Delta + \gamma)$ and $\gamma/(\Delta + \gamma)$ are mean air temperature weighting factors whose sum is 1.0 (6), W is total daily wind run in miles, R_n is daily net radiation in cal cm^{-2}, and G is daily soil heat flux in cal cm^{-2}.

The Penman equation tends to underestimate E^* under high advective conditions (7, 17). Under these conditions, the aerodynamic term proposed by van Bavel (18), $11.505W/[\ln(z/z_o)]$, may be preferred in place of $(15.36)(1.0 + 0.01W)$ providing the roughness parameter used, z_o, is in the range of 0.6 to 1.0 cm. The parameter z is the height at which the windspeed is measured.

Estimates of daily potential evaporative flux, E^*, are converted to depth equivalent (E_{tp}) in inches using 585 cal g^{-1} as the latent heat of vaporization, ($E_{tp} \cong 0.000673\ E^*$).

Net Radiation

Daily net radiation required for the combination equation is estimated using

$$R_n = 0.77\ R_s - R_b \qquad [2]$$

$$R_b = (a \frac{R_s}{R_{so}} + b) R_{bo} \qquad [4]$$

and

$$R_{bo} = (0.32 - 0.044 \sqrt{e_d})(11.71 \times 10^{-8}) \frac{T2_A^4 + T1_A^4}{2} \qquad [5]$$

R_s is observed solar radiation for a day, R_{so} is solar radiation that would be expected on that day if there were no clouds, $0.77\ R_s$ represents the net shortwave radiation absorbed by a green crop with full cover, R_b is the net outgoing longwave radiation, R_{bo} is the net outgoing long wave radiation in cal cm^{-2} on a clear day, e_d is the saturation vapor pressure at mean dew point temperature in mb, 11.71×10^{-8} is the Stefan-Boltzmann constant in cal $cm^{-2} day^{-1}\ {}^\circ K^{-4}$, and $T2_A$ and $T1_A$ are the maximum and minimum daily air temperatures, respectively, in °K.

The constants a and b in equation [4] were originally derived from Davis, California data, obtained from Pruitt[4] (1.35 and -0.35). More recently, evaluations in Idaho under arid conditions where the nights frequently are clear, gave values near 0.75 and 0.25 for a and b, respectively. These variations seem large but they have very little effect with nearly clear skies. As a first approximation, one can assume $a = 1.0$ and $b = 0$.

Soil Heat Flux

An empirical equation is used in the program for daily soil heat flux: G = (average air temperature minus the average air temperature for the three previous days in °F) × 5.

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[4] W. O. Pruitt, personal communication.

Evapotranspiration

Evapotranspiration (E_t) for a given crop and field is estimated using

$$E_t = K_c \; E_{tp} \qquad [6]$$

where K_c is a dimensionless coefficient similar to that proposed by van Wijk and de Vries (21) and E_{tp} is the daily potential evaporative flux expressed in inches. The coefficient, K_c, represents the combined relative effects of the resistance of water movement from the soil to the various evaporating surfaces and the resistance to the diffusion of water vapor from the surfaces to the atmosphere, and the relative amount of radiant energy available as compared to the reference crop (4). The crop coefficient is adjusted for soil surface wetness and the soil moisture level as follows:

$$K_c = K_{co} K_a + K_s \qquad [7]$$

where K_{co} = the mean crop coefficient based on experimental data where soil moisture was not limiting and normal irrigation stands were used; K_a = a soil moisture coefficient that varies from 0.0 to 1.0. In this program, K_a was assumed to be proportional to the logarithm of the percentage of remaining available soil moisture (AM): $K_a = \underline{\ln}(AM + 1)/\underline{\ln}\ 101$; K_s is the increase in the coefficient when the soil surface is wetted by irrigation or rainfall. The maximum value of $K_{co}K_a + K_s$ normally will not exceed 1.0 for most crops. The value of K_s was approximated for the first, second, and third day after a rain or irrigation, respectively using: $(0.9 - K_c)0.8$; $(0.9 - K_c)0.5$; $(0.9 - K_c)0.3$.

Rainfall-Irrigation

Daily rainfall excluding runoff is entered for each field. If runoff occurred, the recorded rainfall was arbitrarily reduced based on local experience and judgement. Estimated increases in evaporation caused by rainfall wetting the soil surface cannot exceed the rainfall.

When an adequate amount of irrigation water was applied, the soil moisture depletion was assumed to be zero on the day of irrigation. With moving sprinkler systems that apply a limited amount of water very uniformly, the amount applied is treated as rainfall.

Drainage

Daily drainage estimates are not part of the present computer program. Drainage estimates are not needed if the amount of irrigation water added is unknown, and the maximum amount of water that can be depleted is based on the maximum amount of water that can be depleted by evapotranspiration for a given soil and crop. Rainfall in excess of that required to reduce the depletion to zero is attributed to drainage on the day that it occurs.

If the maximum amount of water that can be depleted also includes that portion that may drain from the root zone, then a daily drainage estimate can be added as an optional subroutine. Initially this subroutine will be based on the expression proposed by Ogata and Richards (11).

$$W = W_o t^{-m} \qquad [8]$$

where W_o is the water content when $t = 1$, and m is a constant derived experimentally for a given soil. When evapotranspiration occurs, the rate of drainage at a given water content may be less because the hydraulic gradient is also affected by the extraction of water by the crop. However, during the first few days after an irrigation, the hydraulic conductivity is usually large so that the hydraulic gradient is not greatly affected by evapotranspiration, and a correction similar to that proposed by Wilcox (22) could be used (9).

Irrigation Schedules

The number of days before the next irrigation is estimated from the remaining soil moisture that can safely be depleted and the expected average E_t.

$$N = \frac{D_o - D}{\overline{E_t}} \qquad [9]$$

$$N = 0 \text{ for } D > D_o$$

where N = the estimated number of days until another irrigation is needed if additional rainfall is not received, D_o is the maximum depletion of soil moisture allowed for the present stage of growth, D is the estimated depletion of soil moisture, and $\overline{E_t}$ = the mean rate of E_t for the three previous days and three forecast days. Mean evapotranspiration for the crop involved as measured at that location and time could be used if available.

The total amount of water required for the next irrigation at the point of water measurement (W_I) is estimated as follows:

$$W_I = \frac{D_o}{E}, \quad D_o > D \qquad [10a]$$

$$W_I = \frac{D}{E}, \quad D > D_o \qquad [10b]$$

where D is the estimated depletion of soil moisture and E is the attainable irrigation efficiency with the system involved. When necessary, W_I can be adjusted for the leaching requirements.

INPUT DATA

Three categories of input data are required: (a) basic or fixed data for each region and field, (b) current meteorological data for each region, and (c) current data for each field.

Basic Data

The basic data consist of regional constants for the potential E_t equations, and data for each field. The latter involves the farm name, crop code number, alpha-numeric crop and field identification, planting date, estimated effective cover date, estimated harvest date, estimated overall irrigation efficiency for each field based on the system being used, and the maximum amount of soil water that could be depleted by evapotranspiration for each crop. The maximum depletion by evapotranspiration is estimated as the difference between the soil-water content about 4 days after an irrigation on a soil that is about 2-3 feet in depth (covered to prevent evaporation), and the soil-water content reached when the given crop with a developed root system is allowed to grow without irrigation until completely wilted. Although water will still be draining from the soil, Miller (8) has shown that the 4-day waiting period for a shallow soil results in a water content that represents the effective field capacity. A 6- to 10-day waiting period is required for deeper soils and root systems.

Current Meteorological Data

Current meteorological data required for each region are: minimum and maximum air temperatures, solar radiation, dew point temperature, and wind run for each Julian calendar day since the last date of computation and for three forecast days. An optional, brief weather forecast can be included for each region.

Current Field Data

Current data for each field are: the alpha-numeric date of the last irrigation, the allowable soil moisture depletion at the present stage of growth, the date of the last irrigation if it falls within the present computation period, and the rainfall and/or irrigation amount with its date of occurrence.

Where the water table is high, a portion of the water loss by evapotranspiration may be supplied from the saturated zone. When this occurs, the allowable depletion can be increased and the efficiency adjusted to reflect that portion supplied by irrigation.

A brief description of the program steps, the FORTRAN program, sample calculations, and operational guides can be obtained on request from the authors.

MODIFICATIONS UNDERWAY

The U. S. Bureau of Reclamation has modified the program to provide generalized irrigation forecasts for the major crops in an area of similar soils. These forecasts are updated weekly and distributed to cooperators who provide their own field monitoring. This service is being evaluated in 1970 in Idaho by the USBR and Idaho Agricultural Extension Service concurrently with the individual field scheduling service. The cost of the generalized schedules should be less, and the results can be distributed more widely (5). However, rainfall is treated uniformly for the areas and more interpretation by the irrigator is required.

When used in semihumid areas, the probability of rainfall needs to be considered in irrigation forecasts. The addition of expected rainfall to this program is described in the next paper in these proceedings.

In areas where climatic conditions are more variable than in the arid West, a mean E_t rate that is more stable than that provided by a 6-day mean is needed. An estimate of E_t for the balance of the season is also needed when irrigation dates are to be optimized. A simple procedure requiring only the mean maximum potential E_t, its time of occurrence, and a time parameter will be available on an optional basis. This procedure assumes that the distribution of mean potential E_t can be represented by a "normal" distribution function

$$\overline{E}_{tp} = E'_{tp} \exp[-(\frac{t - t'}{\Delta t})^2] \qquad [11]$$

where $\overline{E}_{tp}$ = the mean E_{tp} expected at a given date t (in Julian days), t' = the Julian calendar day when the maximum mean potential evapotranspiration, E'_{tp}, occurs (about July 15 in the Northern hemisphere), and Δt = the days before and after t' when $\overline{E}_{tp} = 0.37\ E'_{tp}$. The suitability of this procedure is illustrated in Figure 1 for southern Idaho and for Akron, Colorado in the next paper. The scatter in the spring is due to highly variable climatic conditions. However, since most crops are planted in southern Idaho between April 10 and June 1, the estimates are needed primarily after June 1. The use of this procedure also eliminates the need for the 3-day forecasts of meteorological data.

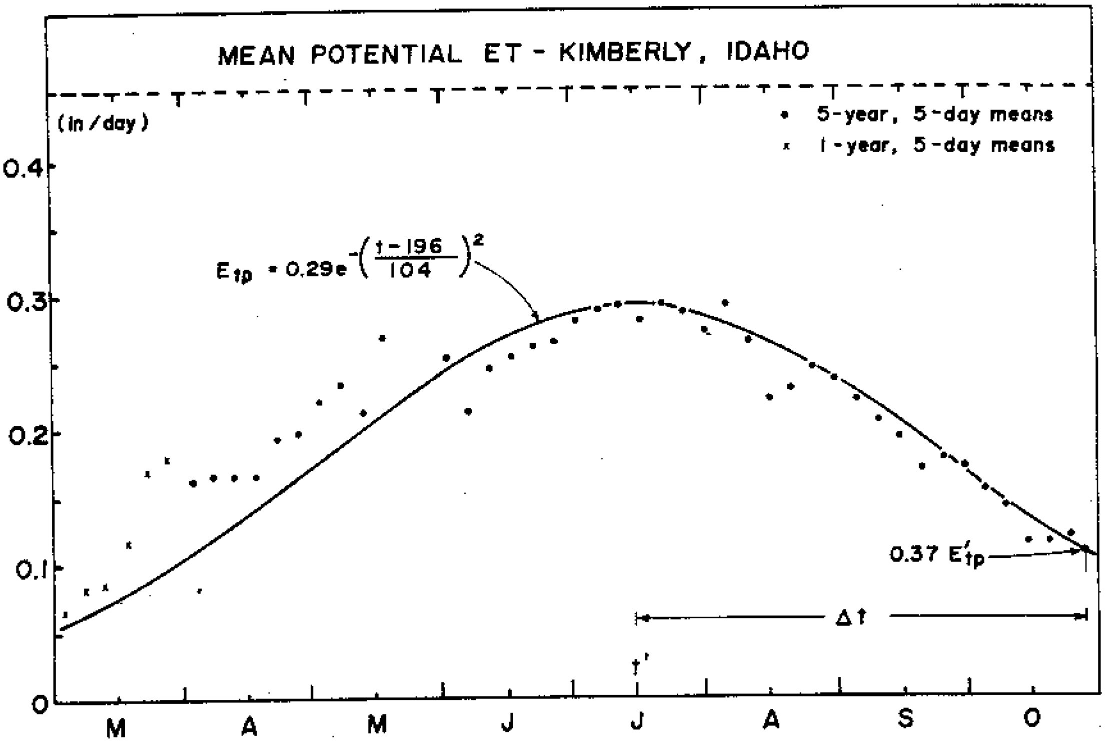

Figure 1. Distribution of mean potential evapotranspiration at Kimberly, Idaho

When the amount of irrigation water applied is known, a drainage component can be added to the program (9). This will require additional data to determine the constants for equation 8. In addition, the maximum amount of water that can be depleted from the soil must also include drainage. The maximum water that can be depleted by E_t and drainage can be defined as: "the maximum amount of water that can be removed by drainage and evapotranspiration, beginning one day after irrigation has ceased, with a given crop from a given soil. For reproducibility, it is assumed that the soil has been irrigated by flooding until the wetting front has advanced beyond the root zone."

An additional, optional subroutine is being developed to predict the optimum timing of limited irrigations for water-short areas or where irrigation water is expensive. Each time the program is run it will estimate the soil moisture depletion throughout the balance of the season and the probable yield reduction if no further irrigation is given. It will then predict the optimum time for applying specified increments of water. This procedure requires rainfall probabilities, the distribution of mean potential E_t, $\bar{E}_{tp}$, and the effect of limited water on yields. The latter item is the most difficult to define at this time for most crops. Data such as that provided by Musick and Dusek (10) can be used to develop approximate relationships. Some approximate models are now available for this purpose (2, 4).

FUTURE REFINEMENTS

Standardized Agricultural Meteorological Data

Many present agricultural weather stations are not in an agricultural environment, especially in arid areas. More accurate data (humidity, air temperature and wind) will be available when these stations are standardized.

Plant Growth Models

More accurate crop coefficients will be available when plant growth models are used to predict leaf-area development and plant maturity. These models also should include the effects of soil moisture deficits at all stages of growth on yields under prevailing climatic conditions.

Evapotranspiration Components

Greater accuracy in irrigation scheduling will be possible when more accurate estimates of the evaporation component of evapotranspiration are available. These estimates are more important in higher rainfall areas.

Drainage Problems

Drainage problems, or wet soil conditions, that affect either plant growth or harvesting operations can be reduced if irrigation scheduling programs are modified to include predictions of adverse effects of late irrigations in semi-humid areas. Also, the contribution to E_t from water in the saturated zone and its effect on soil moisture depletion needs to be incorporated where high water tables exist.

SUMMARY

A simple procedure for scheduling irrigations has been needed for many years. Irrigation scheduling, using meteorological techniques and a computer, is now practical. Computer facilities are presently available to anyone with a telephone in the United States. Such irrigation scheduling can be initiated now while further refinement is underway. Potential economic returns can exceed the costs of such a service by severalfold. The interest and enthusiasm for a service that can provide data and forecasts of this type to the modern farmer for his decision-making processes are very high. With increasing costs of farming and decreasing water supplies, the modern farmer needs such a service to remain solvent. Farmers who depend only on rainfall also need such information to make decisions as to the need for fertilizer--or additional amounts of fertilizer--if it appears that the soil moisture conditions are adequate for higher yields. The information provided with this computer program has also been educational to the irrigation farm manager, because it has increased his understanding of the soil moisture reservoir and its management.

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