Estimating Soil Moisture Depletion from Climate, Crop and Soil Data

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TREMENDOUS international scientific effort has been expended on evaporation and transpiration problems during the past decade as evidenced by hundreds of technical publications, and numerous conferences. However, use of this scientific achievement by agriculturalists, project planners and operators of irrigation farms has lagged behind technological advancements. The lag in adaptation of new technology by the user can be partly attributed to a lack of time, technical training and experience in meteorology, physics and agronomy.

One of the greatest potential applications of evapotranspiration technology is in the management of irrigation farms. Recent studies in the Western States indicate that the timing of irrigations and the amount of water applied have changed very little during the past 25 years. Irrigation scheduling is a decision-making process repeated many times each year, involving when to irrigate and how much water to apply. Both criteria affect the quantity and quality of the crop. Decisions delayed a week, or even a few days, may be costly. Measurements are required to determine when the soil moisture reservoir is full, half-full, or nearly empty. Furthermore, the depletion of soil moisture is complicated because it is determined by meteorological conditions, the growing crop and the unsaturated hydraulic characteristics of the soil. Instruments are available to help determine the soil moisture status, such as tensiometers, soil moisture blocks and the more complicated neutron meter, but these are not used extensively. For these and other reasons, the modern farm manager is generally willing to hire a service that will provide the necessary data and guidelines to assist him in making better and more profitable decisions.

To satisfy such requirements, we developed user-oriented methodology to enable districts, service companies, or mutuals to routinely provide additional information to the irrigation farm manager. The methodology utilizes scientific advancements and removes much of the guesswork in irrigation scheduling. The procedure is based on estimating soil moisture depletion from climate, soil and crop data. Rational, but simple procedures are used to obtain the necessary information.

One reason for maintaining simplicity is that a service providing decision-making data must be continuous. The risk of missing data increases with the complexity of instrumentation. Although the procedures emphasize irrigation applications, they also have potential application to nonirrigated agriculture. Some aspects of the general operating procedures have been provided in previous publications Jensen, 1969 and 1970).

The concept of scheduling irrigations using climatic data is not new (Penman, 1952; Baver, 1954; Pierce, 1960; Pruitt *et al.*, 1955; Rickard, 1957; van Bavel, 1960 and 1952). However, this method had not been adopted for general practical use or tested extensively previously. The mathematical model and the computer program which we have developed for this purpose and have tested for several seasons are described in this paper.

REQUIREMENTS OF THE PROCEDURE

The primary requirements of the system that were considered and adopted are briefly described below:

1 The procedure is "user" oriented, not "research" oriented.

2 The computations are regular and complete, i.e. estimates of soil moisture depletion for each field for each day of the growing season are provided.

3 Estimates of daily depletions of soil moisture within ±10 percent or possibly ±15 percent, which usually results in better accuracy over 10- to 20-day periods, are adequate. As a result, the timing of an irrigation will be within ±1 day with 10-day frequencies or ±2 to 3 days for 20- to 30-day frequencies.

4 If service groups are to provide these data to the agricultural user today, they must use standard meteorological data as recorded by more complete Weather Bureau Stations, or use data that can be obtained easily with reliable instruments.

If complex micrometeorological measurements are required, the general procedure loses much of its utility to an inexperienced service group. As experience and demands for the service increase the techniques can be refined. In general, simple rational equations that require a minimum number of assumptions were preferred over more complicated relationships. Equations that gave integrated daily values from daily inputs were used instead of rate equations that require precise, continuous gradient measurements.

5 Feedback is essential to the satisfactory operation of the system. This feedback consists of rainfall for each field, the dates and, if available, the amounts of irrigation water. Periodic monitoring of the soil moisture status as compared to the predicted status is highly desirable, but not essential. In practice, monitoring enables adjustments for inadequate irrigations, unusually rapid or slow crop development, disease or insect damage, and controlling parameters.

COMPONENTS OF THE MATHEMATICAL MODEL

Soil Moisture Depletion

For convenience, the major dependent variable in the model is soil moisture depletion. The major components affecting soil moisture depletion are related as follows:

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

where D = the 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

Evapotranspiration accounts for most of the depletion. The procedure first estimates the daily potential evaporative flux, E^* (the evaporative flux from a well-watered reference crop like alfalfa with 12 to 18 in. of top growth). Estimates of potential evapotranspiration by the energy balance approach

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would be ideal because of its proven reliability.

$$E^* = R_n - G - A \quad . \; . \; . \; . \; . \; . \; [2]$$

where E^* = evaporative flux (latent heat); R_n = net radiation; G = heat flux to or from the soil; and A = sensible heat flux to or from the air in cal per sq cm per day. However, this method is not practical at this time even though instruments are available for measuring R_n and G on a reference field. These instruments require periodic calibration and maintenance by technicians trained in meteorology and meteorological instrumentation. Furthermore, even though techniques for determining A directly were developed (Fuchs et. al., (1969), they require complex instrumentation and measurement of the "effective" surface temperature of the crop.

Therefore, equations using available meteorological data were needed. A combination equation using daily values of a minimum number of meteorological parameters provides adequate estimates of E^* for this purpose. The basic meteorological data required consist of: (a) daily maximum and minimum air temperatures; (b) daily solar radiation; (c) average dew point temperature or dew point temperature near 8 a.m.; and (d) daily wind run at a known height, preferably in an open area over a surface that does not change greatly in roughness or displacement height during the growing season. The most common combination equation is that presented by Penman (1963) and is recommended where adequate data are available.

$$E^* = \frac{\Delta}{\Delta + \gamma} (R_n - G) + \frac{\gamma}{\Delta + \gamma} (15.36)\ (1.0 + 0.01W)\ (e_s - e_d) \quad . \; . \; . \; [3]$$

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 at maximum and minimum daily air temperature), e_d is the saturation vapor pressure at mean dew point temperature in mb. The parameters $\Delta/(\Delta + \gamma)$ and $\gamma/(\Delta + \gamma)$ are mean air temperature weighing factors whose sum is 1.0 (10, 14), W is total daily wind run in miles, R_n is daily net radiation in cal per sq cm, and G is daily soil heat flux in cal per sq cm.

Daily net radiation estimates are required when the combination equation is used. Since percent of sunshine or degree of cloud cover normally used to estimate the net longwave radiation generally are not available, procedures were developed for estimating net radiation using observed solar radiation for a day (R_s) relative to solar radiation that would normally be expected on that day if there were no clouds (R_{so}). Cloudless day values can be obtained from estimates by Fritz (1949) or by plotting clear day values to obtain an envelop curve through the high points. Net radiation in cal per sq cm was estimated as follows:

$$R_n = (1 - \alpha)\ R_s - R_b \quad . \; . \; . \; [4]$$

where $(1 - \alpha)R_s$ represents the net shortwave radiation received by a green crop with full cover, α is the mean daily shortwave reflectance or albedo and R_b is the net outgoing long wave radiation. Since the reflectance coefficients for most green crops with full cover are about 0.22 to 0.25, 0.23 was used in the program. R_b was estimated as follows:

$$R_b = (aR_s/R_{so} + b)R_{bo} \quad . \; . \; . \; [5]$$

where R_{bo} is the net outgoing long wave radiation in cal per sq cm on a clear day and estimated as follows:

$$R_{bo} = [0.98 - (0.66 + 0.044\sqrt{e_d})]\ (11.71 \times 10^{-8})\ \frac{T2_A{}^4 + T1_A{}^4}{2} \quad . \; [6]$$

where 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 per sq cm per day deg K^{-4}; and $T2_A$ and $T1_A$ are the maximum and minimum daily air temperatures, respectively, in deg K.

Originally the constants a and b in equation [5] were derived using data from Davis, California, obtained in personal communication from Pruitt (1.35 and −0.35). More recent evaluations in Idaho indicated that under arid conditions where the nights frequently are clear, the values are more like 1.2 and −0.2 for a and b, respectively. As a first, one can assume $a = 1.0$ and $b = 0$.

The constants for the Brunt portion of equation [6] are similar to those of Goss and Brooks (1956), who obtained values of 0.66 and 0.040 in California, and Fitzpatrick and Stern (1965), who obtained constants of 0.65 and 0.049 in Australia. These coefficients are expected to vary under different climatic regimes, and regional coefficients should be used if available. The coefficients for the Brunt equation presented by Penman generally are not applicable to arid conditions. Use of the Penman constants in the Brunt equation for arid conditions overestimates the net outgoing radiation under very low humidities as previously reported by Fitzpatrick and Stern (1965).

A simple empirical equation for daily soil heat flux in cal per sq cm based on changes in air temperature is currently being used [G = (average air temperature minus the average air temperature for the three previous days in deg F) × 5]. Where day-to-day temperatures do not change greatly and day-to-day radiation is similar, soil heat flux is relatively small during the summer months and can be neglected.

The combination equation with the aerodynamic terms proposed by van Bavel (1952) was also tested using daily meteorological data. The aerodynamic portion of this equation ($11.505W/[\ln (z/z_0)]^2$ in place of $(15.36)\ (1.0 + 0.01W)$ in equation [3]) is applicable strictly to adiabatic conditions, which generally do not exist for long periods of time under arid conditions. It tends to be more sensitive to high wind, high vapor pressure deficit conditions than the Penman equation and generally overestimates evapotranspiration if one uses a z_0 value greater than about 1 cm in windy areas.

Rosenberg (1969) also found that this equation underestimated evapotranspiration on calm days. We have found that we need to calibrate the van Bavel version of the combination equation by varying the z_0 value. Sellers (1964) also indicated that a transfer coefficient based on the simple logarithmetic profile seemed to be too large, leading to unreasonably high evapotranspiration rates, especially from tall crops. Many transfer functions relating windspeed to the diffusion coefficient have been derived over water surfaces (Sellers, 1964).

Slatyer and McIlroy indicated that the aerodynamic term should be calibrated (1961). A suitable empirical relationship similar to that proposed by Penman, but derived for an aerodynamically rough crop like alfalfa under a wide range of arid or semiarid conditions, can improve the reliability of the combination equation. One reason why the aerodynamic term of the combination equation is more critical under arid conditions, is that advection accounts for a large portion of the required energy in the summer months. Under these conditions, the convective term must be larger than the radiation term contrary to the general concept that the radiation term is rarely smaller than the convective term. In contrast, the latter statement is generally true in the more humid areas. A thorough description of the combination equation, and its development by Penman, Ferguson, and Budyko is presented by Tanner (1968).

Although the Penman transfer coefficient was used in these studies, under large, high advective conditions in midsummer it also underestimated E^*. Similar results were obtained by Rosenberg (1969).

If windspeed and humidity data are not available, a two-parameter empirical energy equation can be used, except when advective conditions are severe (modified Jensen-Haise, 1970).

$$E^{*} = C_T\ (T - T_x)\ R_s \ldots\ldots [7]$$

where C_T = a temperature coefficient per deg F, T = mean daily air temperature, F; $C_T = 1/(C_1 + 13C_H)$, where $C_1 = 68 - 3.6\ E_{ft}/1000$; E_{ft} = elevation above sea level in ft; $C_H = 50/(e_2 - e_1)$, where e_2 = saturation vapor pressure in mb at mean maximum air temperature for the warmest month and e_1 = saturation vapor pressure at mean minimum air temperature for the same month; $T_x = 27.5 - 0.25(e_2 - e_1) - E_{ft}/1000$; and R_s = daily solar radiation in cal per sq cm.

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

Evapotranspiration

Evapotranspiration for a given agricultural crop (E_t) was estimated from potential evapotranspiration (E_{tp}) as follows:

$$E_t = K_c\ E_{tp} \ldots\ldots [8]$$

where K_c is a dimensionless coefficient like that proposed by van Wijk and de Vries (1954). It represents the combined 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 (Jensen, 1968).

Examples of the influence of growth stage on crop coefficients where soil water is not limiting have been presented for grain sorghum by Jensen (1969, 1970), and for corn by Denmead and Shaw (1959). Shaw (1966) also presented ratios of evapotranspiration to evaporation from an open pan for corn and soybeans, along with the leaf area index for soybeans. In this case the type of leaf was greatly different from one crop to the other, but the crop curves and their development were similar. These have also been used for estimating soil moisture. Other researchers are developing similar relationships for other crops. Pruitt, et al., for example, recently presented detailed curves relating evapotranspiration from beans, sugarbeets and tomatoes to E_t from ryegrass.

The crop coefficient is also influenced by the wetness of the surface soil. In our computer model, the crop coefficient was estimated as:

$$K_c = K_{co}\ K_a + K_s \ldots\ldots [9]$$

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 = the relative coefficient related to available soil moisture. In this program, K_a was assumed to be proportional to the logarithm of the percentage of remaining available soil moisture (AM): $K_a = ln\ (AM + 1)/ln\ 101$; K_s is the increase in the coefficient when the soil surface is wetted by irrigation or rainfall. The maximum of $K_{co}K_a + K_s$ normally will not exceed 1.0 for most crops. The value of K_s could be expected to vary as follows:

$$K_s = (K_1 - K_{ci})e^{-\lambda t},\ K_1 > K_{ci} \ldots\ldots [10]$$

where t = days after the rain or irrigation, λ represents the combined effects of evaporative demand, soil characteristics, etc., and K_{ci} represents the average K_c value at the time the rain occurred. To make the program operational initially, the following approximate values were used for K_s for the first, second and third day after a rain or irrigation, respectively: $(0.9 - K_c)0.8$; $(0.9 - K_c)0.5$; $(0.9 - K_c)0.3$.

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 was treated as rainfall.

Drainage

An adjustment for continued drainage was not built into the present computer model. Water applications in excess of estimated soil moisture depletion was assumed to drain from the soil.

Irrigation Estimates

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

$$N = \frac{D_o - D}{\overline{E_t}}$$

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

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 and three forecast days. Mean evapotranspiration for the crop involved at that location and time could be used if available.

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

$$W_I = \frac{D_o}{E},\ D_o > D \ldots\ldots [12a]$$

$$W_I = \frac{D}{E},\ D > D_o \ldots\ldots [12b]$$

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.

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

Discussion

Meteorological Data

Irrigation districts, mutuals or service companies can be expected to equip and maintain a weather station with routine instruments if an irrigated area contains from 10,000 to 25,000 irrigated areas. If data from existing weather stations must be used, each station may represent about 0.25 to 1.0 million acres. Rainfall must be a field-by-field or farm-by-farm variable where local thunderstorms prevail.

Crop Coefficients

Various models of the transport resistance to heat and vapor flux between the surface and some height are summarized by Tanner (1968). Similarly, various internal resistances such as those encountered with mulched soil, bare soil, plant leaves and canopies are discussed by Tanner. From an energy balance viewpoint, the crop coefficient represents the relative heat energy converted to latent heat. The major energy terms of the soil-plant-air continuum are:

$$K_c = \frac{R_n + G + A}{R_{no} + G_o + A_o} \ldots [13]$$

The subscript o designates concurrent values for the reference crop in the immediate vicinity (in this case alfalfa). The terms are positive for input to the crop-air zone and negative for outflow. The sensible heat flux term (A) is the most difficult to determine or predict in estimating the crop coefficient. The terms given in equation [13] can be rewritten using the Bowen ratio (β).

$$K_c = \frac{1 + \beta_o}{1 + \beta}\ \frac{R_n + G}{R_{no} + G_o} \ldots [14]$$

When crops are grown under irrigation and at similar plant densities, the crop coefficient tends to be very similar from one area to the next for sugarbeets grown in Twin Falls, Idaho; Bushland, Texas; and Phoenix, Arizona (Jensen and Erie, 1971). The maximum value of the crop coefficient will probably be less than 1.0 for the same crop grown under dryland conditions with very low planting rates and wide row spacings.

To calculate the relative effects of widely spaced dryland row crops with low planting rates, one must consider the relative leaf area and the leaf resistances along with some factor accounting for the increased resistance within the soil, since the root system also would probably be less dense, and the degree of exposed soil is greater. Existing experimental data probably could be used to approximate the coefficient for use in decision-making computations.

With irrigated crops and experimentally derived crop coefficients under conditions where soil moisture is not limiting, adjustments are needed for decreasing soil moisture with most crops and soils. However, evidence indicates that for a dense system and low evaporative demands, there may be no appreciable reduction in the rate at which soil moisture is withdrawn as compared to a less dense root system and high evaporative demand, such as indicated by Shaw and Laing (1966).

The number of studies relating evapotranspiration of crops to various evaporative pans and other evaporation devices are too numerous to mention. There has been an increase in estimates of soil moisture for planning purposes using computed values of potential E_t and coefficients for a crop (Baier and Robertson, 1968). In this case, the coefficients take into account the moisture tension characteristics of the soil. Others consider the apparent diffusion resistance of crops and its relation to degree of cover, Rijtema (1959). Studies such as these increase the general technology of soil moisture management.

Drainage

The drainage rate from a soil that has been irrigated when evapotranspiration is zero generally can be related to time by the expression proposed by Ogata and Richards (1957).

$$W = W_0 t^{-m} \qquad [15]$$

where W_0 is the water content when $t = 1$, and m is a constant derived experimentally for a given soil.

When evapotranspiration is not zero, the rate of drainage at a given water content will be less than this value due to water withdrawal by the crop. During the first few days after an irrigation, the hydraulic conductivities are large enough that the hydraulic gradient is not affected greatly by the water withdrawal, and a correction similar to that proposed by Wilcox (1960) could be used.

Drainage could be approximated by estimating the evapotranspiration for a given day and subtracting it from the water content first, and then use this value of W to estimate the drainage. This general technique is currently being tested (personal communication with D. E. Miller) and the subroutine will be available for optional use during the 1971 crop season. However, if the amount of water applied is not known, this addition is not needed.

Gardner (1968) presented a general solution of a similar equation which gives the amount of water transpired by the plant, and would have otherwise been lost from the soil profile by drainage. This solution could also be adapted to this problem.

Testing the Mathematical Model and Computer Program

Net Radiation Estimates

Meteorological data collected by a U.S. Weather Bureau Agricultural Station were used for these estimates. The station is located about one-half mile south of the alfalfa field irrigated only once in the spring and about one-half mile north of the fields in which the other measurements were made. The meteorological data included daily maximum and minimum air temperatures, dew point temperature at 8 a.m., daily solar radiation and daily wind run at a height of 12 ft. The windspeed was adjusted to a height of 2 m for use in the Penman equation by assuming a logarithmic profile with a z_0 value of 1 cm.

Comparisons of estimated daily net radiation vs net radiation measured with a Fritchen net radiometer, an electronic integrator and a data logging system for 1967 and for 1968 showed that most of the daily estimates were within ±10 percent except in 1968 during the heavy cloud cover in August.

The coefficients derived for Davis, California were used in equation [5]. If the Idaho coefficients had been used, the estimates for the heavy cloud period would have been improved. These data indicated that under semiarid conditions with many cloudless days or only partly cloudy days, the simplified equation for estimating net radiation and adjusting for net long wave radiation without using the percentage of sunshine of cloud cover appears to be satisfactory.

Estimates of Daily Potential Evapotranspiration

Estimates of daily evapotranspiration for sugarbeets in 1968, assuming a crop coefficient of 1.0 and using the Penman equation, were compared with evapotranspiration determined by the Bowen ratio technique. The estimates with the Penman equation were very good but they tended to be a little low when the evaporative demand was high. The ratio of the sum of the estimated values to the sum of the energy balance values was 1.00. Similar estimates were obtained with the van Bavel combination equation with a z_0 value of 0.5 cm. In this case, the ratio was 1.02. When a z_0 of 1 cm was used, the ratio was 1.14. When a z_0 of 5 cm was used, which might be expected for crops such as these, the estimate was much too high and the ratio was 1.65.

Similar estimates were obtained in 1968 using alfalfa and a weighing lysimeter. Most of these values were obtained late in September when advective energy was very high. In this case, the Penman estimates generally underestimated E_{tp}, and the ratio was 0.91. Estimates with the van Bavel equation with a z_0 of 1.0 were better. Estimates for September were more accurate using a z_0 of 1 cm, but many of the other estimates were too high; the ratio was 1.05. With a z_0 of 5 cm, the ratio was 1.52.

Even though scatter is apparent in the daily values, a summation of 5- to 10-day means shows significant improvement. Generally, estimates for 5-day periods were within 5 to 10 percent of the measured values in the summer months for the three equations used, except when using a z_0 value greater than 1 cm in the van Bavel equation.

Soil Moisture Depletion Estimates

In general, one would expect cumulative estimates of evapotranspiration to be more accurate if the errors are random. Evaluations were made using small plots in 1967 and 1968, and tensiometers were used as checks in fields in 1968. Measurements made in 1969 were compared with the computer output in which the Penman equation was used to estimate potential evapotranspiration. Soil moisture depletion was recorded by a precise weighing lysimeter with a surface area of 6 x 6 ft and a depth of 4 ft, located in a field of alfalfa about 500 ft sq. The estimates and the measured depletion are presented in Fig. 1.

Depletion values as measured with the lysimeter are shown as the solid line and the computer output for the days in which the runs are made are

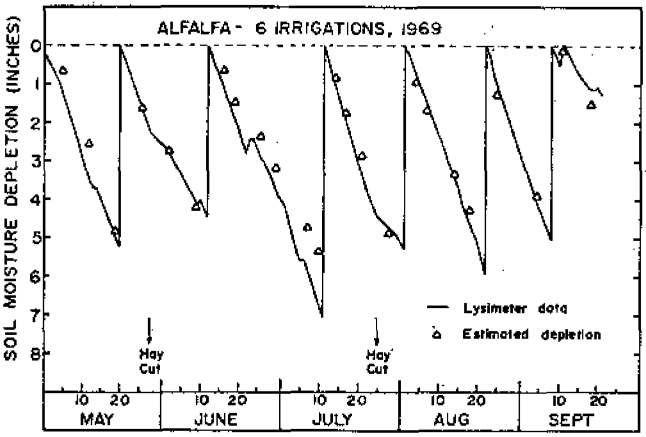

FIG. 1 Estimated versus measured cumulative evapotranspiration with water not limiting, Kimberly, Idaho, 1969.

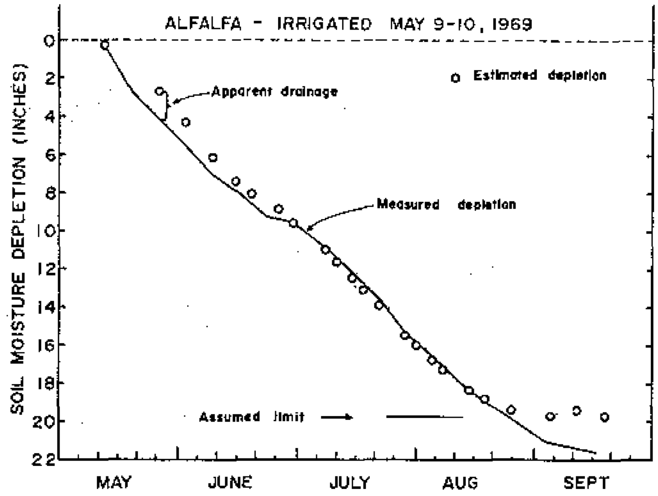

FIG. 2 Estimated versus cumulative soil moisture depletion with decreasing soil moisture, Kimberly, Idaho, 1969. (Measured depletion by R. A. Kohl.)

shown by the triangular points. There were several rains in midsummer and two cutting dates. Cutting effects are taken into account in this manner: Immediately following cuttings, the crop coefficient is reduced from 1.0 to 0.5. It is then increased linearly to 1.0 over a period of 20 days.

The only period in which a significant deviation occurred was from the middle of June to the middle of July. The computer program underestimated the depletion of soil moisture, 5.4 in. vs 6.7. Since the total amount that can be depleted was near 12 in., this underestimate would not significantly affect crop production. However, estimated evapotranspiration using the Penman equation for this period in 1969 was only 85 percent of the 5-year average because of climatic conditions. If the van Bavel aerodynamic term with $z_0 = 1.0$ cm had been used for this period, excellent agreement would have been obtained between the estimated and measured depletion.

A comparison of estimates for alfalfa that was irrigated thoroughly on May 9 and May 10 and then was not irrigated for the balance of the season is shown in Fig. 2. Measurements were made using two access tubes and a neutron probe. The computer program utilizes a limit on available soil moisture, which was assumed to be 19.7 in., but the limit was underestimated about 2 in. The deviation early in the season can largely be attributed to drainage following the heavy irrigation, since the first reading began the day after irrigation.

These data indicate that the adjustment for decreasing soil moisture for a deep rooted crop with full cover like alfalfa appears sufficient. The results obtained on alfalfa that was not irrigated for a 4-month period also indicate that a program such as this may have utility under dryland conditions.

Row crop coefficients may need to be modified at maximum cover for stand density. For example, in the Great Plains it is not uncommon to find sorghum planted at a low seeding rate under dryland conditions at a spacing of 40 to 80 in. Under these situations, a high proportion of soil is exposed, the density of the root system is less, and the leaf area index may be very low. Studies are underway testing a similar program using dryland data (personal communication with Dale Heermann).

The first version of this model was tested on about 50 fields in Idaho and 60 fields near Phoenix, Arizona in 1968 using equation [7]. In 1969, this program was tested on 43 fields and about 15 crops in Idaho and the same 60 fields in Arizona (Franzoy, 1969) using equation [3]. The A&B Irrigation District near Rupert, Idaho, in cooperation with the Bureau of Reclamation, scheduled 86 fields of several crops in 1969 and is expected to expand the service to 200-300 fields in 1970.

Valid direct benefits from scheduling are difficult to obtain. Fields or portions of fields used as checks provide some indications. However, the irrigation schedules provided influence the farmer's irrigation decisions so that such checks are not completely independent. The farmer's opinion of the beneficial effects of scheduling and his desire to continue or expand this service have been the primary criteria used to evaluate the effectiveness and value of this program.

Service companies are considering adding this type of service to their normal agricultural services now provided. Similar services apparently are being provided to a limited degree in England and in France. If a service such as this is provided in semiarid areas, or where rainfall plays a greater role, then longer range climatic forecasts, including estimates of rainfall, may be required. Trained personnel are important. The program is only a tool that is valuable in the hands of an expert. In areas where climatic conditions do not vary greatly from one year to the next, and where average values of measured evapotranspiration are available, they might be used in the forecast of E_t instead of the current daily computations.

The computer program served as an excellent educational tool for the irrigation farm manager, since it increased his understanding of the soil moisture reservoir and its management.

Summary

Net radiation can be estimated in arid areas using appropriate constants, maximum and minimum air temperatures, dew point temperature, observed solar radiation and clear day solar radiation. The coefficients proposed by Penman for estimating net radiation do not appear to be applicable in arid areas of the U.S. or in Australia (Fitzpatrick and Stern, 1965).

A combination equation and daily meteorological data, including daily wind run, results in daily estimates of evapotranspiration appropriate for scheduling irrigations. The estimates obtained with Penman's aerodynamic version were not as sensitive to wind effects as van Bavel's version. If used with z_0 as a calibration term under southern Idaho conditions, z_0 in van Bavel's equation should be 0.75 cm. Over longtime periods, Penman's version gives identical results to van Bavel's version when using a z_0 value of 0.5 cm in southern Idaho.

A two-parameter empirical equation using only solar radiation and air temperature provides adequate estimates when advection is not severe. It can also be used to schedule irrigations in

the summer months if more complete meterological data are not available.

During the past two years, we have demonstrated that irrigations can be scheduled using these techniques and computer facilities now are available to anyone with a telephone in the United States. Such irrigation scheduling is practical and economical even though further refinement is needed. The potential economic returns can exceed the costs of such a service by severalfold, depending on the starting point. The interest and enthusiasm for a service that would provide data of this type to the modern farmer for his decision-making processes are very high because it has been needed for many years.

With increasing farming costs and decreasing water supplies, the modern farmer will demand a service such as this to remain solvent in this highly competitive field of irrigation agriculture. Farmers who depend only on rainfall will be demanding information such as this to make decisions as to the need for fertilizer or additional amounts of fertilizer if it appears that the soil moisture conditions are adequate to sustain higher yields. There are other potential uses of this information in planning and management.

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