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that as the ODR of a soil decreases, stomata close, independently of other factors like soil-water status or light intensity.

Leaf diffusive resistance (R_s) is an indicator of stomatal aperture. When R_s is high, stomata are closed; when R_s is low, stomata are open. Figure 1 shows the effect of ODR on R_s for wheat grown in soil at equilibrium with gas mixtures of 0, 4, and 21 percent O_2. Soil temperatures were varied also to give 9°, 15°, and 21° C treatments. These two factors combined to create a range of ODRs. At low ODRs R_s increases sharply, indicating stomatal closure. This occurs despite the maintenance of uniformly favorable soil water status in all treatments.

Similar responses have also been found in tomato, cotton, sunflower, and jojoba. Figure 2 demonstrates the R_s increases of sunflower and jojoba in an experiment similar to the wheat experiment. Evidently, the R_s of both sunflower and jojoba responds to soil temperature. At high soil temperatures, the respiration rate of roots (O_2 demand) increases, as does competition for soil O_2 by soil microorganisms. Higher soil temperatures thus induce an oxygen shortage, which results in greater stomatal closure. Interestingly, crop damage caused by excessive soil water is usually more severe in warm weather than in cool weather. This follows from our results since stomatal closure due to flooding would prevent the normal transpirational cooling of plant tissues.

These findings have practical implications. When stomata are closed, we can expect not only heat stress to occur, but also photosynthesis to be reduced. These data may promote rethinking of the practice of flood-irrigating some crops, particularly on fine-textured soils, or when excessive canopy temperatures are likely. They also help us to better understand one mechanism of crop damage resulting from unwanted soil flooding.

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Simplified but scientific irrigation scheduling

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In the past, when irrigation water was ample and its cost negligible, the obvious management strategy was to eliminate water as a limiting factor in producing crops at the lowest possible cost. As irrigated agriculture competes for the limited water supplies and costs of both energy and water rise, effective on-farm water management programs are needed to maximize irrigation efficiency. This report describes a new approach to developing and disseminating irrigation scheduling information among California's agricultural water users.

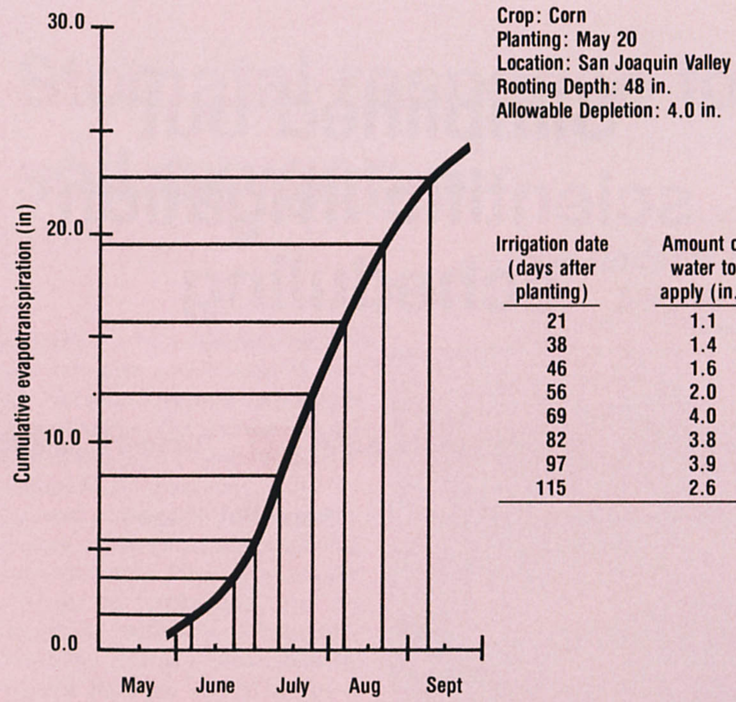
In designing their seasonal water-management programs, farmers are confronted with three essential questions: (1) how often should each field be irrigated; (2) how much water should be applied at each irrigation; and (3) which irrigation management techniques should be used to efficiently apply the needed amounts of water at the appropriate levels? Although we address only the first two questions here, the answers may be academic without evaluating the adequacy and efficiency of individual irrigation practices.

Among the many procedures commonly used to schedule irrigations, the water-budget method is the most prevalent. In the water budget the crop root zone is visualized as a reservoir of crop-available water. Water is withdrawn from the reservoir through evapotranspiration (ET) or drainage and added through rainfall and irrigation. If the volume of the reservoir and the amount that can be used without stressing the plant (called the allowable depletion [AD]) are known, along with the depletion rate (ET), the date of the next irrigation can be predicted. Effectiveness of the method hinges on an accurate determination of AD and ET. Research over many years has established the ET requirements of several crops in California and made possible the day-by-day prediction of ET. Water retention properties of the principal soils are also well known, as are typical rooting depths of many crops. What is now needed is to make this information available in a form that the average farmer or irrigator can use.

A useful characteristic of summer weather in California's interior valleys is the constancy in evaporative demand. The absence of rainfall and the small year-to-year variations in summer weather make long-term averages of weather parameters attractive for use in prediction. Early studies conducted by the University of California at Davis and the State Department of Water Resources in several locations throughout the Central Valley documented the variability in ET rates during the irrigation season, indicating that 90 percent of the time, 10-day to 2-week forecasts of ET based on long-term averages are within 10 percent of actual ET.

The relative constancy in ET demand during a good part of the irrigation season and the availability of long-term ET records and accurate crop coefficients for many crops in the Central Valley make it possible to use average or normal year crop ET to predict irrigation dates and amounts for management purposes. Recently, many large-scale irrigation scheduling programs have been implemented by various agencies and private consultants. Computer programs based on the water-budget concept are now being used to help provide irrigation scheduling services in large areas of the western states.

Field verification of computer predictions is necessary, however, because of uncertainty



Irrigation date (days after planting)	Amount of water to apply (in.)
21	1.1
38	1.4
46	1.6
56	2.0
69	4.0
82	3.8
97	3.9
115	2.6

Fig. 1. An irrigation management program (IMP) for a corn crop on a medium-textured soil in California's San Joaquin Valley.

about the depth of water actually applied at each irrigation; uncertainties in evaluating the crop rooting depth, soil water storage capacity, and allowable depletions; the spatial variability of soil water-holding characteristics within each field; uncertainties in computations of crop ET, particularly in the early growth stages; and the need to evaluate the effective rainfall on each farm.

This need for field checks and frequent calculations is perhaps one of the most important factors limiting broad acceptance of irrigation scheduling techniques among farmers. Although in some parts of the Central Valley, irrigation scheduling services may be contracted for, in many other areas where the apparent economic benefits do not justify the cost of such services, farmers do not have the time or expertise to make detailed water budget calculations and field checks. Therefore, despite significant efforts by various agencies and the University, adoption of detailed water budgeting techniques by farmers has not been widespread so far. A simplified approach to scheduling irrigations is needed that, at the same time, will have predictive value.

Irrigation management programs

If the ET data for a normal year are combined with the water-holding characteristics of a particular soil, an irrigation management program (IMP) may be designed that indicates when to irrigate and how much to apply under average or normal-year conditions. The example presented in figure 1 shows cumulative ET for any time after planting. The vertical distance between two adjacent horizontal lines represents the allowable depletion for each irrigation cycle. The irrigation date is determined by drawing the horizontal line to intersect the ET curve, and then a vertical line to the date line at the base of the graph.

This IMP, presented in tabular form or on a graph, is an easy-to-use, predictive tool that requires much less effort for irrigation programming by the farmer than do detailed water-budget calculations. If more accuracy is desired, the normal-year IMP provides an excellent base for irrigation scheduling: the ET curve is simply updated periodically with values from the current year and the irrigation dates changed accordingly. Once the appropriate IMP has been designed for a given soil-crop combination, it can then be used as a rational basis for irrigation scheduling with only periodic checks. In California these checks must be made more frequently at the start and end of the irrigation season, when unpredictable weather conditions may cause large year-to-year variations in ET rates.

The IMPs are valuable aids in predicting requirements for water, labor, and other essential inputs. They are also helpful in planning the date of the last irrigation so that expected winter rainfall will be stored within the root zone of next year's crop. And although they are based on the crop's being fully supplied with water, they are helpful in

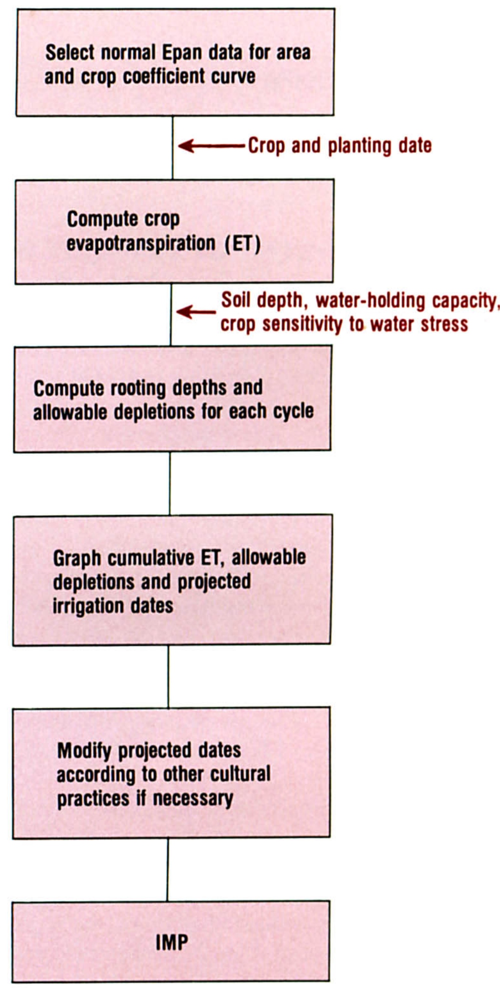


Fig. 2. Operation of IMP computer program.

adjusting cropping patterns, planting dates, and other strategies when the preseason prediction is for a less-than-normal water supply.

It should be pointed out that under any irrigation scheduling method there are uncertainties in evaluating crop ET, the soil water-holding capacity, allowable depletion, and the volume of water applied at each irrigation and stored within the root zone, as well as its variability throughout the field. Thus the need for precise estimates of other parameters, including crop ET, may be questioned. Where soil water-holding capacity is low, water costs high, or crops very sensitive to water stress, the use of more sophisticated techniques for scheduling irrigations may be justified, however. Therefore, a computer model was developed so that IMPs could be designed for any crop-soil-management condition.

Designing IMPs

The irrigation scheduling model used in designing IMPs requires input of two parameters: crop evapotranspiration and allowable soil moisture depletion. Once these are known, a water budget is used to determine irrigation dates and amounts. The flow chart (fig. 2) illustrates the sequence followed by the computer program in designing an IMP.

A. Estimating crop evapotranspiration. ET is computed by using long-term pan evaporation data for either the Sacramento or the San Joaquin Valley. Crop ET is calculated as:

$$\text{ETcrop} = \text{Epan} \times \text{Kp}$$

where Epan is the evaporation from a class A pan, and Kp is an experimentally or empirically determined crop coefficient that varies with time after planting. In this program the Kp values for a given crop and planting date are fitted to a cubic spline function, which draws a smooth curve through the data points allowing for interpolation at any required time interval.

B. Estimating allowable soil moisture depletion. Allowable soil moisture depletion, AD, is estimated for any given time in the growing season as follows:

$$\text{AD} = \text{AW} \times \text{RD} \times \%\text{AD}$$

where AW is the available water-holding capacity of the soil, RD is the rooting depth at the time of the estimate, and %AD is the percentage of available soil water that can be extracted from the root zone without reducing crop yield.

The AD level depends on plant factors (rooting density and developmental stage), soil factors (AW and soil depth), and atmospheric factors (current ET rate). The extensive body of literature and current knowledge of crop responses to water stress were used to select appropriate AD levels in designing the IMPs.

To estimate the extent of the root zone in an annual crop as it develops, a simple root growth model based on the functional balance between shoot and root growth was developed. In this model, the rate of vertical root growth into the soil profile is assumed to be proportional to the rate of vegetative growth above the soil surface. Using the crop coefficient, Kp, as a quantitative measure of vegetative growth, the change in root depth with time is correlated directly to the change in the crop coefficient with time. Whenever the crop coefficient reaches a maximum (which occurs near full canopy cover), root depth, limited by either soil depth or the crop's growth characteristics, is also a maximum. Although the root development model may be too simple to work under all situations, it provides a needed approximation in the absence of data on root development under field conditions.

Several management options may be included in the design of the IMPs. Soil intake rate or system considerations may limit the depth of water that may be applied during a single irrigation, regardless of the storage capacity of the soil. The program can be modified to impose irrigations at fixed time intervals under situations where water delivery to the farms is on a rotation cycle. The need to supply the ET losses since last irrigation then becomes the main emphasis.

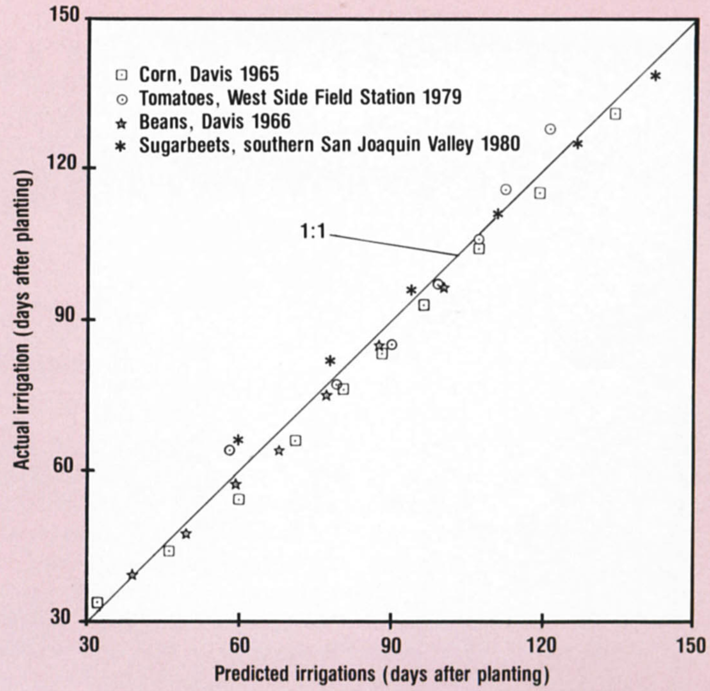


Fig. 3. Comparison of actual versus predicted irrigation dates, based on actual and normal ET data, respectively.

Test of the IMP

A number of tests were carried out using the computer program to first design IMPs for a given year and then compare the predicted irrigation dates for that year with those obtained using the long-term average Epan data as input. Four crops, four years, three locations, and several soil types in the Central Valley were used to compare actual with normal-year irrigation dates (fig. 3).

There was good agreement between predicted and actual irrigation dates calculated with current-year ET data. Most of the discrepancies occur for the first irrigation where year-to-year variations in ET are generally greatest. These tests support our hypothesis that long-term average ET may be safely used in designing the IMPs.

IMPs for many important crops of the Central Valley are now being developed based on different planting dates and a wide range of allowable soil-water depletion levels. Leaflets containing the IMP and a simple form to update it will be made available. The farmer, assisted by a farm advisor, Soil Conservation Service engineer, or consultant, will evaluate the water-holding capacity, crop rooting depth, and soil depth to select the appropriate IMP. The IMP can then be adjusted to the farmer's method of irrigation and other cultural operations.

The IMP is a simplified, practical approach, which we are optimistic will receive much greater acceptance than past efforts to involve farmers in using technical data to schedule irrigations. It is a ready-to-use, precalculated irrigation program that takes into account evaporative conditions, the crop and its stage of growth, and soil factors determining water availability. By selecting the IMP developed for a particular crop and adjusting for the planting date and allowable depletion expected in the specific soils, the farmer can much more easily make technically sound irrigation decisions. When evaporative conditions depart from the normal pattern, the IMP can be readily corrected to adjust the irrigation schedule or depth of water to be applied, or both. Use of these IMPs will help meet the need to achieve a high level of efficiency in agricultural consumption of the state's limited water resources.

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