Programming irrigation for greater efficiency implies maximizing water use efficiency. However, though this itself is an important objective for water-deficient areas, the farm manager or owner is more interested in maximizing his net income by optimum use of irrigation water, fertilizers, and other inter-related inputs. Fortunately, if maximum net income is achieved, optimum water use efficiency usually has also been attained. More progress toward greater efficiency can be expected by working toward the goal of greater net income rather than greater water use efficiency, *per se*.

Evaluations of farm irrigation practices in the western United States during the late 1950's and early 1960's (Tyler et al., 1964; Willardson, 1967) showed little change in irrigation scheduling practices in 25 years (Israelsen, 1944). No single factor related to the system, soil, or crop appeared to be limiting irrigation efficiency. During this same era, irrigation science and technology made significant advancements.

There are two major reasons why irrigation scheduling practices, involving both timing and amount of water applied, have not changed substantially: (1) The needs of managers of irrigated farms and the acceptability of suggested scheduling procedures have not been adequately evaluated; (2) The cost of irrigation water often has not been significant, and indirect costs such as yield reductions caused by delayed irrigations and additional nitrogen requirements created by excessive water applications are not easily recognized or quantified. Also, crop and soil damage costs encountered on lower-lying areas by excessive water use on upper areas are not always borne by the upper-
Irrigation scientists and technologists know how to optimize production by manipulating irrigation practices, but these specialists are not making current irrigation decisions on each farm. Irrigation decisions are made by people who have limited time and training. They do not have the meteorological and crop growth data and forecasts to predict the next date of irrigation so that farm work can be planned accordingly. The modern farm manager can acquire irrigation equipment to apply the amount of water needed when it is needed, but he still must decide "when" and "how much" water to apply. Predictions of needed irrigation several days in advance are essential for planning other farm work and for completing the required irrigations when the capacity of the irrigation system or allotted flow is limited.

Basically, current estimates and predictions of irrigation needs are not available to most managers of irrigated farms, or at least they are not available in a form that can be used. Irrigation scheduling is a decision-making process requiring current information, trends, projections, and alternatives much the same as required by managers of large industries. The modern farm manager needs and wants a continuing service that gives the present soil water status on each of his fields, predicts irrigation dates, and specifies the amounts of water to apply on each field. He could also use predictions of adverse effects, such as the effects of delaying an irrigation for several days, or perhaps terminating irrigations, on the yield of marketable products. This information would increase the manager's skills in making better and more profitable irrigation decisions.

An irrigation management service is often needed to supplement practical irrigation experience with irrigation science on a day-to-day basis. The potential economic returns to the farm manager or owner can exceed the cost of this service severalfold. Moreover, the increase in net income to the farmer and greater water use efficiencies are not the only benefits to be derived from this service. The recipients of the irrigation forecasts have found the data to be useful in planning other farm work, such as cultivation and spraying for insect control. In semihumid areas, it might enable farmers to begin irrigating their crops in sufficient time to cover all of the fields before soil
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moisture deficits become severe. With the current high interest and enthusiasm by the managers of irrigated farms in the United States for a service such as this, and the establishment of new irrigation service companies or the addition of irrigation scheduling services to existing companies, it is expected that a significant portion of the irrigated farms in the United States will be scheduled using procedures such as described in this chapter within the next few years.

Alternative Methods of Improving Irrigation Programming

There are currently four general approaches to improving irrigation scheduling practices.

A. Irrigation Programming Instruments

Tools and instruments, such as tensiometers, soil water blocks, evaporation pans, and soil sampling augers and tubes have long been recommended or supplied to farm managers with instructions for their use. These instruments are often supplemented with guides to interpreting the results obtained. This has been the general approach taken by most irrigation technologists during the last three decades to improve irrigation water management, and there are numerous technical publications and manuals on this subject. New and better soil water instruments are technical aids to the solution of the problem, but do not in themselves ensure a practical solution, as evidenced by continued poor irrigation practices in many areas.

B. Irrigation Management Services Using Instruments

An irrigation management service by trained service groups or private firms using some of the tools mentioned in the previous section is a practical alternative and is being used to a limited extent in some areas of the western United States. Average evapotranspiration data determined experimentally in the area may be used for predicting the date of the next irrigation. Irrigation management services based on soil sampling are in use in Arizona and Washington, U.S.A. (Franzoy and Tankersley, 1970; Marshall, 1971). In general, a service involving soil sampling has not been widely adopted because farm managers are not
always aware of the need and benefit of good irrigation water management. Services using tensiometers are more common, especially with high-value crops, but these instruments must be read frequently, which involves significant travel and labor costs.

C. General Irrigation Forecasts

Generalized forecasts of irrigation needs for common crops and the major soils in the area based on local or regional experimental data are frequently used in areas needing only infrequent supplemental irrigations. This approach is economical, but generally requires the farm manager to interpret the forecasts and monitor his own fields to verify the predictions (Jensen, 1969). This type of service has also been adapted to arid conditions. For example, a general forecast service is being developed in southern Idaho with the predictions provided by the U.S. Bureau of Reclamation and the A & B Irrigation District of the Minidoka Project (Brown and Buchheim, 1971).

D. Field Scheduling and Monitoring

Irrigations are predicted for each field utilizing meteorological data combined with soils, crop, and experimental data, but these predictions are supplemented with a field monitoring service. This alternative has been tried and is readily accepted by the managers of irrigated farms (Jensen et al., 1970; Franzoy and Tankersley, 1970).

Irrigation Management Service Requirements

The scientific knowledge to estimate and predict the depletion of soil water by evapotranspiration has been the subject of world-wide research since the late 1940's, but estimating or predicting soil water depletion solves only part of the problem. Some of the additional requirements that are essential in providing an irrigation management service are described in this section.

A. Technical Competence

A service group such as a governmental agency, irrigation district, or a private firm must have the necessary
technical competence to collect and interpret essential basic data and develop the predictions. There are advantages in private groups providing this service, as the private consultant can supply other personalized management services to the farm manager. Many private firms, for example, have the skills in other areas such as fertilizer management, pesticide control, cost accounting, and general agronomy. Private service groups should develop self-regulating standards of staff competence to assure dependable recommendations for irrigation clients. If this is not done, state licensing as required for other professional services, will soon be required.

B. Economic Feasibility

Unwarranted accuracy or complexity should be avoided in order for a service to be self-supporting. The costs of an irrigation scheduling service should be economical relative to other irrigation operation and maintenance costs. This means that expensive instrumentation and detailed measurements on each farm probably will not be feasible. Also, it means that some basic meteorological data cannot be used because complicated instrumentation, data processing, and instrument servicing would be required. The service company or agency must utilize meteorological data that are easily obtainable from existing weather stations, or that can be obtained with reliable instruments that function throughout the season with few or minor mechanical problems.

C. Basic Farm Data and Records

The servicing group must collect background information on each field, including soils data, the crops to be grown, past cropping history where soil fertility is involved, characteristics of each existing irrigation system, and current practices of each farm manager. It must also maintain essential records for each farm and field involved. If a generalized service is provided, the amount of record keeping involved is substantially reduced, but the accuracy of generalized forecasts for each field may be lower, especially if field monitoring by skilled technicians is not provided.
D. Communications

When operating on a field-by-field basis, a two-way communication system must be an important part of the program and has been one of the major problems encountered by service groups. Complete reliance on a mail service has not been fully satisfactory because of the time lag occasionally encountered. Also, farm managers frequently neglect to promptly provide the desired feedback information, such as the date a field has been irrigated, which would be valuable even to a company that relies on soil sampling. A telephone service for collecting the feedback information has been tried. However, this procedure has not been satisfactory because the farm manager frequently is not in when called, or the service company office may be closed when the farm manager chooses to make his own call. Private service groups in Southern Idaho are considering installing automatic telephone recording systems so that the farm manager can call the service center and provide feedback information at his convenience.

The Salt River Project at Phoenix, Arizona, is contemplating using remote computer terminals connected by telephone network to a central computer. The remote terminals will be located in outlying field offices where the farm managers regularly stop to order irrigation water. The terminal operator can reach the central computer files and obtain an updated printout for the manager's farm without delay. The printout lists the predicted irrigation dates for each of the fields involved in the scheduling program. This arrangement is desirable when an irrigation district is providing the service since it also controls water distribution and maintains records of irrigation water deliveries. As an alternative, the Salt River Project is evaluating the use of a time-sharing terminal in the main office with data available to the field by telephone.

E. Verification and Field Inspection

The success of an irrigation management service will, to a large extent, depend on periodic monitoring or soil samplings of the fields to verify the adequacy of previous irrigations and the accuracy of predicted irrigation dates. This part of the service can be provided by a technician experienced in irrigation water management, or the soil
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sampler in a soil sampling program. Preferably, one technician serves a specific group of farm managers so that the manager develops a personal rapport with his service technician. He looks to the technician or his supervisor as an expert in irrigation water management, and one who can also provide guidance on other aspects of surface or sprinkler irrigation. The Salt River Project at Phoenix, Arizona utilizes technicians in this manner with one technician serving about 20 farms. He visits each farm weekly, and if he encounters questions that he cannot answer, his vehicle is equipped with a two-way radio so that he can call his supervisor or a specialist in the central office to obtain a specific recommendation.

Meteorological Data Limitations

Energy balance and, in some cases, mass transfer measurements have become reliable and accurate methods of determining daily evapotranspiration in experimental studies. However, the cost, technical skills, and data processing required effectively prohibit these techniques on a continuing daily basis even for a single reference field within a project. Instead, estimates of "potential evapotranspiration," or evapotranspiration that occurs with a well-watered reference crop like alfalfa with 30 to 50 cm of growth within the area, are adequate. Also, if a combination equation is used, only daily values of meteorological data are needed to provide the necessary accuracy of ±10 to 15% on a daily basis. The accuracy for 5- to 20-day periods will be better if the errors are random.

There are also other problems in obtaining the necessary meteorological data. In some areas, a service company must establish its own weather station. In the Western United States, a weather station centrally located within an irrigated project of 50,000 to 100,000 hectares can provide adequate data to compute the daily evaporative demand. Observer skill and instrument calibration are major problems encountered in the collection of meteorological data. Table 1 indicates the degree of skills that should be considered when collecting various meteorological data. This table is based on personal experiences of encountering erroneous data where meteorological stations are not properly maintained, or where meteorological readings are not taken by trained technicians. Some of the refined measurements
required for energy balance computations may actually re-
quire a scientist's daily attention. Since this degree of
skill is not practical for most irrigation scheduling ser-
vices, procedures that require daily, precise meteorologi-
cal measurements are restricted.

**TABLE 1**

Technical Skills Required to Obtain Reliable Daily
Meteorological Data on a Routine Basis without Daily
Supervision by a Research Engineer or Scientist.
(The x's denote an acceptable level of training.)

<table>
<thead>
<tr>
<th>Meteorological parameters</th>
<th>Training required</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observers</td>
</tr>
<tr>
<td><strong>Air temperatures</strong></td>
<td></td>
</tr>
<tr>
<td>Max-min thermometers</td>
<td>x</td>
</tr>
<tr>
<td>Thermographs</td>
<td>x*</td>
</tr>
<tr>
<td><strong>Humidity (dew point)</strong></td>
<td></td>
</tr>
<tr>
<td>Sling psychrometer</td>
<td>x*</td>
</tr>
<tr>
<td>Hygrograph</td>
<td>-</td>
</tr>
<tr>
<td><strong>Wind (daily run)</strong></td>
<td></td>
</tr>
<tr>
<td>Integrating anemometer</td>
<td>x*</td>
</tr>
<tr>
<td><strong>Solar radiation (daily)</strong></td>
<td></td>
</tr>
<tr>
<td>Actinograph</td>
<td>-</td>
</tr>
<tr>
<td>Integrating unit</td>
<td>-</td>
</tr>
<tr>
<td>(sensor-integrator)</td>
<td></td>
</tr>
<tr>
<td>Sunshine hours</td>
<td>-</td>
</tr>
<tr>
<td><strong>Net radiation</strong></td>
<td></td>
</tr>
<tr>
<td>Integrating unit</td>
<td>-</td>
</tr>
<tr>
<td><strong>Evaporation</strong></td>
<td></td>
</tr>
<tr>
<td>Standard pans</td>
<td>-</td>
</tr>
</tbody>
</table>

* Periodic calibration, maintenance and instruction needed.
† Periodic calibration, maintenance and instruction by a trained meteorologist, research engineer or scientist.
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Effective Use of Regional Experimental Data

In the U.S.A., the amount of research data available for most large irrigated areas is often extensive and represents a large investment of private and public funds. The interpretation of experimental data for optimum irrigation water management requires skills in the science of agronomy and plant-soil-water relations. Similarly, the collection and interpretation of soils data available from previous experiments requires practical knowledge of soil-water principles. Workshops are frequently conducted for farm managers. Similar but more technical workshops are needed for the professional staff members of service companies. There are some circumstances in which knowledge of soil-water storage is of no avail. These usually occur when the irrigation system can apply only a limited amount of water per irrigation, less than the generally allowable soil water depletion for a given soil and crop, and when expected rainfall is insignificant. In such cases, the actual allowable depletion of soil water between irrigations will be largely determined by the irrigation system and not by soil characteristics.

USDA-ARS-SWC Irrigation-Scheduling Computer Program

A. History of Development

The USDA computer program was developed cooperatively with farm managers and service groups as a tool for providing managers of irrigated farms with scientific estimates of irrigation needs for each field. This approach is not the only solution to the problem, but it is one that has gained rapid acceptance. The computer program requires limited input data and uses simple, basic equations so that each can be replaced as more accurate relationships are developed. The principles and procedures involved are described in several recent publications (Heermann and Jensen, 1970; Jensen, 1969; Jensen and Heerman, 1970; Jensen et al., 1971). A summary of the computer program is given in the next section.

The basic components of the irrigation management service were evaluated in 1966 and 1967 in southern Idaho. The computer program was evaluated in 1968 and 1969 on about 50 fields in Idaho and a similar number in Arizona by
the Salt River project (Franzoy and Tankersley, 1970). During 1970, a number of service groups and companies gained experience in the use of this general concept of irrigation scheduling. The Salt River Project at Phoenix, Arizona, for example, has used the program for three years. After the first two years, the original program was revised, retaining the basic components, but the input-output data and format and some of the crop curves were changed to fit local facilities and crops (Franzoy and Tankersley, 1970). The irrigation predictions should be updated twice a week when shallow-rooted crops are involved or when evapotranspiration rates are high. Weekly updating suffices for most field crops.

The U.S. Bureau of Reclamation has modified the program to provide general irrigation forecasts for major crops in an area. This service was made available to southern Idaho for 54 farm operators in 1970. A field-by-field scheduling and monitoring service was provided for 68 fields on 15 farms within the same area (Brown and Buchheim, 1971). The general forecasts were updated once a week and distributed to cooperators who provided their own field monitoring. An agricultural technician made weekly visits throughout the irrigation season on the 15 farms on the field-by-field program. Additional changes have been made for 1971 which include both the General Irrigation Forecasts and Field Scheduling and Monitoring Methods. These methods will be used in 1971 on two irrigation districts in southern Idaho with field monitoring provided by trained technicians on each farm.

An agriculture technology company in McCook, Nebraska is using a modified version of an earlier program in Nebraska and Kansas (Corey, 1970). This company is also planning to add fertilizer management to its service in 1971.

Approximately 8,000 hectares were scheduled in 1970 by various groups in Idaho, Nebraska, and Arizona. An estimated 50,000 hectares will be scheduled in 1971, with nearly half of the area involving cotton on the Salt River Project. Other private companies are adding this service to their regular farm management services in Idaho, Washington, Kansas, and California. The Bureau of Reclamation is also expanding its irrigation management program to other areas such as the Central Valley of California, and the Rio Grande Valley of Texas.
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The concept of scheduling irrigations using climatic data is not new. Das (1936) suggested using climatic data to control irrigations in the 1930's. The concept received more attention following the publications of Penman (1948, 1952) and Thornthwaite (1948). In 1954, Baver stated:

The meteorological approach to irrigation has the advantage of simplicity of operation when compared with methods based upon measurement of soil moisture changes. If it is proved satisfactory, the costs of using this system would be relatively small. Undoubtedly, new techniques will be developed that will give an integrated measure of daily temperature, sunshine and solar energy. When such methods are available, meteorological data can be correlated better with evapotranspiration.

Many others have since discussed this approach (Baier, 1957, 1969; Pierce, 1958, 1960; Pruitt and Jensen, 1955; Rickard, 1957; van Bavel, 1960; van Bavel and Wilson, 1952). However, prior to 1965 this method had not been adapted for general practical use or tested extensively in the United States. The Penman equation is often referred to as being too complex for practical use (Fitzpatrick and Cossens, 1965). However, with modern low cost computers, there is no justification in using less refined methods of computation when the meteorological data are easily obtainable.

B. Operating Costs

The current costs of this service range from $4.00 to $10.00 (U.S.) per hectare. The lower cost is for large acreages, crops requiring less frequent monitoring, and short-season crops.

C. Operational Steps

The program first estimates daily evaporative flux from a well-watered reference crop like alfalfa with 30 to 50 cm of top growth, E*. The basic meteorological data required for this estimate are: (1) daily maximum and minimum air temperatures; (2) daily solar radiation; (3) average daily dewpoint temperature or dewpoint temperature observed at or near 8:00 A.M.; and (4) daily wind run at a known height,
preferably in an open area over a surface that does not
change significantly in roughness or displacement height
during the growing season. Prior to 1971 (Jensen et al.,
1971), the combination equation as presented by Penman
(1963) was used in the following format:

\[ E* = \frac{\Delta}{\Delta + \gamma} (R_n + G) + \frac{\gamma}{\Delta + \gamma} (15.36)(1.0 + 0.0062u_2^2)(e_s - e_d) \]

where \( \Delta \) is the slope of the saturation vapor pressure-tem-
perature curve, \((de/dT)\), mb °C⁻¹; \( \gamma \) is the psychrometric
constant \((0.66\ \text{mb °C}^{-1}\ \text{at 20°C and 1 bar pressure})\); \( e \) is
the mean saturation vapor pressure in mb \((\text{mean at maximum}
\text{and minimum daily air temperatures})\); and \( e_d \) is the satu-
ration vapor pressure at mean dewpoint temperature in mb; \( u_2 \)
is total daily wind run in km day⁻¹ at a height of 2 m; \( R_n \)
is net radiation in cal cm⁻² day⁻¹, and \( G \) is heat flux from
the soil in cal cm⁻² day⁻¹ \((\text{negative when the heat flux is}
to the soil})\). The parameters \( \Delta/(\Delta + \gamma) \) and \( \gamma/(\Delta + \gamma) \) are
mean air temperature weighting factors whose sum is 1.0.

Since the percent of sunshine or degree of cloud cover,
normally used to estimate net longwave radiation, are
generally not available, or are qualitative rather than quan-
titative, procedures were developed for estimating net ra-
diation using observed daily solar radiation, \( R_s \), 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 various tables such as those by Fritz
\((1949)\) or Budyko \((1956)\) or by plotting observed solar radi-
ation to obtain an envelope curve through the high points.
Net radiation in cal cm⁻² day⁻¹ is then estimated as fol-
lows:

\[ R_n = (1 - \alpha) R_s - R_b \]

where \( \alpha \) is the mean daily shortwave reflectance or albedo,
and \( R_b \) is the net outgoing longwave radiation. An albedo
of 0.23 is currently used in the program. \( R_b \) is estimated
as follows:

\[ R_b = (a_1 \frac{R_s}{R_{so}} + b_1) R_{bo} \]

where \( R_{bo} \) is the net outgoing longwave radiation on cloud-
less days. The constants \( a_1 \) and \( b_1 \) derived with data from
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Davis, California\(^1\) are 1.35 and -0.35, respectively, and for Idaho 1.22 and -0.18, respectively (Wright and Jensen, 1971).

The net outgoing longwave radiation on cloudless days is estimated using:

\[ R_{bo} = (a_2 + b_2 \sqrt{e_d})(11.71 \times 10^{-8}) \left( \frac{T_2^4 + T_1^4}{2} \right) \]  \hspace{1cm} (4)

where \( e_d \) is the saturation vapor pressure at mean dewpoint temperature in mb; \( 11.71 \times 10^{-8} \) is the Stefan-Boltzmann constant in cal cm\(^{-2}\) day\(^{-1}\) °K\(^{-4}\); and \( T_2 \) and \( T_1 \) are the maximum and minimum daily air temperatures, respectively, in °K. The constant, \( a_2 \), formerly used was 0.32. However, recently a slight variation in the constant \( a_2 \) improved the estimates of net radiation (Wright and Jensen, 1971):

\[ a_2 = 0.325 + 0.045 \sin \left[ 30(M + D/30 - 1.5) \right] \]  \hspace{1cm} (5)

where \( M \) is the month, 1-12, and \( D \) is the day, 1-31. The constant, \( b_2 \), now used is -0.044, which is the average of the value obtained by Goss and Brooks (1956) in California, 0.040, and the value obtained by Fitzpatrick and Stearn (1965) in Australia, 0.049. These constants in the Brunt equation for effective atmospheric emittance were found to be more suitable for arid conditions than those originally proposed by Penman.

Daily soil heat flux, \( G \), is estimated with a simple empirical equation using the difference between mean daily air temperature and the average temperature for the three previous days. This component is currently being revised. For practical purposes, it can be assumed to be zero under a crop with a full cover, such as alfalfa.

Estimates of daily evaporative flux for the reference crop, \( E^* \), in cal cm\(^{-2}\) day\(^{-1}\), are converted to depth equivalent, \( E_{tp} \), using 585 cal g\(^{-1}\) as the heat of vaporization. Evapotranspiration for a given agricultural crop, \( E_t \), is estimated from the daily reference evaporative flux as follows:

\[ E_t = K_c E_{tp} \]  \hspace{1cm} (6)

where \( K_c \) is a dimensionless coefficient similar to that

\(^1\)W.O. Pruitt, personal communication.
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proposed by van Wijk and De Vries (1954) and Makkink and van Hermet (1956). This crop coefficient 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, as well as the relative amount of radiant energy available as compared to the reference crop (Jensen, 1968).

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

(7)

where \( A \) is the sensible heat flux to (-) or from the air (+) and \( G \) is the sensible heat flux to (-) or from the soil (+); and \( R_n \) is net radiation to the crop-soil surface (+). The subscript \( o \) designates concurrent values for the reference crop in the immediate vicinity (in this case, alfalfa). The major term affecting \( K \) is \( A \), which is usually negative on a daily basis for crops with small amounts of leaf area in arid zones, but it may be positive for alfalfa. The crop coefficient can also be expressed in terms of mean daily Bowen ratios and net radiation (Jensen, 1968).

Typical examples of the effects of growth stage on the crop coefficient where soil water is not limiting have been presented for grain sorghum by Jensen (1968), and for corn by Denmead and Shaw (1959). More recently, there have been numerous publications presenting observed relative rates of evapotranspiration as compared to an estimate or measurement of the evaporative potential (e.g., Ritchie, 1971; Ritchie and Burnett, 1971). Mathematical models of \( K \) based on leaf area index, leaf stomatal resistance to diffusion of water vapor, soil water, and other relevant parameters, may be used in place of experimental values when they become practical for use with limited data.

Since the actual crop coefficient \( K_c \) is generally influenced by the wetness of the soil surface, it is automatically adjusted in the computer program as follows:

\[ K_c = K_c^0 K_a + K_s \]  

(8)

where \( K_c^0 \) is the expected crop coefficient based on experimental data where soil water is not limiting and normal plant densities are used; and \( K_a \) is the relative coefficient related to available soil water. Currently \( K_a \) is assumed to be proportional to the logarithm of the percentage
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of remaining available soil moisture (AM):

\[ K_a = \ln \frac{(AM + 1)}{\ln 101} \]

\( K_a \) is the increase in the coefficient as a result of the soil surface being wetted by irrigation or rainfall. The maximum value of \( K_a \) normally will not exceed 1.0 for most crops. Currently, the values for \( K_a \) for the first, second and third day after a rain or irrigation have been taken as follows: \((0.9 - K_{co}) \) 0.8; \((0.9 - K_{co}) \) 0.5; and \((0.9 - K_{co}) \) 0.3, respectively.

Soil water depletion after an irrigation is calculated as follows:

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

where \( D \) is the depletion of soil water (after a thorough irrigation \( D = 0 \)); \( R_e \) is effective rainfall (excluding run-off); \( I \) is irrigation water applied, \( W_d \) is drainage from the root zone or upward movement from a saturated zone; and \( i = 1 \) for the first day after a thorough irrigation when \( D = 0 \). The terms on the right hand side of the equation are daily totals in centimeters.

The date of the next irrigation is predicted by the remaining soil water that can be safely depleted and the current average \( E_t \).

\[ N = \frac{D_0 - D}{E_t} \]

\[ N = 0 \text{ for } D > D_0 \]

where \( N \) is the estimated days to the next irrigation if no rain occurs; \( D_0 \) is the current optimum depletion of soil water in cm; \( D_0 \) is the estimated depletion to date in cm; and \( E_t \) is the current mean rate of \( E_t \) in cm day\(^{-1}\). The magnitude of \( D_0 \) will vary with each crop and field, and will be partially dependent on the irrigation practice used. The amount of water added to a given soil by furrow irrigation during a 12-hour irrigation, for example, will be affected by furrow slope, stream size, etc.

The amount of water required for the next irrigation, \( W_I \), is calculated by dividing \( D_0 \) by the attainable efficiency for the irrigation system.
Adjustments for leaching can be made, if necessary. At this time periodic monitoring of the salt concentration in the soil is recommended. If the amount of water applied and its salt concentration are known, then automatic adjustments for leaching can be added to the program.

D. Input Data

There are three categories of input data required which should be provided by the service groups working with the farm managers.

**Basic Data**: Basic data consist of the regional constants for the $E^*$ equations, taking into account the differences in height of wind measurements, and the crop-soil system data for each field. The latter item involves the farm name, crop code number, crop-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 a soil water content about four days after irrigation of a soil that is about 60 to 90 cm deep and has been covered to prevent evaporation (Miller, 1967), and the soil water content reached when the given crop with a fully developed root system is allowed to grow without irrigation until growth ceases. If the amount of water applied is known, then a function for $W_a$ can also be used in equation (9).

**Current Meteorological Data**: Current meteorological data required for each region are: daily minimum and maximum air temperatures, daily solar radiation, daily dewpoint temperature, and total daily wind run for each day since the last computation date. An optional brief weather forecast can be included for each region, and a coefficient adjusting the expected $E^*$ for the next five days either upward or downward can be included based on current forecasts.

**Current Field Data**: Current data for each field are: date of the last irrigation, the allowable soil water depletion at the present stage of growth (this can be included in the program), and the rainfall and/or irrigation amount and its date of occurrence if it falls within the present computation period.
E. Output Data

The output data can be modified by the service groups to suit their operating procedures and facilities. A typical example of the output received by a farm manager is illustrated in Computer Output Sheet A.

A typical example of a portion of the output provided the farm managers receiving generalized forecasts of irrigation needs is given in Computer Output Sheet B.

F. Recent Modifications

Calibration of E* Equations: Under arid conditions, the constants in the Penman equation tend to underestimate E* during high advective conditions (Jensen et al., 1971; Rosenberg, 1969). Under these conditions, the magnitude of the aerodynamic portion of the combination equation is significantly larger than in semihumid areas. This can best be illustrated by use of several examples and a derivation similar to that presented by van Bavel (1966) as follows:

\[
E^* = \frac{\Delta}{\Delta + \gamma} (R_n + G) + \frac{\gamma}{\Delta + \gamma} L B \frac{d_a}{v} \tag{11}
\]

where \( L \) is the latent heat of vaporization; \( B \) is a transfer coefficient, \( g \text{ cm}^{-2} \text{ min}^{-1} \); and \( d_a \) is the saturation vapor pressure deficit of the air, \( \text{mb} \). By algebraic manipulation of equation (11) and the energy balance equation given in the next paragraph, it can be shown that:

\[
L B \frac{d_a}{v} = E^* + \frac{\Delta}{\gamma} A \tag{12}
\]

For the examples, assume the following energy balance equation and meteorological conditions:

\[
E^* = (R_n + G) + A
\]

\( T = 26^\circ C \)

\( P = 1000 \text{ mb} \)

Under these conditions,

\[
\frac{\Delta}{\gamma} = 3, \quad \frac{\Delta}{\Delta + \gamma} = 0.75, \text{ and } \frac{\gamma}{\Delta + \gamma} = 0.25
\]
**REGION:** BURLEY-TWIN FALLS

**FARM:** JOHN DOE EXAMPLE  
**DATE OF COMPUTATION:** JULY 28, 1969

<table>
<thead>
<tr>
<th>CROP-FLD</th>
<th>COEF</th>
<th>TO DATE</th>
<th>OPTIMUM</th>
<th>RATE</th>
<th>LAST</th>
<th>RAIN=0</th>
<th>W RAIN</th>
<th>CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>W WHEAT</td>
<td>0.10</td>
<td>3.5</td>
<td>15</td>
<td>0.1</td>
<td>JUL 10</td>
<td>NONE</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BEANS</td>
<td>1.01</td>
<td>1.8</td>
<td>5</td>
<td>0.7</td>
<td>JUL 26</td>
<td>AUG 3</td>
<td>AUG 3</td>
<td>9</td>
</tr>
<tr>
<td>PEAS</td>
<td>0.10</td>
<td>11.0</td>
<td>11</td>
<td>0.1</td>
<td>JUL 07</td>
<td>AUG 3</td>
<td>AUG 3</td>
<td>17</td>
</tr>
<tr>
<td>POTATOES</td>
<td>0.90</td>
<td>3.0</td>
<td>5</td>
<td>0.6</td>
<td>JUL 24</td>
<td>AUG 1</td>
<td>AUG 1</td>
<td>7</td>
</tr>
<tr>
<td>SUG BEETS</td>
<td>0.90</td>
<td>3.7</td>
<td>8</td>
<td>0.6</td>
<td>JUL 23</td>
<td>AUG 4</td>
<td>AUG 4</td>
<td>12</td>
</tr>
<tr>
<td>CORN</td>
<td>0.93</td>
<td>2.5</td>
<td>8</td>
<td>0.6</td>
<td>JUN 25</td>
<td>AUG 5</td>
<td>AUG 5</td>
<td>12</td>
</tr>
<tr>
<td>ALFALFA</td>
<td>0.67*</td>
<td>12.3</td>
<td>18</td>
<td>0.4</td>
<td>JUL 11</td>
<td>AUG 9</td>
<td>AUG 9</td>
<td>27</td>
</tr>
<tr>
<td>PASTURE</td>
<td>0.87</td>
<td>0.0</td>
<td>8</td>
<td>0.6</td>
<td>JUL 28</td>
<td>AUG 10</td>
<td>AUG 10</td>
<td>12</td>
</tr>
</tbody>
</table>

PROBALLY RAIN NEXT TWO WEEKS = 0.1 CM

**FORECAST:** PARTLY CLOUDY & WARM

*The low coefficient for alfalfa reflects the effects of a recent cutting.*
**Computer Output Sheet B**

**CONSUMPTIVE USE AND SCHEDULING INFORMATION**

**JULY 14, 1970 - A&B IRRIGATION DIST -2- SILT LOAM SOIL**

<table>
<thead>
<tr>
<th>DATE OF NEXT IRRIG AT LEFT IF DATE OF LAST IRRIG IS SHOWN BELOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEXT IRRIG</td>
</tr>
<tr>
<td>JUL 14</td>
</tr>
<tr>
<td>JUL 15</td>
</tr>
<tr>
<td>JUL 16</td>
</tr>
<tr>
<td>JUL 17</td>
</tr>
<tr>
<td>JUL 18</td>
</tr>
<tr>
<td>JUL 19</td>
</tr>
<tr>
<td>JUL 20</td>
</tr>
</tbody>
</table>

*Computer Output Sheet 1970 - "General" Method. (Adapted from Figure 3, Brown and Buchheim [1971]).*
Example (1) advective conditions:

\[
(R_n + G) = 370 \text{ cal cm}^{-2} \text{ day}^{-1} \\
A = 130 \text{ cal cm}^{-2} \text{ day}^{-1} \\
E^* = 500 \text{ cal cm}^{-2} \text{ day}^{-1}
\]

From equations (11) and (12), the following results are obtained:

\[
E^* = 0.75(370) + 0.25[3(130) + 500] = 277.5 + 0.25(890) = 500 \text{ cal cm}^{-2} \text{ day}^{-1}
\]

Example (2) sensible heat transfer to the air:

\[
(R_n + G) = 370 \text{ cal cm}^{-2} \text{ day}^{-1} \\
A = -70 \text{ cal cm}^{-2} \text{ day}^{-1} \\
E^* = 300 \text{ cal cm}^{-2} \text{ day}^{-1}
\]

When these data are substituted into equations (11) and (12), the following results are obtained:

\[
E^* = 0.75(370) + 0.25[3(-70) + 300] = 277.5 + 0.25(90) = 300 \text{ cal cm}^{-2} \text{ day}^{-1}
\]

These two examples clearly illustrate that the aerodynamic term becomes significantly larger when there is warm air advection. Consequently, the aerodynamic term must be more accurate under arid conditions where warm air advection is common (a negative mean daily Bowen ratio) than in semihumid areas where sensible heat is generally transferred to the air from the crop surface (a positive mean daily Bowen ratio).

Since the Penman equation underestimates \( E^* \), Wright and Jensen (1971) developed the following empirical coefficients for a linear wind function in equation (1) using lysimeter data and local U.S. Weather Service meteorological observations:

\[
f(u) = 0.75 + 0.0114u_2^2
\]

where \( u_2 \) is the windspeed measured at a height of 2 m in km day\(^{-1}\). This wind function gives essentially the same results at moderate windspeeds as does the van Bavel
OPTIMIZING THE SOIL ENVIRONMENT

aerodynamic term \((7.15u_0/[\ln(z/z_0)]^2\) in place of \(15.36(1.0 + 0.0062u_0^2)\) in equation \(1\), providing that the roughness parameter, \(z_0\), is no greater than 1 cm.

Probability of Rainfall: Heermann and Jensen (1970) modified the computer program to include expected rainfall in predicting the date of the next irrigation. They also modified the estimates of expected potential evapotranspiration when the irrigation date is more than five days in the future, as follows:

\[
E[E_{tp}] = E_{tp} \exp \left[-\left(\frac{t - t'}{\Delta t}\right)^2\right] \tag{14}
\]

where \(E[E_{tp}]\) is the expected value of potential evapotranspiration \(t'\) at a given day \(t\) (in Julian days); \(t'\) is the Julian calendar day when the maximum mean potential evapotranspiration, \(E_{tp}\), occurs (about July 15 to July 25 in the northern hemisphere); and \(\Delta t\) is the days before and the days after \(t'\) when \(E[E_{tp}] = 0.37E_{tp}\). Normally a different value of \(\Delta t\) is used for \(t < t'\) as compared to \(t > t'\). The major advantage of this procedure is that expected potential evapotranspiration is represented by a simple 3-parameter equation using \(E_{tp}\), \(t'\), and \(\Delta t\). For example, in southern Idaho \(E_{tp} = 0.81\) cm, \(t' = 206\), and \(\Delta t = 150\) for \(t < t'\) and 93 for \(t > t'\).

Two expected dates of the next irrigation are then calculated: one assuming no rain, and one assuming 50% probable rainfall. Daily depletion is first calculated until \(D > D_o\) using equations (9) and (15).

\[
(E_{t})_i = (K E[E_{tp}])_i \tag{15}
\]

Then this date is extended by the expected rainfall during the intervening period. If the next irrigation is predicted within the next five days, then \(E[E_{tp}]\) is increased or decreased by a current forecast coefficient.

Effective Field Capacity: A better estimate of "effective field capacity" can be obtained by estimating cumulative drainage expected between irrigations. Estimates of the cumulative drainage, \(W_D\), between irrigations can be obtained using the following equations that are based on the empirical relationship of water content and time for a soil that is draining:

\[
W = cW_o t^{-m} \tag{16}
\]
where \( W \) is the water content in cm; \( W_0 \) the water content when \( t = 1 \); \( m \) is a constant for a soil; and \( c \) is a dimensional constant, \( t^m \) (Ogata and Richards, 1957). Accordingly,

\[
\frac{dW}{dt} = -mW \left( \frac{W}{cW_o} \right)^{\frac{1}{m}}
\]  

(17)

The cumulative drainage can be calculated in a manner similar to that proposed by Wilcox (1962):

\[
W_D = \sum_{i=1}^{\infty} m[W_{i-1} - (E_t)_{i-1}] \left( \frac{W_{i-1} - (E_t)_{i-1}}{W_o} \right)^{\frac{1}{m}}
\]  

(18)

where \( W_D \) is drainage, cm; \( i \) is the number of the day after irrigation; and \( E_t \) is the evapotranspiration for the day in cm. The most representative time to sample a soil that has been covered to prevent evaporation after a thorough irrigation can be obtained by integrating equation (17) between the limits of \( W_0 \) and \( W_D \).

\[
t = \left( \frac{cW_o}{W_o - W_D} \right)^{\frac{1}{m}}
\]  

(19)

Since \( dW/dt \) rapidly \( \to 0 \) using equation (17), about 5 to 20 days of calculations are needed before \( dW/dt < 0.01 \) cm day\(^{-1}\). Example calculations based on data from southern Idaho and unpublished data from D.E. Miller (USDA-ARS-SWC, Prosser, Washington) are summarized in Table 2. In these examples, \( E_t \) was assumed to be 0.8 cm day\(^{-1}\). In detailed laboratory measurements, Miller and Aarstad (1971) found that sampling 3.5 days after irrigation slightly underestimated the available water for the 0- to 70-cm depth, and sampling at 5.5 days closely represented the available water in the 0- to 120-cm depth with \( E_t = 0.81 \) cm day\(^{-1}\). Equation (16) can be used to estimate drainage because the hydraulic gradient near the lower part of the profile at higher soil water levels is similar with or without \( E_t \) occurring.
### OPTIMIZING THE SOIL ENVIRONMENT

#### TABLE 2

*Estimated Time to Sample a Soil to Determine the "Effective Field Capacity."*

<table>
<thead>
<tr>
<th></th>
<th>Portneuf silt loam</th>
<th>Portneuf silt loam</th>
<th>Ritzville loam</th>
<th>Ritzville loam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-60 cm</td>
<td>0-105 cm</td>
<td>0-60 cm</td>
<td>0-105 cm</td>
</tr>
<tr>
<td>( W_0 ), cm</td>
<td>21.4</td>
<td>38.8</td>
<td>19.8</td>
<td>41.5</td>
</tr>
<tr>
<td>( m )</td>
<td>0.043</td>
<td>0.043</td>
<td>0.106</td>
<td>0.111</td>
</tr>
<tr>
<td>Daily ( E_t ), cm</td>
<td>.8</td>
<td>.8</td>
<td>.8</td>
<td>.8</td>
</tr>
<tr>
<td>( W_D ), cm</td>
<td>.49</td>
<td>1.61</td>
<td>2.11</td>
<td>7.30</td>
</tr>
<tr>
<td>( W_0 - W_D ), cm</td>
<td>20.91</td>
<td>37.19</td>
<td>17.69</td>
<td>34.20</td>
</tr>
<tr>
<td>( t ), days</td>
<td>1.7</td>
<td>2.7</td>
<td>2.9</td>
<td>5.7</td>
</tr>
</tbody>
</table>

#### G. Modifications Underway

If the water table level is relatively close to the soil surface or close to the bottom of the root zone, an adjustment can be included in the crop coefficients to account for the movement of water upward from the saturated zone using concepts presented by Gardner (1958). For bare soil, the amount of water moving upward, \( W_u \), can be estimated using:

\[
W_u = 0.9 \left( \frac{z_c}{z_w} \right)^n E_{tp} \tag{20}
\]

for \( z_w > z_c \)

with a crop,

\[
W_u = \left( 1 - \frac{AM - a_4}{100 - a_4} \right) \left( \frac{z_c}{z_w - z_r} \right)^n E_t \tag{21}
\]

where \( z_c \) is the effective height of the capillary fringe above the water table, cm; \( z_w \) is the depth to the water table, cm; \( z_r \) is the depth of roots, cm; AM is available soil.
M. E. JENSEN

water to \( z_r \) in percent; \( a_4 \) is a constant (about 25); and \( n \) is a constant for a given soil and crop (expected to vary between 1 and 3). An example of this approximation of \( W_u \) is presented in Figure 1 using unpublished data from L.N. Namken (USDA-ARS-SWC, Weslaco, Texas). (Constants used in equation (20) are \( z_w = 273 \) cm, \( z_c = 50 \) cm, \( n = 1.22 \), and \( a_4 = 25\% \).)

![Figure 1](image_url)

Figure 1. Comparison of estimated weekly mean amount of water moving upward, \( W_u \), with observed \( W_u \). (Observed data provided by L.N. Namken, USDA-ARS-SWC, Weslaco, Texas.)
M. E. JENSEN

accuracy of all projected irrigations.

Summary

Irrigation programming practices have not changed appreciably in many areas during the past three decades because suggested techniques have not been acceptable, and the direct and indirect effects of excessive water use were not readily apparent. Several alternative methods of programming irrigations are now available. The scheduling of irrigations for each field using meteorological, soil, and crop data, coupled with field inspection, appears to be an economical and acceptable irrigation management service in the U.S.A. An irrigation management service requires technical competence and a good communications network. Reliable meteorological data also require technical competence, and periodic calibration of instruments.

The USDA-ARS-SWC irrigation scheduling computer program using meteorological techniques and soil-crop data is described in this chapter. Since its development and use for several years in Arizona, Idaho, and Nebraska, several modifications have been completed and others are under way. This problem has enabled private firms and service agencies to gain experience in providing irrigation management service while additional refinements are under way.

References


