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SCIENTIFIC IRRIGATION SCHEDULING FOR SALINITY CONTROL OF IRRIGATION RETURN FLOWS

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ABSTRACT

A comprehensive review is presented of irrigation water management principles, factors to be considered in improving irrigation water management, leaching requirements, climatological approaches to irrigation scheduling, scope of irrigation scheduling services in 1974, basic concepts of scheduling services, and probable effects of scientific irrigation scheduling on salinity of return flows. A definition of irrigation water management efficiency is presented to evaluate the annual volume of irrigation water used relative to the optimum amount needed for maximum annual crop production or income. The term considers the minimum but essential water needed for both consumptive and nonconsumptive uses. The lack of significant changes in irrigation efficiency during the past several decades is discussed and attributed to problems associated with the management of a complex soil-crop-environment system, a lack of economic incentives to make improvements, and ineffective traditional approaches to improve irrigation water management. New proposed minimal leaching practices are discussed. The author concludes that substantial improvements in irrigation efficiencies can be made before the potential minimal LF is reached on most western irrigated projects.

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CONCLUSIONS

1. Efficient irrigation water management requires basic decision-making data that generally are not available to most farm manager/operators of irrigated farms.

2. Few economic incentives to improve irrigation efficiency have existed during the past several decades.

3. Increasing labor costs have decreased inputs for operating surface irrigation systems, and unless offset by significantly improved irrigation facilities, decreased labor inputs have contributed to a lack of significant improvements in irrigation efficiencies.

4. Rapid expansion of commercial and agency irrigation scheduling services, which include weekly field monitoring by trained technicians, during the past 5 years represents the beginning of a new era in irrigation water management.

5. Substantial improvements in irrigation water management efficiencies could be made before potential minimal leaching fractions for maintaining salt balance in soils are reached on most western USA irrigated projects.

6. About a 10 percentage point improvement in average farm irrigation efficiencies, which now averages about 40%, could be expected during the next decade without significantly increasing energy requirements. Part of this improvement could be expected with improved irrigation scheduling technology, but some adoption of more efficient gravity irrigation facilities and practices will be needed. This change is not expected to significantly influence salin-

ity in return flows except where salt pickup is a major factor.

7. Major improvements in gravity or low pressure surface irrigation systems and practices, along with changes in water delivery policies controlled by institutions and state organizations regulating water rights, will be needed to achieve sufficient increases in irrigation water management efficiencies to significantly reduce salt loads in irrigation return flows without large energy inputs. Scientific irrigation scheduling can significantly reduce the salt load in return flows with irrigation systems that enable uniform applications of known amounts of irrigation water. Potential efficiencies of new irrigation systems and potential reductions in salt loads probably could not be achieved without scientific irrigation scheduling. Scientific irrigation scheduling is economically feasible with most existing irrigation systems, but will be more effective with new and better irrigation systems. Major benefits to the farm manager/operator result from improved crop yields and quality, and general improvement of irrigated farm management.

SECTION II

RECOMMENDATIONS

1. Significant improvements in irrigation water management efficiency will require improved irrigation scheduling and facilities to uniformly apply a known volume of water. Decision-making data must be made available to farm manager/operators if they are to utilize modern irrigation management science and technology because they have limited available time to independently obtain these data.

2. Greater emphasis should be placed on new innovative approaches to improving irrigation management rather than continuing traditional approaches that have been relatively ineffective over the past 3 decades.

3. A major effort should be directed toward developing an urgently needed portable and rapid technique so irrigation management service groups can accurately measure the soil water content with depth, or the integrated water content, without first inserting access tubes or drilling holes. Microwave or combination microwave nuclear techniques should be considered.

4. Increased effort is needed to complete the development of a second generation computer program for irrigation water management, which incorporates recent improvements in simulation models for energy balance, evaporation and transpiration, and plant growth.

5. As techniques for irrigation scheduling services are improved, workshops are needed to rapidly acquaint professional staffs of irrigation scheduling service groups with the latest practical technology and operating procedures, and assist new service groups to initiate similar services in new areas.

6. Similar increased efforts to hasten the development of gravity irrigation or low pressure irrigation facilities and systems and workshops should be planned on this subject.

7. As major irrigation scheduling services are initiated to improve irrigation water management efficiency and reduce salt pickup in selected areas, a data base should be established to document the direct benefits that can be attributed to more intensive application of irrigation science and technology in irrigation water management.

SECTION III

INTRODUCTION

IRRIGATION WATER MANAGEMENT

Irrigation is the application of water to soil, supplementing natural precipitation, to provide water essential for plant growth. Water plays a vital role in transporting mineral nutrients and translocating materials in solution throughout the plant. There is a liquid phase continuity from the water in the soil through the plant to the liquid-gas interface at evaporation sites in the leaves of all actively growing plants (Slatyer, 1967). The root system provides an extensive absorbing surface through which virtually all the water and mineral nutrients utilized by plants pass. In a crop-soil-climate system, maintaining the soil water level within an optimum range is essential to avoid adverse effects on plant growth and crop production.

Managing the soil water reservoir is not easy. The manager/operator of an irrigated farm must regulate a reservoir which has a level that is neither visible nor uniform throughout the field. There is essentially no lateral flow to equalize the reservoir, and the farm manager/operator cannot control the outflow rate. In addition, since water transpired by plants and evaporated from the soil surface is salt free, sustained crop production also requires controlling the concentration of soluble salts in the soil solution. Leaching, in which a fraction of the water penetrating the soil surface passes through and leaves the root zone at a higher salt concentration, is the only practical way to control soluble salts and specific toxic ion concentrations in the root zone. Control of soluble salts and sodium is probably one of the oldest problems encountered by irrigated agriculture.

It is difficult to efficiently manage the soil water reservoir component of a complex crop-soil-climate system. But the farm manager/operator, who has a limited understanding of the complicated mechanisms that control the system, is expected to use water very efficiently. Many assume he will automatically achieve full benefits of irrigation water if it is delivered to some high point of his land. Irrigation water management, with the objective of maintaining the soil water reservoir within an optimum range, requires daily or weekly decisions. A single overirrigation during the growing season can drastically lower the seasonal irrigation efficiency. Opportunities for mismanagement are less with some systems. For example, excessive water applications are not as frequent with sprinkler irrigation systems because water is applied at a relatively low rate which is controlled by the system and not the soil. Thus the amount of water applied can more easily be prescribed and controlled, but the time of application is still very flexible. In contrast, most surface or gravity irrigation systems allow little opportunity to control the amount of water applied. Sufficient water must be applied so it flows from the upper to the lower end of each field. The rate water is added to the soil reservoir is controlled by the soil surface and the water must be allowed to run long enough to permit sufficient intake at the lower ends of the fields. Many older systems do not have water measurement devices, adjustable control structures, and lined channels or enclosed distribution systems. Under these conditions, opportunities for mismanagement are greater and generally irrigation efficiencies are lower.

An important fact often overlooked is that irrigation scientists, engineers, and technicians do not make the required daily or weekly irrigation decisions. Irrigation management decisions generally are made by very busy people with limited technical background and training in the management of a complex crop-soil-climate system. In addition, the desired decision-making data seldom are available to those who make these decisions on a day-to-day basis. What are the desired decision-making data? Efficient irrigation water management requires knowing: (1) the current level and expected change in available soil water for each field during the next 5 to 10 days; (2) the expected latest date of the next irrigation for each field to avoid detrimental plant water stress, and the earliest date to permit efficient irrigation and avoid overirrigation; (3) the amount of water to be applied on each field if the irrigator is able to determine and control the amount; and (4) some indication of the adverse effects of irrigating too early, too late, or perhaps terminating irrigations. These data are required for efficient operation of existing systems, and as irrigation systems are improved these data become even more important if the farm manager/operator is to realize full benefits of a modern irrigation system. An exception would be a fully automatic system controlled by soil water sensors.

SECTION IV

IMPROVING IRRIGATION WATER MANAGEMENT

FACTORS INVOLVED

There are many factors that affect the management of an irrigation system and the soil water reservoir. The most obvious is the quantity of water available for irrigation. When the average annual water supply is significantly less than the net consumptive water requirement for maximum yields, many assume that the primary factor limiting crop production is the water supply. What is not obvious is that because of obsolete facilities and poor management practices, a limited water supply may be used very inefficiently. Why would limited water supplies be used inefficiently? Institutional policy, water rights, and limited storage facilities may cause water to be delivered only at preset time intervals regardless of the rate of water use by the crop. Under these conditions the farm manager/operator, not knowing the soil water level or the depletion rate by evapotranspiration, applies water when available regardless of the amount that can be stored in the soil. Why would more water be applied than be stored? Because the manager/operator cannot risk delaying the irrigation until his next turn and he cannot apply a light irrigation with most surface irrigation systems. For example, basin irrigation may require the application of at least 100 to 150 mm of water to cover all high spots in the basin, but a shallow-rooted crop may have depleted only 30 to 50 mm since the previous irrigation or rain. The excess water applied drains through the profile carrying accumulated soluble salts and some plant nutrients, like nitrogen. Some leaching may be needed, but the localized areas with above average salt concentration usually are in the high spots, not the low areas. Under these conditions, it is very difficult to improve irrigation efficiencies or significantly change the quality of irrigation return flow from deep percolation.

In some countries, and to some extent in some projects of the USA, water delivery is controlled by people technically trained in the hydraulics and not in the agricultural aspects of irrigation. Their goal is to operate the system efficiently from a hydraulic viewpoint. Under these circumstances, significant improvement in irrigation water management will be difficult to achieve, even if all desired irrigation decision-making data were available, because the control of the main irrigation distribution system does not rest with the farm manager/operators.

When adequate water supplies are available, irrigations often are delayed which may reduce crop yield and quality, followed by excessive irrigations with their adverse effects. Studies of irrigation practices have shown this to be a common practice, along with irrigating too soon and generally applying more water than the soil will hold.

The soils also significantly influence irrigation water management. Areas with extremely low or high infiltration rates, like those with high silt or sandy soils, are extremely difficult to manage efficiently with gravity irrigation systems. Nonuniformity of soils within a field influences the uniformity of water application with surface systems. Sodium problems and restricted natural subsurface drainage further complicate irrigation water management.

IRRIGATION EFFICIENCY CONCEPTS

The effectiveness of irrigation water management and the unavoidable losses of water must be known to plan, operate, and improve irrigation projects. The term "irrigation efficiency" is used to describe the effectiveness of one or more irrigation operations. This term is commonly used to describe the application efficiency, or ratio of water stored in the soil during an irrigation relative to the volume of water delivered to the field or other unit area (E_a). If water is delivered uniformly to the unit area at a rate equal to evapotranspiration, or if just enough water is delivered to the area to replace the soil water that has been depleted since the previous irrigation and uniformly applied, the irrigation efficiency will be 100%. The return flow from the unit area under these conditions will be $(1 - E_a) = 0$. But a high application efficiency does not necessarily result in good irrigation water management for crop production. A high application efficiency for a single irrigation can easily be achieved if only half as much water is applied as can be stored. Under these conditions, plant growth and crop production may be adversely affected in portions of the field if the next irrigation is not applied early enough to avoid excessive depletion of soil water.

The common general definition of irrigation efficiency is the ratio of water used in evaporation and transpiration by crops on an irrigated field, farm, or project, to the water pumped or diverted from a river or other natural source for this purpose. A variation in the definition of irrigation efficiency includes the ratio in the volume of water required for other beneficial uses. The main terms in the numerator are the water used in evapotranspiration plus the amount <u>necessary</u> for leaching.

Israelsen (1950) defined irrigation efficiency as "the ratio of the water consumed by the crops of an irrigation farm or project to the water diverted from a river or other natural water source into the farm or project canal or canals."

$$E_i = 100 \frac{W_{cu}}{W_r} \qquad [1]$$

where W_{cu} = the irrigation water consumed by the crops on an irrigation farm or project during their growth period, W_r = the water diverted from a river or other natural source into the farm or project canals during the same period of time. He also defined two other terms, W_f, the water delivered to the farms of a project during a given period of time, and W_s, the water stored in the soil root zone. He also illustrated with an example how the overall irrigation efficiency is a product of the conveyance and delivery efficiency and the farm irrigation efficiency. He considered as losses surface runoff, deep percolation and evaporation from the soil. Thus, basically Israelsen proposed irrigation efficiency to represent the ratio of the water used in transpiration to that diverted from a river or other natural water source into the farm or project canal or canals.

Israelsen also defined water application efficiency as

$$E_a = 100 \frac{W_s}{W_f} \qquad [2]$$

and described the sources of losses of irrigation water from the farm as surface runoff, R_f, and deep percolation below the root zone, D_f. Then, neglecting evaporation during the time of application,

$$W_f = W_s + R_f + D_f \qquad [3]$$

$$E_a = 100 \left| \frac{W_f - (R_f + D_f)}{W_f} \right| \qquad [4]$$

The concept of irrigation efficiency is needed for two major purposes: (1) for engineering and planning to determine the storage supply; and (2) for determining the required capacities of components of the water distribution and delivery system. Israelsen did not consider the water needed for other beneficial uses, like leaching, in defining irrigation efficiency. Most irrigation specialists conveniently assume that irrigation efficiency is the ratio of the amount of water needed for evapotranspiration relative to the water applied per unit area for this purpose. The amount of water that must be applied to maintain a salt balance, or the required leaching fraction, was basically considered a loss. The required leaching fraction is dependent on the concentration of salts in the irrigation water and the concentration of salts in the soil solution that can be tolerated by the crop. Thus, the more saline the water, the lower maximum irrigation efficiency that could be achieved. This concept, however, has resulted in many misleading statements about irrigated agriculture because as the concentration of soluble salts in the water increases, the maximum attainable irrigation efficiency decreases regardless of how well the irrigation system was designed, constructed, and operated.

Since leaching is the only practical way to maintain a favorable salt balance in the crop root zone, it therefore is one of several beneficial uses of water. Other beneficial uses are for germination, and for frost protection which has become very common in orchards and vineyards. When irrigating for frost protection, sprinklers are operated during freezing periods to prevent bud damage. The quantity of water evaporated is relatively small as compared with the quantity necessary to achieve frost control.

Future redefinitions of the irrigation efficiency can be expected as practical techniques for controlling evaporation from the soil surface are developed. Evaporation control will reduce the consumptive water requirement for a given crop in a specific climate. Also, as competition for water increases, greater emphasis will be placed on agronomic-economic assessment of water use, like crop production per unit volume of water diverted from a natural source for irrigation purposes.

Engineers and planners also use the term "irrigation efficiency" to describe the performance of existing systems, or expected performance of new methods and systems for distributing water. The American Society of Civil Engineers (ASCE) Committee on Irrigation Water Requirements recently described several components of irrigation efficiency (Jensen, 1974). The components are very similar to those described by Israelsen, except they included the efficiency of storing water in a reservoir specifically for irrigation and described the unit irrigation efficiency as the ratio of the water required for beneficial use in a unit area to the volume of water delivered for that purpose. These terms are:

"Reservoir storage efficiency, E_s, is the ratio of the volume of water available from the reservoir for irrigation to the volume of water delivered to the storage reservoir--surface or underground--for irrigation.

"Water conveyance efficiency, E_c, is the ratio of the volume of water delivered to the point of use by an open or closed conveyance system to the volume of water introduced into the conveyance system at the supply source or sources.

"Unit irrigation efficiency, E_u, is the ratio of the volume of irrigation water required for beneficial use in the specified irrigated area to the volume of water delivered to this area.

"The efficiencies of components of an irrigation system are defined so that the product of the component efficiency terms, expressed as ratios, gives the overall irrigation efficiency.

$$E_i = \frac{E_s}{100} \frac{E_c}{100} \frac{E_u}{100} 100 \qquad [5]$$

"The component efficiency terms may be applied to any project or segment thereof for any specified period of time. For clarity and comparative purposes, all efficiency values reported should be identified as to the size of the unit, the period of time or number of irrigations involved, the adequacy of irrigations, and the computational procedure used in obtaining the efficiency values."

Traditionally, in arid areas the main irrigation water management objective has been to obtain near maximum crop yields. The objective of most yield vs evapotranspiration experiments that have been conducted has been to determine the optimum level of evapotranspiration needed to produce near maximum yields. In areas that have more precipitation and where irrigation water supplies have been limited, many studies have been conducted to determine the maximum production or income per unit of annual irrigation water. These management objectives may be the same for many farm crops in some areas. For example, Jensen and Sletten (1965) reported the maximum grain sorghum production per unit of irrigation water applied annually in the Southern High Plains during a 4-year period occurred on the same treatment that produced the maximum average yield per unit area. Musick, et al. (1971), working in the same area, found that a preplanting irrigation, which increased the total irrigation water applied by 25%, decreased the 3-year average production per unit of annual irrigation water as compared with seasonal irrigations without the preplant irrigation.

Since the major emphasis in this report concerns the effects of irrigation water management on return flow, particularly irrigation scheduling, the effectiveness of irrigation water management must be considered. Irrigation water-use efficiency (defined as the increase in crop yield over nonirrigated yields per unit of irrigation water applied annually) has been used to evaluate the effectiveness of irrigation practices (Jensen and Sletten, 1965). Shmueli (1973) describes optimum irrigation efficiency as the minimum seasonal water application necessary to raise crop yields and reduce the amount of irrigation water applied below the evapotranspiration level (maximum Y/W_a). Also, since irrigation is complementary to precipitation stored in the soil, these resources should cover the water requirement for maximum production or income.

With this background, and assuming that the annual change in available water in the root zone is negligible,

$$W_I + P = W_{cu} + W_u \qquad [6]$$

where W_I = the total volume of water diverted annually from a river or from some other natural source for irrigation (irrigation water), P =

annual precipitation in the irrigated area, W_{cu} = the volume of water consumptively used annually in the irrigated area, and W_u = the volume of water beneficially used annually within the same area but not consumed or evaporated. W_u represents the volume of water that is potentially available for return flow from an agricultural area ($W_u = W_I + P - W_{cu}$). It normally equals return flow if water is not diverted from the area or consumed or evaporated in other nonagricultural processes. The optimum amount of irrigation water required per unit area is

$$(W_I)_{opt} = (W_{cu} + W_u - P)_{min} \qquad [7]$$

where $(W_{cu} + W_u - P)_{min}$ = the minimum amount of water for maximum sustained crop production or income.

The overall efficiency of beneficial irrigation water use within an irrigation project, or *irrigation water management efficiency*, E_{im}, can now be defined as

$$E_{im} = 100 \frac{(W_I)_{opt}}{(W_I)_{opt} + |W_I - (W_I)_{opt}|} \qquad [8]$$

where $(W_I)_{opt}$ = the optimum annual irrigation water required per unit area, if uniformly applied without surface runoff and without deep percolation, to obtain maximum sustained annual crop production or income. $(W_I)_{opt}$ includes the minimum, but essential water needed for other nonconsumptive agricultural uses, like frost protection, leaching, hydrating a crop like potatoes before harvest to control bruising, etc., and the minimum amount of water required to germinate a crop if it will not germinate without irrigation. The minimum water required for leaching is based on the latest available practical technology. It may necessitate leaching during the nongrowing season, like irrigating after winter precipitation, or in some cases before winter precipitation. The minimum amount of water required for germination is that amount needed using the latest available practical technology. The use of the absolute quantity, $|W_I - (W_I)_{opt}|$, in the denominator of equation 8 provides for the case where less irrigation water is applied than the optimum for maximum sustained crop production or income.

EARLY EFFORTS TO IMPROVE IRRIGATION WATER MANAGEMENT

As irrigation expanded in the USA in the late 1800s, numerous studies were conducted to improve irrigation water management. Studies of crop water requirements were initiated in the late 1880s and early 1890s to evaluate the quantity of water being used, crop returns, and water losses by evaporation and deep percolation. Overirrigation was cited as the first and most serious mistake made by early settlers (Buffum, 1892). Israelsen, et al. (1944) conducted nearly 150 field tests in the late 1930s and 1940s to evaluate water application efficiencies. They found that the dominant factors resulting in low water application efficiencies were excessive applications, uneven water distribution over the land, and high soil water contents before irrigation. Excessive water applications and irrigating too soon are interrelated and are important factors in scheduling irrigations.

Irrigation scheduling involves determining the optimum time to irrigate and the optimum amount of water to be applied with existing irrigation systems. As irrigation systems are improved, the optimum values may change. Numerous procedures have been proposed and advocated for decades to assist the farm manager/operator in scheduling irrigations. Probably the earliest and most common procedure proposed is to note the appearance of the soil in the root zone using a probe or shovel. But, typically, authors of irrigation publications indicate that irrigators are reluctant to expend this effort to assess irrigation needs. Plant appearance is also used to schedule irrigations, but generally by the time the plant shows symptoms that soil water is limiting growth, crop yield and/or quality have already been irreversibly affected. Using tensiometers to determine when to irrigate has been advocated for many years and they are commonly used for this purpose in citrus groves.

However, tensiometers have not been routinely used by farm manager/operators to determine when to irrigate most farm crops. Why? There are several key reasons. They require the farm manager/operator's time for installing and removing instruments and recording observations several times each week. Tensiometers may interfere with cultivation, and may be a nuisance to service. Interpreting the values recorded (especially for those crops that do not need to be irrigated frequently to keep the soil water level in the tensiometer range), can be complicated, and erroneous readings caused by poor contact with the soil, leaks in the unit, etc. are confusing.

Similarly, electrical resistance or soil moisture blocks also have been proposed for many decades to determine when to irrigate. Generally, tensiometers and soil moisture blocks can be used effectively by trained irrigation technicians and irrigation scientists in research, or by trained technicians monitoring farm fields, but they are not used extensively by farm manager/operators. Thousands of tensiometers and soil moisture blocks have been sold to farm manager/operators, but they are rarely used by the farm manager/operator to determine when to irrigate most farm crops. Similarly, evaporation devices like the U.S. Weather Service Class A pan, and various other special evaporation devices have been advocated for many decades to assist in predicting when to irrigate. For example, use of evaporation data to schedule irrigations has been promoted for several decades in the State of Washington (Hagood, 1964; Jensen and Middleton, 1970; and Pruitt, 1956). Coefficients for use with a standard pan have been determined experimentally for most farm crops after full crop cover has been established. Daily pan evaporation is broadcast or published in newspapers. Irrigation scheduling boards have also been developed for different crops based on pan evaporation as an index of the climatic effect on evapotranspiration. In Canada, a black, porous plate supplied with water has been used extensively for irrigation scheduling in orchards, as well as for some other farm crops (Wilcox and Brownlee, 1969).

Suggested general dates and amounts for irrigations can effectively improve irrigation water management efficiency on soils with deep-rooted crops not highly sensitive to water stress like cotton, and for climate that does not vary widely from year to year. Calendar schedules work best where rainfall does not significantly affect soil water during the main part of the growing season. The recommended dates are usually derived from irrigation experiments in which the treatments included both the time and amount of irrigations.

Significant improvements in irrigation water management efficiency have been achieved during the past few decades in some areas, especially where water is expensive or scarce. A significant portion of these improvements can be attributed to the development and availability of new irrigation facilities. Basically, the traditional approach to encouraging improved irrigation scheduling generally has not been very effective. The traditional approach requires the farm manager/operator to use some device like an evaporation pan to indicate the climatic effect on the rate of evapotranspiration, or an instrument to indirectly evaluate the soil water status. Most traditional approaches basically require that the farm manager/operator <u>first</u> understand the processes involved and the factors governing soil moisture depletion. In addition, if a tool or an instrument is required, he also must understand how it functions and its direct relationship to the soil water status or its indirect relationship to the soil water depletion rate. Actually, the traditional approach to improving irrigation scheduling may have handicapped progress over the past several decades because alternative procedures have not been developed and evaluated. For example, would we consider advising farmers to <u>first</u> study chemistry and associated techniques to obtain representative soil samples, make the necessary analyses, and then independently determine the amount of fertilizer needed? No. We recognized the complexity of soil and plant analyses, the interpretation of these analyses, and the training and time required. In lieu of the usual approach, we provided or encouraged them to use service laboratories, both private and commercial, to supply this information. But why have we insisted that the farm manager/operator first understand the principles of soil water management, atmospheric physics that control the evaporation rate, and hydraulics that control water distribution over his field to apply these principles and improve his irrigation water management efficiency?

I firmly believe, perhaps from hindsight, that we have overemphasized a single academic approach to improve irrigation water management. We have not adequately considered alternative procedures to provide the vital decision-making data needed to improve irrigation water management. But we have recognized that if the time and amount of water applied can be controlled by the irrigation system, irrigations can be programmed more easily or automated with appropriate soil water sensors to achieve efficient irrigation water management. This approach does not require that the farm manager/operator first acquire technical knowledge and training before he can apply irrigation science and technology. Instead, with an automated system he learns how the complete system responds to changes in climate, precipitation, and crop growth stage by observing the irrigation frequency and observing the quantity of water used.

Efficient irrigation water management with most existing irrigation systems requires daily or weekly decisions and judgments. Irrigation scheduling with most irrigation systems is a decision-making process that requires current information involving trends, projections, and effects of alternative actions similar to that 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" (Jensen, 1972).

Based on my experience during the past two decades, I feel that the traditional approach to improving irrigation water management will not result in further significant changes in irrigation water management, unless the cost of water increases substantially. When the cost of applying irrigation water is low, as it is in many areas using natural reservoirs, unlined open channels, and surface irrigation systems, improved irrigation water management will require improving both irrigation scheduling and irrigation facilities.

Irrigation facilities will be improved more rapidly if the farm manager/operator realizes that he is unable to achieve the desired control of irrigation water to efficiently maintain the soil water reservoir within the optimum range. Irrigation scheduling services can stimulate the desire to improve the irrigation system. Improvements in irrigation scheduling with most existing systems will require the availability of irrigation scheduling services for the busy farm manager/operator. Irrigation scheduling services can be defined as follows:

Irrigation Scheduling Services (ISS) - A modern service, based on the latest irrigation science and technology, which provides up-to-date information on the status of available water in individual fields; projected date of next irrigation, if another will be needed, or daily rate water should be applied with high frequency irrigation systems to maintain the desired soil water level in each field. The service recommends the allocation and time of water application when the water supply or its application cost is the primary variable input that will control the net return from the farming enterprise during the current cropping season. The service recommends the allocation of water and timing to optimize net returns when another variable like fertilizer, will limit net returns, and provides related recommendations concerning the operation of the farm irrigation system to improve the uniformity of water distribution, reduce water losses, maintain a favorable salt balance in the soil, etc. so as to increase the managerial skills of the operator/manager and his net returns from the farming enterprise.

SECTION V

DEVELOPMENT OF SCIENTIFIC IRRIGATION SCHEDULING

FACTORS AFFECTING IMPROVEMENTS IN SCHEDULING

Improvements in irrigation scheduling, utilizing recent advancements in irrigation science and technology, progressed slowly during the past two decades while significant advancements were made in irrigation science and technology and related sciences, like agricultural meteorology. During the same period, irrigation water management efficiency, E_{im}, on some projects improved where water was scarce or expensive, but changed little on many projects.

Improving E_{im} on most existing projects requires both improved irrigation scheduling techniques and improved irrigation facilities for better control of irrigation water. There are several reasons why little progress has been made in controlling irrigation water use. First, water measurement or volumetric water deliveries to each field requires special control structures with surface irrigation systems. Control structures on many irrigation projects and farms have not changed appreciably during the past 20 to 50 years. Some older projects do not even have water measuring structures at farm turnouts, and most irrigated farms do not have water measurement facilities. Second, the cost of water for many older projects is very low because the original development costs have been repaid and there have been few apparent incentives to upgrade systems. Third, water rights, which are usually limited to beneficial use, have not been enforced as irrigation technology has improved and allowed for more efficient use of irrigation water. Basically, there has been little need to improve E_{im}.

Where good water control structures and measurement devices are available, the water delivered to farms can easily be measured with sufficient accuracy, but the magnitude of losses as seepage in unlined on-farm distribution systems, deep percolation at the upper ends of the fields, and surface runoff generally are not known to the farm manager/operator. Also, he is not interested in measuring the amount of water applied or lost as runoff or deep percolation from each field if he does not receive direct economic benefits. Direct benefits from improved water management are difficult to document, especially where direct water costs are low. The farm manager/operator is not interested and cannot justify expending additional funds, time, and encountering various inconveniences involved in measuring water just to collect data.

Large increases in labor costs during the past two decades have also been a major factor in the lack of change in irrigation water management efficiency. A high proportion of the farm irrigation systems in use today cannot be operated at a high efficiency unless labor input is relatively high. As labor costs increased, or as labor became scarce, irrigation water management efficiency either remained relatively unchanged, or even decreased as labor input decreased. In some cases, reduced labor input was offset by improvements in the irrigation system.

Improved irrigation scheduling can result in direct and indirect economic benefits, even when used on most existing systems, but new techniques are needed. As mentioned in the previous section, numerous devices like atmometers, evaporation pans, tensiometers, and soil moisture blocks are tools that have been available to the manager/operator for many years to determine when to irrigate. A summary of numerous methods of evaluating soil water is presented by Haise and Hagan (1967). The extent to which these instruments are used by farm manager/operators is extremely low, even though many of these devices have been available for 30 years. Scientists and irrigation technologists continue to improve these instruments and frequently state that "a farmer could easily decide when to start irrigating and the amount of water required by reading these instruments in a field." After 20 to 30 years of advocating using these instruments without much success, it is time to recognize that perhaps these instruments are not acceptable for practical use by the farm manager/operator. The lack of change in irrigation scheduling practices by the farm manager/operator also strongly implies that procedures for providing irrigation scheduling information have not been very effective. Irrigation water scheduling information must be current, economical, and any irrigation scheduling information, whether directly used by the farmer or by a service group, only supplements, but does not replace, irrigation experience.

Some research instruments for measuring soil water have been greatly improved, like the neutron probe. The neutron probe is now a very reliable, standard instrument for soil water measurement, but its use is largely restricted to research and investigations conducted by experienced and trained personnel. New and better instruments for measuring soil water could improve irrigation scheduling, but experience has shown that instruments in themselves do not automatically result in improved irrigation scheduling.

Scientific irrigation scheduling can be based on gravimetric soil sampling, on instruments that measure soil water directly, or instruments that indirectly indicate the soil water level, and evaporation devices. The extent to which trained personnel provide irrigation scheduling services with these instruments is very limited in the USA. Scientific irrigation scheduling also can be accomplished utilizing climatological, soil, and crop data with sophisticated electronic computers or electronic desk calculators to perform the tedious computations. Most of the recent advanced techniques for scheduling irrigations rely heavily on a climatological approach, coupled with simple plant growth and soil water models that simulate daily changes in soil water.

CLIMATOLOGICAL APPROACHES

Scheduling irrigations using current climatological data seems to be the most attractive, promising technique for improving irrigation scheduling where the farm manager/operator controls the irrigation system. The concept of scheduling irrigations using climatic data is not new. Das (1936) suggested using climatic data to control irrigations in the 1930s. The concept received more attention after 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, before 1965 this method had not been adapted for general practical use or tested extensively in the USA. Since 1969, several procedures that utilize computer technology and current climatic data in planning irrigation schedules and in providing irrigation scheduling services have been described (Buras, et al., 1973; Jensen, 1969; Lord and Jensen, 1975; and Corey and Franzoy, 1974).

DEVELOPMENT OF SCIENTIFIC IRRIGATION SCHEDULING

Probably the most widely used general procedure for providing scientific irrigation scheduling services is the USDA-ARS Computer Program for Irrigation Scheduling, released in 1970 and modified slightly in 1971 (Jensen, et al., 1971). (Copies of the computer program with sample input-out data and general operating guides are available from the author.) Many service groups modified the program to suit their special needs. This program was developed cooperatively with farm managers and service groups, thus enabling the incorporation of farm and service manager reactions during formative stages. The computer program is only a tool for use by technical service groups to provide manager/operators of irrigated farms with current estimates of the soil water status by individual fields, and predictions of future irrigations. The computer program was purposely based on simple mathematical models and equations so that limited input data could be used. Also, program operators must clearly understand how to manipulate or make changes in the input data to compensate or adjust for irregular conditions. As components of the original program are improved, they will be replaced with more accurate subroutines.

The irrigation scheduling program, operated on a manual basis, was evaluated in southern Idaho in 1966 and 1967. The computer program and management services were evaluated in cooperation with farm manager/operators, the Idaho Agricultural Extension Service, and the Salt River Project in Arizona in 1968 and 1969. About 50 fields in Idaho, and a similar number in Arizona were scheduled during this period. A workshop on operational procedures for the computer program was held at the Snake River Conservation Research Center in Kimberly, Idaho, in March 1971 (Jensen, 1972; Jensen, et al., 1971; Lord and Jensen, 1975).

SECTION VI

BASIC CONCEPTS OF IRRIGATION SCHEDULING AND SCHEDULING SERVICES

OBJECTIVES

The main objective of irrigation water management for food and fiber production is to maintain the soil water level within a range that does not significantly limit plant growth and crop production when adequate irrigation water supplies are readily available and irrigation water costs are small. When water supplies are limited, and maximum crop production is needed for seed crops, food, and fiber, the main objective may shift to optimizing production per unit of irrigation water. When irrigation water costs are high and represent a major part of production costs, the main objective may shift to maximizing net income per unit of irrigation water. Net income may be affected by crop quality, its quantity, or both.

IRRIGATION WATER MANAGEMENT

As previously stated, efficient irrigation water management requires daily and weekly applications of agricultural and irrigation technology. It requires frequent decisions throughout the irrigation season, except with fully automated systems, and it requires uniform distribution of 5,000 to 15,000 m^3 of water to each ha of irrigated land each year.

With fully automated systems and water available on demand, the time of application and the quantity of water applied can be controlled by soil water or salinity sensors and related control valves and structures (Humpherys and Stacey, 1975). Most soil water sensors respond to soil water pressure changes. Salinity sensors respond to the concentration of soluble salts in the soil solution or drainage water. For efficient automatic, high-frequency irrigation and salinity control, which requires a small amount of continual drainage, sensors must respond to the drainage from the bottom of the root zone, or respond to the salt concentration (Rawlins, 1973; Rawlins and Raats, 1975; van Schilfgaarde, et al., 1974). Fully automated systems usually require a larger capital outlay per unit area and a higher level of on-site technical skills as compared with most surface irrigation systems.

The complexity of efficiently managing a soil-crop-climate system can be described with an example. Figures 1 and 2 illustrate a typical example of irrigation water management for a shallow-rooted crop in southern Idaho. Figure 1 shows typical variations in evapotranspiration rates in an arid area. The dashed line connects daily estimates of "potential evapotranspiration" or evapotranspiration for a well watered reference crop like alfalfa. These estimates were made with the Penman combination equation. The solid line connects daily evapotranspiration as measured with a lysimeter (Wright, 1975). Typically, the evaporation rate from the soil increases immediately after irrigating a field before a crop, like snap beans, emerges. The evaporation rate decreases rapidly during the first few days after an irrigation as the soil surface dries. The evaporation rate remains very low, less than 1 mm/day, until the soil is again wetted by an irrigation, or precipitation such as on June 5, until the bean plants begin to emerge about June 10. When leaf area is very sparse, the rate of evapotranspiration increases, like on June 14 and June 21, after each irrigation, which wets the soil. After the bean plants emerge, the evapotranspiration rate with a dry soil surface increases relative to potential evapotranspiration until the leaf area index (LAI) approaches 3 (near July 1). When a complete actively growing crop cover exists, LAI > 3, the rate of evapotranspiration is essentially equal to that of the reference crop or potential evapotranspiration (July 1 to August 12). As the crop begins to mature, the evapotranspiration rate decreases relative to the reference crop.

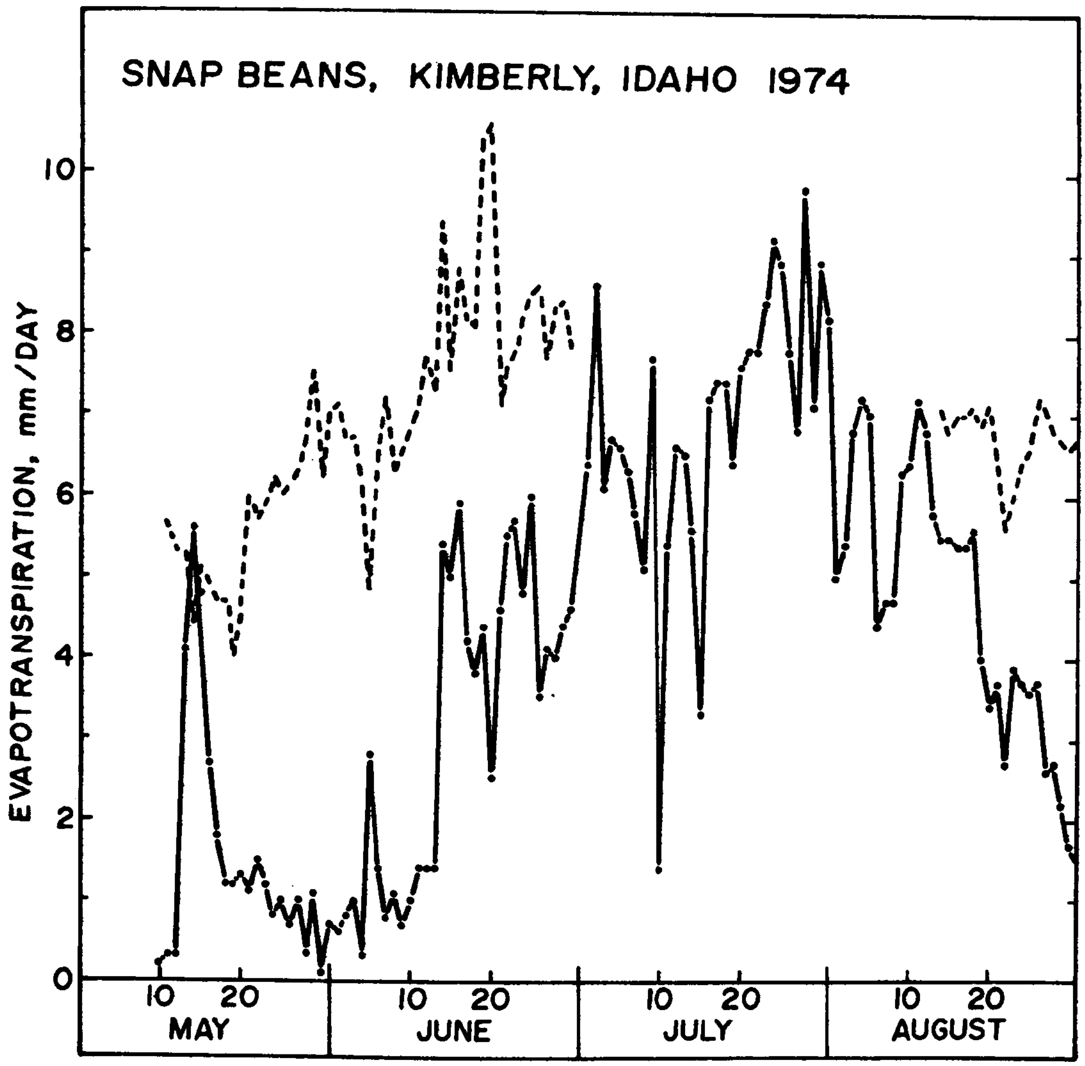


FIG 1. TYPICAL EXAMPLE OF DAILY EVAPOTRANSPIRATION (POTENTIAL, DASHED LINE) FROM A ROW CROP IN AN ARID AREA. (WRIGHT, 1975)

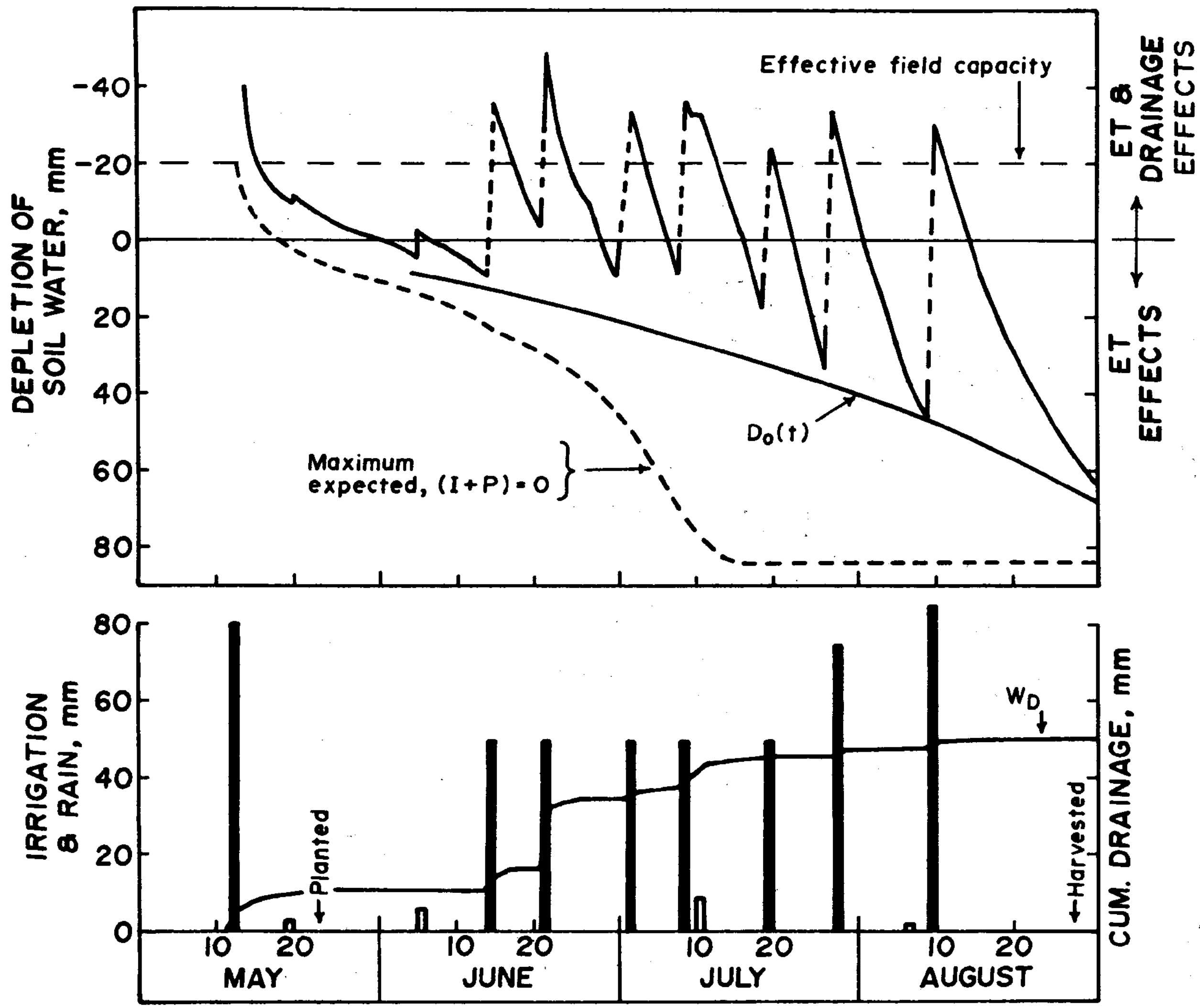


FIG 2. SIMULATED SOIL WATER STATUS, IRRIGATION AND RAINFALL, AND DRAINAGE.

ESTIMATING SOIL WATER DEPLETION

The previous example illustrates the complexity of managing a soil water reservoir when considering only the factors affecting evapotranspiration rates. Modern irrigation scheduling considers the evapotranspiration rates and simulates the soil water status to estimate the soil water status and forecast irrigation dates. The soil water status in this example is simulated in Figure 2, using estimates of potential evapotranspiration and evapotranspiration measured from the shallow-rooted bean crop. In this example, a drainage rate of 0.1 mm/day was considered negligible. The rate of unsaturated drainage from the soil profile is strongly dependent on the soil water content above field capacity, $dW/dt \leq 0.1$ mm/day. Ogata and Richards (1957) showed that the water content for a soil that is draining can be expressed by

$$W = cW_o t^{-m} \qquad [9]$$

where W is the water content; W_o the water content when $t = 1$; m is a constant for a soil; c is a dimensional constant for t^m; and t is the time after irrigation has stopped. The drainage rate is

$$\frac{dW}{dt} = - mW\left(\frac{W}{cW_o}\right)^{\frac{1}{m}} \qquad [10]$$

When using daily time increments, the cumulative drainage can be approximated using the following equation, which is similar to that proposed by Wilcox (1960)

$$W_D = \sum_{i=1}^{\infty} m[W_{i-1} - (E_t)_i] \left(\frac{W_{i-1} - (E_t)_i}{W_o}\right)^{\frac{1}{m}} \qquad [11]$$

where W_D = the cumulative drainage; i is the number of days after irrigation; and E_t is the evapotranspiration for the day. The values of the empirical coefficients in equations 9 and 10, as used in Figure 2 are: $m = 0.043$, and $W_o = 214$ mm for Portneuf silt loam (0 to 0.6 m depth). Miller and Aarstad (1974) reported m values for several other soils that range from 0.1 to 0.15.

Under conditions in southern Idaho in 1974 there was very little rainfall. Without irrigation on this field, the maximum depletion of soil water expected with this crop is represented by the dashed line in the upper part of Figure 2. For this illustration, root growth was assumed to reach the maximum depth of rooting before the soil water content began to affect the evapotranspiration rate. As the available soil water was depleted, the evapotranspiration rate was assumed to be proportional to the ratio, $\underline{\ln}\ (AW + 1)/\underline{\ln}\ 101$, where AW represents the percentage of available water in the root zone on a given day. Extensive experimental data indicate that the soil water could be safely depleted $(D_o(t))$ to some progressively increasing fraction of the maximum available water for many crops before an irrigation is needed as illustrated by the curve $D_o(t)$ (Figure 2). For most farm crops, the optimum depletion generally can approach the maximum value near harvest.

The simulated irrigations (solid bars) and the 1974 precipitation (open bars) are shown on the lower part of Figure 2, along with the cumulative drainage, W_D. If the crop involved is not sensitive to soil water stress and is deep-rooted, less water can be applied than that required to refill the soil profile so that drainage during the irrigation season is negligible. In contrast, when high soil water levels must be maintained for crops sensitive to soil water stress and with a shallow root system (as in this case), it is very difficult to control irrigations with present surface irrigation systems to avoid significant drainage after an irrigation or appreciable unexpected precipitation.

There are alternative approaches to managing the soil water reservoir (as illustrated in Figure 3) for a crop like snap beans. For example, after the preplant irrigation, available soil water may be depleted about 30%, at which time an automatic irrigation system could be activated to apply essentially the same amount of water that has been evapotranspired $(I + P = E_t)$. After initiating such a practice, the soil water content remains constant (as illustrated by the solid horizontal line in Figure 3). The maximum depletion, illustrated by the dashed

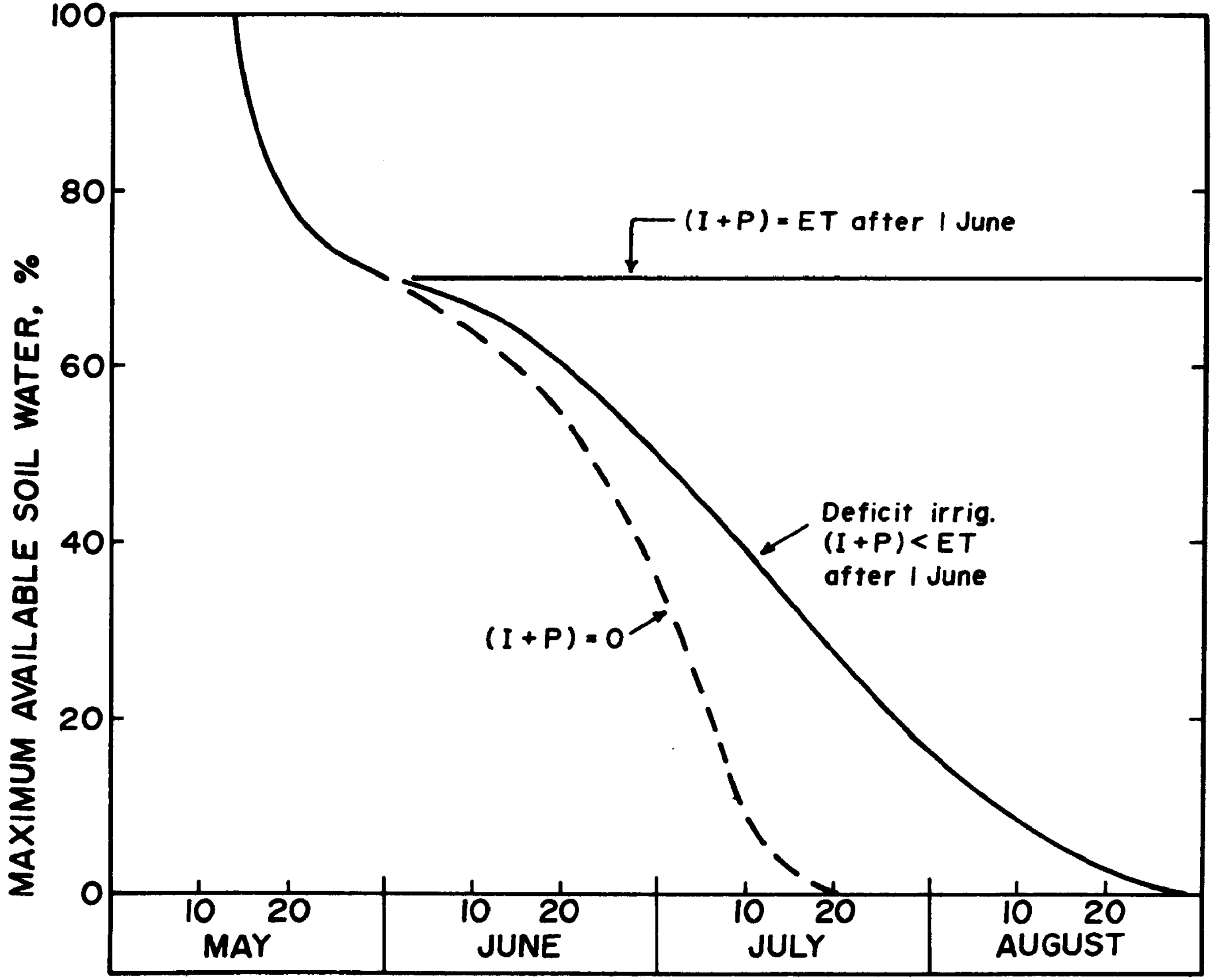


FIG 3. ALTERNATIVE SOIL WATER MANAGEMENT GOALS FOR SHALLOW-ROOTED CROPS IN SOUTHERN IDAHO

line, represents the expected depletion of soil water with no irrigation or precipitation $(I + P = 0)$. Under southern Idaho conditions, and this shallow-rooted crop, no seed beans would be produced using this practice. In contrast, in some areas, like the Southern High Plains, a fair crop can be produced with only a preplant irrigation for a crop like grain sorghum (Musick, et al., 1971).

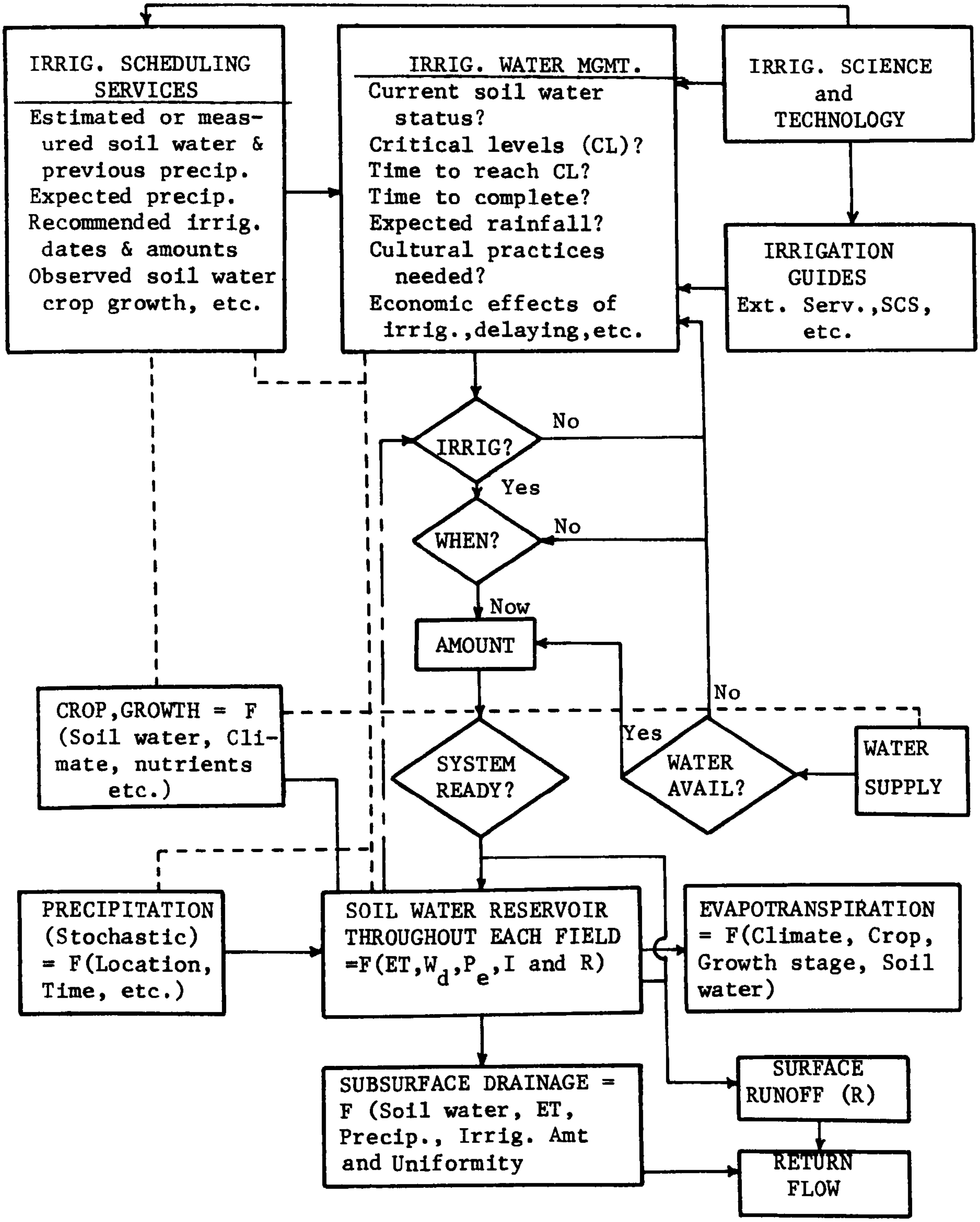
SCHEDULING IRRIGATIONS

Some of the factors affecting the decision-making process that must be considered by the farm manager/operator in irrigation water management on a unit area are schematically illustrated in Figure 4. The daily and weekly decisions involve: The status of available soil water for each crop and field; critical soil water levels, or levels that significantly affect plant growth or quality under current climatic conditions; the projected or estimated time when the soil water level will reach the critical level if an irrigation is not applied; the time required to complete the irrigation of a field; the expected soil water change during irrigation since the entire field can seldom be irrigated at once; the expected precipitation and its influence on soil water after an irrigation, and future irrigations; the need for cultural practices, like cultivation or spraying, which must be completed before an irrigation can be applied; and the economic effects that may result from irrigating too soon or too late, or from terminating irrigations.

Irrigation water management concerns the soil water extraction rate by the crop relative to potential evapotranspiration and the absolute quantity of soil water. Irrigation scheduling groups estimate the soil water depletion after a thorough irrigation or general precipitation with the following equation:

$$D = \sum_{i=1}^{n} (E_t - P_e - I + W_d)_i \qquad [12]$$

Figure 4. IRRIGATION WATER MANAGEMENT PROCESSES



------------- Observations, direct and indirect

— - —— - Automatic control

———————— Flow of information, mass, and coupling of related processes where D is soil water depletion (after a thorough irrigation $D = 0$); P_e is effective daily precipitation (excluding runoff); I is the daily irrigation applied; W_d is the daily drainage from the root zone or upward movement for a saturated zone; and $i = 1$ for the first day after a thorough irrigation when $D = 0$.

The expected date of the next irrigation is predicted by considering the difference between the present depletion and the soil water that can be safely depleted, D_o, and the current or expected average depletion rate before the next irrigation:

$$N = \frac{D_o - D}{E[dD/dt]} \quad [13]$$

$$N = 0, \text{ for } D \geq D_o$$

where N = the estimated days to the next irrigation; D_o = the current optimum depletion of soil water; D = the estimated depletion to date; and $E[dD/dt]$ is the expected mean rate of soil water depletion until the next irrigation is needed. The expected mean E_t and P_e are usually modified for the first 5 days by the current weather forecast, after which long-term means are used. The contribution from the saturated zone is based on AW, depth of roots, depth to the water table, and soil characteristics (Jensen, 1972). Most computer programs evaluate $(D_o - D)$ on a daily basis until $D \geq D_o$.

Under some conditions, the soil water-holding characteristics have little effect on the optimum depletion level that will determine the date of the next irrigation. For example, when the amount of water that can be applied during an irrigation is limited by either the irrigation system or the soil, D_o is the net irrigation depth if the soil water content is maintained above a constant level, $(D - D_o)$ = a constant.

Most current estimates of daily evapotranspiration for each crop are based on a crop coefficient, K_c, and either the evapotranspiration for a well watered reference crop like alfalfa with more than 10 cm of top growth, or an estimate of potential evapotranspiration, E_{tp}. Most current estimates of E_{tp} are based on either the combination equation developed by Penman (1948), or a two-parameter empirical equation that uses only solar radiation and air temperature (Jensen and Haise, 1963).

$$E_t = K_c E_{tp} \quad [14]$$

where K_c is a dimensionless coefficient similar to that proposed by van Wijk and deVries (1954), and Makkink and van Hermst (1956). Most crop coefficients are derived experimentally and represent the combined relative effect of the resistance of water movement from the soil to the various evaporating surfaces and the resistance to diffusion of water vapor from the surface to the atmosphere, and the relative net radiation as compared with the reference crop (Jensen, 1968). New procedures separate estimates of evaporation and transpiration with $(T + P) \leq E_{tp}$. The daily crop coefficient, K_c is adjusted for the wetness of the soil surface and for decreasing soil moisture as follows:

$$K_c = K_{co} K_a + K_s \quad [15]$$

where K_{co} 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 a relative coefficient related to available soil water. The USDA-ARS computer program assumes K_a to be proportional to the logarithm of the percentage of remaining available soil water (AW):

$$K_a = \underline{\ln} \, (AW + 1)/\underline{\ln} \, 101 \quad [16]$$

K_s is the increase in the crop coefficient when the soil surface has been wetted by irrigation or rainfall. The maximum K_c value normally will not exceed 1.0 for most crops, except when short grass is used as the reference crop. Values for K_s for the first, second, and third day after a rain or irrigation are estimated in the USDA-ARS computer program as follows: $(0.9 - K_{co})0.8$; $(0.9 - K_{co})0.5$; and $(0.9 - K_{co})0.3$, respectively.

The USDA-ARS computer scheduling program has also been modified for scheduling irrigations with center-pivot sprinkler irrigation systems and evaluated in the eastern Colorado area (Heermann, et al., 1973).

There are much more complicated models that have been proposed for managing water resources, which use linear and dynamic programming. Several extremely important assumptions must be carefully considered if models that incorporate modern irrigation science and technology are to be used to improve irrigation water management. The individual or service group utilizing the models must thoroughly understand how the models operate, and service groups also must have access to facilities and input data that may be required by complex models. Neglect of these basic assumptions is probably the major reason why very few complex models have been utilized to date in practice. Individuals involved in developing models for management purposes should first determine who will be using the models and the probable input data that will be available. Also, the degree of refinement relative to the ability to control the variables in the field, in addition to the degree of complexity that a service group or the farm manager/operator will accept, must be considered.

The general interrelations involved in irrigation water management are illustrated in Figure 4. Currently, most new developments in irrigation science and technology are assimilated by groups like the Extension Service and the Soil Conservation Service. These groups develop and provide general irrigation guides to farm manager/operators. As irrigation science and technology continue to advance, it becomes more and more difficult to provide comprehensive irrigation guides that are readily understood by busy farm manager/operators to achieve greater control and improved management of irrigation water. As labor costs increase and becomes less available, the available time they have to pursue modern technology may decrease. Thus, commercial or agency irrigation scheduling services will be playing a more significant role in applying modern irrigation science and technology in the day-to-day irrigation water management activities.

The professional staff of irrigation scheduling service groups utilize currently available science and technology, and periodically measure the soil water status and sometimes record precipitation on each farm that is served. Expected precipitation is estimated and irrigation dates and amounts are recommended to the farm manager/operator. These recommendations are updated at least once weekly and the fields are inspected about once weekly during the summer growing season and once every 2 weeks during the winter season. Some irrigation scheduling groups provide professional guidance or irrigation system operating or redesigning recommendations so that the farm manager/operators can achieve better irrigation water control. Service groups must be technically competent, provide economical service, maintain basic farm data and records related to current and previous irrigation practices, maintain active communications with farm manager/operators, and periodically verify the estimated soil water status of the fields utilizing trained and experienced technicians.

NEED FOR IMPROVED IRRIGATION SCHEDULING

Figure 5 illustrates a typical example of recent irrigation practices on a single field in southern Idaho which resulted in a low seasonal irrigation efficiency. This example is not too different from current practices on most irrigated projects. The first two irrigations were applied because young seedlings needed water, but only a small amount of water could be retained in the root zone. Less water was applied in the third irrigation than the soil would hold, which was followed by an excessive irrigation, apparently in an attempt to assure refilling the soil profile. The fourth irrigation resulted in a large amount of deep percolation and a water application efficiency of only 46%. If improved irrigation water management is to influence return flows, the quantity of water applied must be measured or controlled so that the amount of water applied is limited to or less than that which has been depleted

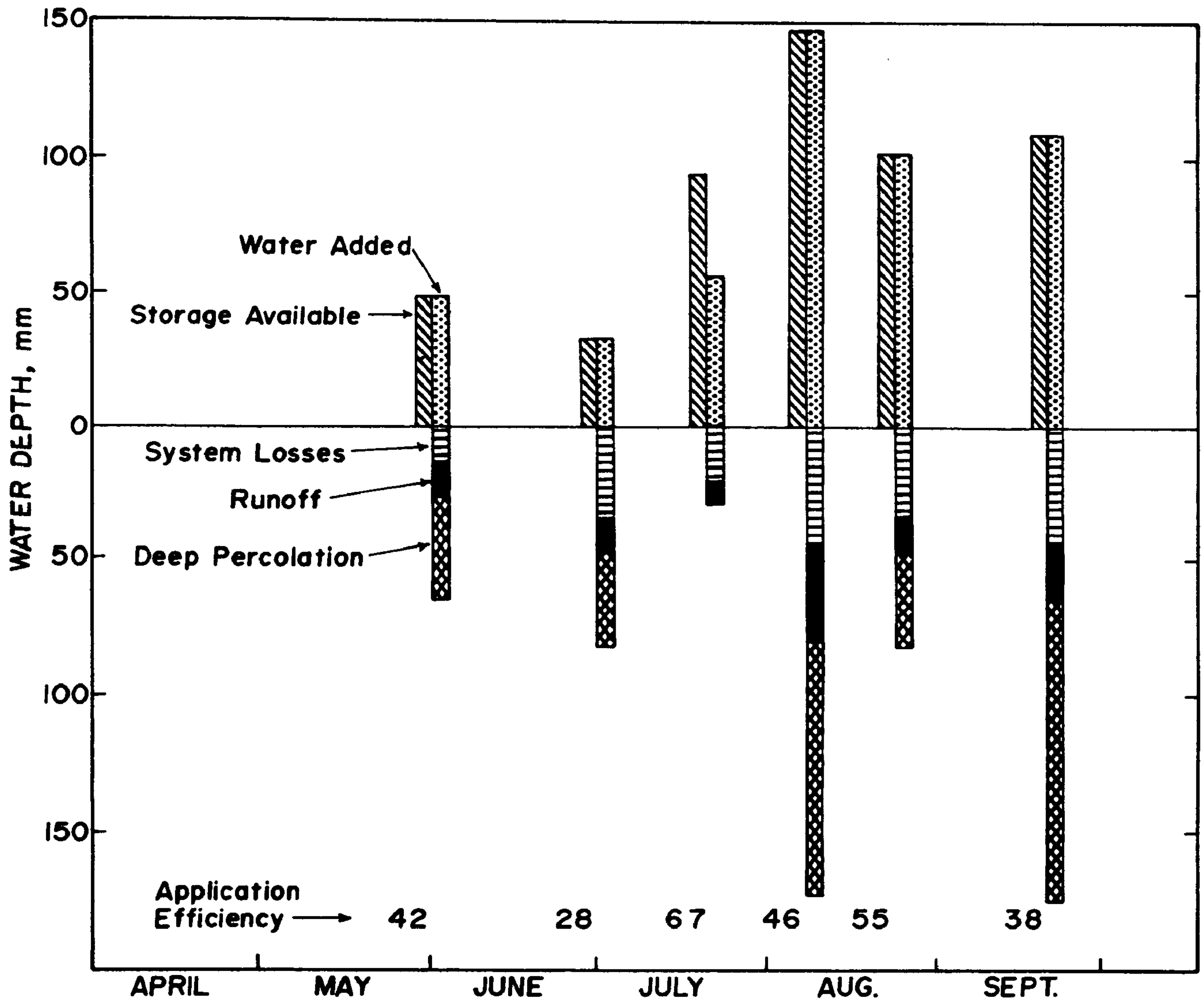


FIG 5. TYPICAL EXAMPLE OF GRAVITY IRRIGATION

by evapotranspiration. If less water is applied than has been depleted at each irrigation, sufficient available soil water must make up the balance of water needed for crop growth during the growing season. The entire root zone normally must then be filled some time before the next crop by off-season precipitation, preplant irrigations, or both.

OTHER RECENT PROPOSALS TO IMPROVE IRRIGATION SCHEDULING

Buras, et al. (1973) developed a computer program similar to that described above for planning irrigation schedules before the irrigation season and for updating schedules within the irrigation season. This program considers the hydraulics of the distribution system, the irrigation methods, climate, farming practices, and general farming conditions. The planning operations are generally based on monthly data.

Woodruff (1968) and Woodruff, et al. (1972) described irrigation scheduling procedures recommended for irrigating corn which were developed for Missouri, an area with significant summer precipitation. Woodruff, et al., observed that the highest corn yield since 1888 was obtained in 1965. They analyzed the precipitation distribution and soil water during that year and found that the surface soil water was always within the tensiometer range, but soil water at lower depths was progressively depleted. The average depletion rate was 4.6 mm/day (0.18 in/day). They observed that annual precipitation in Missouri varied about 34%. while pan evaporation varied only 12%, thus precipitation was the primary variable involved in their procedures. Basically, the recommended amount of water to be applied is less than that which could be held by the soil. This procedure, which can be considered "deficit irrigation," has also been evaluated under arid conditions (Miller and Aarstad, 1975). It is similar to irrigating in alternate furrows and not completely filling the soil to field capacity at each irrigation, or irrigating with center-pivot sprinklers whose average application rate is less than the average evapotranspiration rate. The Missouri procedure is started when the corn is 30 to 45 cm high and the soil water deficit is about 50 mm.

Wilcox and Brownlee (1969) summarized many years of experimental work in developing irrigation scheduling procedures in British Columbia. The idea of scheduling irrigations, utilizing some measure of climatological data, began in the early 1950s, after publications like those of Penman (1948) and Thornthwaite (1948). Because of the availability of evaporation data, although they considered the Class A pan to be too cumbersome, they elected to use Bellani plates as a measure of climatic effects (Korven and Wilcox, 1965). A balance sheet procedure was developed similar to that proposed by others for recording water use, rainfall, and critical soil water depletion after the first irrigation. The evapotranspiration rate relative to measured evaporation must be calibrated for each of the various crops. Wilcox and Brownlee emphasized that many growers wait too long and they apply too much water, and that scheduling does not compensate for inadequacies in the irrigation system. One technique for communicating information on evapotranspiration and precipitation to growers involved using blackboards along the main thoroughfare where farmers could stop and record rates of evapotranspiration and daily precipitation. A detailed description of these procedures, including estimates of net irrigation water requirements, precipitation lost by deep percolation or runoff, or both, and risk analyses, can be found in a recent technical bulletin (Wilcox and Sly, 1974).

Hagood (1964) described similar procedures in use in the Columbia Basin of Washington based on Class A pan evaporation. Many years of experimental work have been invested in developing crop coefficients after full crop cover for use with the Class A pan in Washington.

Brosz and Wiersma (1970) developed an accounting procedure for eastern South Dakota to assist farmers to determine when and how much water to apply. This procedure was based on average expected evapotranspiration rates for corn and alfalfa. Busch (1971) developed a computer program that uses weather forecasts for scheduling irrigations on cotton. Hiler and Clark (1971), and Hiler, et al. (1974) developed procedures for scheduling irrigation utilizing a stress-day index. The index was based on a coefficient related to the crop's susceptibility to stress and a parameter characterizing the magnitude of daily stress. The magnitude of daily stress was derived either from direct plant measurements or from one of several methods of estimating potential evapotranspiration.

Allen and Lambert (1971a) described concepts for a general model to be used for deciding whether to irrigate or postpone an irrigation based on irrigation costs and probable yield losses. The objective was to minimize seasonal losses and costs, and calculate the corresponding risk. They tested this program, using data for three growing seasons and found that the new criterion resulted in less total cost and better utilization of water than the 50% depletion criterion (Allen and Lambert, 1971b).

Corey and Franzoy (1974), who operate a commercial irrigation scheduling service company in the Central Great Plains and the Arizona-New Mexico area, use their computer program to assist their technicians in making field decisions. After several years of experience, their mode of operation involves periodic visits to each farm serviced to evaluate field conditions. At each visit, a recommendation sheet requires the experienced technician to write in the date of the last irrigation, to estimate the present depletion of soil water, and enter the estimated next irrigation date for each field from weekly updated estimates of evapotranspiration and projected irrigation dates for various crops. Instead of giving the quantity of water to be applied, they give the hours of set for either a furrow or sprinkler system and make other general recommendations.

There are many other proposals for scheduling irrigations and proposals for optimizing the use of water from surface reservoirs, like that described by Huang, et al. (1975). But, to my knowledge, water use optimization programs are not being used in day-to-day water management practices in the western USA.

Many of the current procedures used by irrigation scheduling service groups utilize general procedures described by Jensen (1969). The computer program, described by Jensen, et al. (1970, 1971), was released in 1970 and updated in 1971, and has formed the basis for many of the computer programs used by service groups.

SIMULATION MODELS FOR IRRIGATION SCHEDULING

The preceding discussion illustrates the trend toward using models that simulate the soil water status. A digital simulation model of the soil water reservoir enables a service group to estimate daily changes in soil water since the last field inspection and to project future changes based on expected climatic conditions, growth stage, and direct changes in soil water due to precipitation. A simulation model that includes all aspects of water management on a farm becomes very complex since water supplies, cultural practices, alternative costs, soil type, crop responses to soil moisture and climate, plant density, plant nutrient levels, etc. all become involved. The development of a simulation model requires the consideration of the developmental costs, operational costs, the costs of obtaining the necessary current input data, and the availability of computer facilities on which to run the simulation model. Many service groups operate on a relatively small scale and cannot justify using complex simulation models. Experience by irrigation scheduling groups also has shown that it is difficult to prove direct economic benefits from using their services as compared with current scheduling practices where water supplies are plentiful and perhaps overirrigation is the rule rather than the exception. Many farm manager/operators, however, believe the guidance provided and field monitoring is worth a significant part of the fee charged.

The simulation model is mainly needed to estimate the change in soil water, since the field was last irrigated or inspected, to forecast the next irrigation date. If general recommendations are made before planting specific crops, then the simulation model could utilize historical data to evaluate alternative management practices for planning purposes. But, once seasonal decisions have been made and crops planted, the simulation model is used mainly between irrigation intervals. Where water supplies are very limited, decisions to irrigate perhaps only one to three times during the season, or not at all, may be made early in the growing season. Under these conditions, estimates may need to be updated only once or twice during the growing season. These procedures are used where rainfall is significant and where more frequent irrigation may not be profitable.

The main use of a simulation model under semihumid conditions may be to estimate when irrigations must begin after a general rain to complete the next irrigation on all fields before soil water deficits become severe and crop yields or quality decrease. Typically; farm manager/operators wait too long before they begin to irrigate after a general rain. This problem is very common in areas where summer precipitation provides much of the water required by crops. Lembke and Jones (1972) used a simulation model to evaluate when to begin irrigating in humid areas.

Irrigation scheduling utilizing simulation models has also enabled scheduling center-pivot sprinkler systems so that they operate only during off-peak electrical load periods. Stetson, et al. (1975) have shown that the peak power demand by an irrigation district can be reduced if center-pivots are scheduled to operate when industrial, home, and air conditioning loads are below normal. Simulation models have also been used to determine design capacities for sprinkler systems where rainfall is significant (Heermann, et al., 1974; Stegman and Shah, 1971).

Numerous related simulation models have been developed during the past 5 years. Yaron and Strateener (1973) developed a very detailed simulation model to estimate yield functions and determine optimal irrigation policies under stochastic rainfall conditions. This model was developed utilizing 4 years of experimental data in Israel and would be very site-specific. Its main benefit would be for use in years of low rainfall. Mapp, et al. (1975) developed a very detailed, but site-specific, simulation model of soil water and atmospheric stress-crop yield relationships for economic analyses in the central basin of the Ogalala formation of the Southern High Plains of Texas, the Oklahoma panhandle, and southwestern Kansas. The model was developed for a specific soil, but is based on many years of experimental data for grain sorghum, winter wheat, and corn collected in the general area. This simulation model was tested, utilizing 20 years of data to evaluate alternative irrigation strategies like the combination of dryland and irrigated farming and the effects of reduced pumping on crop yields. Empirically derived rainfall probabilities for 2-week periods are used along with an estimate of the initial soil moisture at the beginning of the growing season. The crop yield model is a function of the soil moisture, the soil moisture depletion during various stages of growth, and a measure of atmospheric stress based on pan evaporation relative to critical pan evaporation. This model could be very effective in determining optimum management decisions for nonirrigated and irrigated farming conditions in the area.

Dudley, et al. (1971) used a two-state dynamic programming model to evaluate optimal intraseasonal irrigation water allocations. The decision variable involved the available soil water depletion level. Evapotranspiration was estimated as the function of pan evaporation. This particular model lacked verification with experimental data, and some of the biological assumptions may not have been based on extensive available experimental data. A very comprehensive computer simulation model of cotton growth was developed by Stapleton, et al. (1973). The developers of this model indicated that by using this model a knowledgable manager will broaden his information base and complement his experience in managing the crop for profit.

Simulation models utilize many different techniques for arriving at the needed estimates. Similarly, operators of commercial firms providing

ISS utilize many different techniques for modifying simulation models for scheduling purposes. Further discussion of simulation models for soil water and crop production can be found in Agricultural Meteorology, Vol. 14, pages 229-320, 1974.

The demand for climatological data to provide irrigation scheduling services using simulation models also has provided new challenges for meteorologists of the U. S. Weather Service. For example, a 2-year evaluation of the accuracy in forecasting climatological data versus the accuracy of forecasting a change in evapotranspiration at Kimberly, Idaho, indicated that evapotranspiration estimates calculated with forecasted climatological parameters were more accurate than direct estimates by the meteorologist of above or below normal potential evapotranspiration. The direct estimates were less accurate because the meteorologist estimated expected changes in radiation, windspeed, temperature, and humidity more accurately because of his many years of experience in meteorology than estimates of the composite effects on potential evapotranspiration.

Simulations used in irrigation scheduling also may involve very simple relationships. For example, one company that has provided irrigation scheduling services for many years in the Columbia Basin routinely takes gravimetric soil samples, plots these values on a master chart along with direct measurements of water applied with center-pivot sprinkler systems. Periodically, the master chart of soil water is updated and a copy mailed to the farm manager/operator with recommendations for increasing or decreasing the daily rate of water application. In addition, recommendations for plant nutrients and other aspects of the system management also are made on the chart.

EXPECTED IMPROVEMENTS IN OPERATIONAL SIMULATION MODELS

Improved simulation models will be adopted by service companies if models are very general. A company must have coefficients for plant growth rate, crop cover development, maturation, etc. for 10 to 15 crops before it can justify a major revision of an existing operating computer program. The actual cost of running the simulation model is a minor part of the cost of providing irrigation scheduling services. The bulk of the cost is in the professional staff, trained technicians, and travel costs associated with weekly monitoring of each field served.

There will be many minor improvements in the energy balance-evapotranspiration model, particularly improvements in estimates of net radiation, vapor pressure deficit, and the wind function for use with the combination equation. In addition, estimates of soil temperature, or actual measurements of soil temperature can be expected in the near future. Another significant change to be expected is to separate daytime windspeed and vapor pressure from nighttime values, which should significantly improve the accuracy of estimating potential evapotranspiration.

Equations have been developed to offset the contributions to evapotranspiration from the saturated zone where a shallow water table exists. Some of these equations have been adapted to computerized scheduling programs, but the field technicians have not yet gained full confidence in adjusting the proper coefficients to match conditions in the field. In addition, in the near future crop production functions probably will be incorporated into most computer programs along with programs for estimating the plant nutrient status and predicting nutrient deficiencies.

The first major improvement in the scheduling programs will be to separate evaporation from transpiration, which will greatly improve the accuracy of existing models from the time of planting to the development of full crop cover. This is the principal area where the current simulation models seem to overestimate evapotranspiration and where existing models do not properly respond to adverse climatic conditions which may significantly delay germination, emergence, and development of leaf area.

Ritchie (1972) presented a model for separating evaporation from transpiration. In this model, evaporation from the soil surface during the first stage is controlled by climatic conditions. After a given amount of water has evaporated from a soil type, the cumulative evaporation increases proportionally with the square root of time. Net radiation that reaches the soil surface is estimated by considering the increase in leaf area and the absorption of solar radiation by the foliage. Scientific literature during the recent past 5 years contains numerous measurements of leaf area for crops like soybeans, grain, sorghum, corn, and alfalfa. With the data available in the literature, generalized models for evaporation and transpiration are being developed which can be substituted into existing computer scheduling programs in place of the experimentally derived crop coefficients. Improvements in the square root of time evaporation equation coefficient during the transition period are expected as the result of a paper recently prepared by Jackson, et al. (1975). The square root of time evaporation coefficient also seems to be related to soil temperature-vapor pressure relationships. Other techniques for estimating evaporation that will be considered are those of Gardner (1973), and Staple (1974). Similarly, Hanks (1974) developed a model to predict plant yield as influenced by water use, which separates evaporation and transpiration and relates plant growth to transpiration. This concept will form the basis of significant improvements in irrigation scheduling models. Separating evaporation from transpiration and including the effect of soil salinity like that proposed in the model developed by Childs and Hanks (1975) also will be considered.

SECTION VII

SCOPE OF IRRIGATION SCHEDULING SERVICE IN 1974

SURVEY CONDUCTED

A survey of irrigation scheduling services (ISS), which were described in Section IV, was conducted to determine the scope and nature of services provided in 1974 following the release of the USDA-ARS computer program in 1970. The survey was restricted to those agencies and commercial firms providing day-to-day and week-to-week decision-making information to farm manager/operators. Many service groups also provide engineering services and general recommendations to improve irrigation supplies, improve facilities to deliver and distribute water over the fields, and other services like soil and plant analyses, pest management, etc. Agencies or commercial service groups that contacted farm manager/operators or visited individual fields less than three or four times per season were not considered to be providing irrigation scheduling services as defined. Only those groups that provided current information weekly and visited farms or fields one to three times per week during the summer growing season were included in this summary.

The scope and nature of ISS provided in 1974 are summarized under two categories: (1) professional or commercial services; and (2) agency, produce company, project or district services. The principal differences between the two categories is that the first group represents independent, private entrepreneurs who provide this service for a fee. They could also be considered as consultants to farm manager/operators. Commercial groups are competitive and must remain competitive to remain in business and operate at a profit, which stimulates new techniques and personalized service. The consultants essentially work for the farmers' best interests. As consultants, they normally should not sell products or receive commissions on products being sold, since this represents a basic conflict of interest.

Several commercial groups seem to have some conflict of interest.

Groups in the second category provide similar services, but farm manager/operators receiving ISS may be required to either pay only a portion of the costs, or all of the costs are borne by the service group. This category, however, represents an arrangement whereby a group of small farmers can obtain ISS since commercial firms prefer to select mainly the large farm manager/operators.

The survey was believed to have reached a high percentage of the larger commercial firms, but not all of the smaller independent firms operating in the California area. Most of the questionnaires sent to groups in the western USA were returned, including several sent to Alberta, Canada. General characteristics of these groups are summarized in Table 1. Additional details are presented in Appendix Tables A1 and A2.

PROFESSIONAL IRRIGATION SCHEDULING SERVICES (COMMERCIAL)

The commercial ISS groups contacted in the western USA had 1 to 19 years of experience. Of the 10, seven had 5 years or less. ISS were provided for a fee to about 4,450 fields involving over 100,000 ha (> 250,000 ac) of summer crops in 1974 in eight western states. All 10 commercial firms also provide plant nutrition services, seven provide pest management services, six provide engineering services to either improve the farm irrigation system or its operation, or improve the system so that it could be operated to provide uniform distribution of the desired amount of water.

Gravimetric soil samples (either by weighing and drying in an oven, or by the "speedy" method which involves the addition of calcium carbide to weighed sample of the soil placed in an enclosed cylinder which produces acetylene gas in proportion to the soil water content) were used to monitor the soil water level or schedule irrigation on about one-half of the area. Estimated evapotranspiration, based on current climate and crop data, was used to estimate changes in soil water on about 90% of

Table 1. CHARACTERISTICS OF GROUPS PROVIDING IRRIGATION SCHEDULING SERVICES IN 1974 IN WESTERN USA

Parameter, total or weighted averages	Commercial service for a "fee"	Agency service without direct fees
Experience, years	5.6	5.5
Size of operation:		
No. of fields	4,477	3,465
Total area (summer crops) ha	102,100	53,640
Services provided:		
Irrigation scheduling, %	100	100
System improvements, %	60	14
Plant nutrition, %	100	23
Pest management, %	56	18
Scheduling method used:		
Gravimetric samples, %	48	19
Tensiometers or blocks, %	3	7
Pan evaporation, %	34	42
Climatic estimates of E_t, %	90	100
Monitoring method used:		
Gravimetric samples, %	27	26
Tensiometers, %	37	15
Probe and "feel," %	83	100
Plant symptoms, %	12	---
Area per field technician, ha	2,350	2,370
Average daily round trip, km	190	110
Field visits per week	1.5	1.1

the area served. Evaporation from a USWS Class A pan was used on about 33% of the area, and tensiometers alone were used to schedule irrigations on about 5% of the area. Since most firms use more than one method, these percentages total more than 100%.

The area served by an irrigation technician, or the professional when he worked alone, averaged 2,350 ha (5,800 ac), and his average daily round trip to monitor fields was 190 km (120 mi). All fields served were visited an average of 1.5 times per week.

Some of the main reasons customers gave for continuing to use commercial ISS were: (1) improved water management; (2) increased yield and/or quality; (3) lower production costs; and (4) general satisfaction with the service. Some of the main reasons customers gave for discontinuing commercial ISS were: (1) unable to see a direct benefit or value; and (2) poor service and communications, or because they learned nothing new.

Major problems encountered by commercial ISS groups in providing their services were: (1) lack of farm managers' confidence the first year; (2) soil variability; (3) difficulty of arranging discussions with customers; (4) lag time in getting the results of soil and plant tissue analyses from state laboratories; and (5) difficulties with getting gravimetric soil samples and finding reliable employees to obtain the samples. Additional information on commercial groups can be found in Table A1.

AGENCY, CANAL COMPANY, PROJECT OR DISTRICT IRRIGATION SCHEDULING SERVICES

Many groups have initiated ISS on a developmental basis and several districts have added ISS as a routine service to their members or the water users they serve. Tax supported agencies providing ISS on a developmental basis assume that costs of the services will eventually be borne by the irrigation districts involved, or commercial firms will become established in the area, or a joint agency/commercial arrangement will be established to satisfy the needs of the water user/farm manager.

Two state agencies, one federal, the U. S. Bureau of Reclamation (USBR) operating at 16 locations, three produce companies, and one irrigation project had 1 to 10 years of experience. Of the 22, 21 had 5 years or less. ISS were provided without direct costs to the farmer on about 3,500 fields involving over 54,000 ha (133,000 ac) of summer crops in 1974 in 12 of the 17 western states. About 25% of these groups also provide plant nutrition services, 20% provide pest management services, and about 15% provide engineering services.

Gravimetric soil samples were used to monitor and schedule irrigations on about 25% of the area, but evapotranspiration estimates based on current climate, crop, and soil data were used on 100% of the area served. Pan evaporation and crop coefficients were used along with climate-based estimates on about 40%, and tensiometers were used on about 7% of the area. The average area served per technician was about the same as for the commercial groups, but the average daily round trip to monitor fields was less, about 110 km (70 mi) because specific areas were selected for these developmental efforts. All fields were visited an average of 1.1 times per week.

Some of the customers' main reasons for continuing to use the free ISS were: (1) improved water management; (2) increased yield and/or quality; and (3) lower production costs. Some of their main reasons for discontinuing ISS were: (1) scheduling did not fit operations; (2) they could do as well without it, or did not have time; and (3) service and communications were poor, or they learned nothing new.

Major problems encountered by agency ISS groups in providing their services were: (1) communications; (2) lack of farm managers' confidence the first year; (3) unknown amount of water applied or stored in the soil during an irrigation; (4) unavailability of trained personnel and/or temporary summer employees who lacked the desired incentive; (5) getting farm managers to modify current practices; and (6) obtaining water when needed. Additional information on agency ISS groups can be found in Table A2.

GENERAL INFORMATION ABOUT ALL USA ISS GROUPS

Field-by-field ISS were provided to 7,900 fields and over 155,000 ha (> 385,000 ac) of summer crops in 1974. In addition to field-by-field services, the USBR has been trying two other types of services. One provides weekly estimates for each major crop on each farm and are based on early, medium, and late planting dates, and the general soil type involved. This service was not accompanied by regular scheduled visits by irrigation technicians. General irrigation guides for major crops in an area which are not accompanied by regular farm visits were also provided. The USBR provided current weekly farm and general irrigation guides for about 10,000 fields involving about 94,000 ha (233,000 ac) in 1974.

Estimates of evapotranspiration from which the current soil water status is estimated, and the projected next irrigation date were based on some measure or index of the current potential evapotranspiration rate (E_{tp}) and crop coefficients. Crop coefficients relate the evapotranspiration rate for a given crop to the potential rate. These coefficients vary with the stage of crop growth and most computer programs adjust the coefficients for the wetness of the surface soil after a rain or an irrigation. E_{tp} estimates for 57% of the area were based on the Jensen-Haise equation, 37% on the Penman equation, 7% on long-term E_{tp} means for the region, and about 3% on evaporation from the USWS Class A pan. Since groups alternated between methods, these total more than 100%. The major improvement requested by ISS groups was more accurate crop coefficients or curves, especially early in the season. Better techniques for automatically adjusting these curves, as the crop develops, are also needed. Currently a time-based method is used by most groups to adjust the crop coefficient.

AGENCY ISS IN CANADA

Similar agency ISS were provided by the Alberta Department of Agriculture in Canada. About 140 fields and 4,500 ha (11,000 ac) were scheduled in 1974 on a field-by-field basis and guides were provided to about 100 fields totalling about 3,200 ha (8,000 ac). Evapotranspiration was estimated, using atmometers and crop coefficients. Plant nutrition and pest management services were not provided, but services were provided for improving the operating efficiency of irrigation systems. Reasons for continuing or discontinuing the services and problems encountered were similar to those reported in the USA.

ACCEPTING OR REJECTING ISS

Table 2 provides additional information on the reasons for continuing or discontinuing ISS. Reasons listed are basically the same for both commercial and agency service groups. Some exceptions are reasons for discontinuing services (items 4 and 5).

CLIMATIC DATA

Table 3 summarizes comments on the adequacy of climatic data. These comments indicate that improved procedures are needed to facilitate access to good climatic data.

COMMUNICATIONS

Table 4 summarizes the principal mode of communications used between various personnel in the ISS groups. Telephone, oral, and written procedures are used extensively. Two-way radios for technical communications and data transmission by telephone probably will be used more extensively in the future.

MAJOR PROBLEMS ENCOUNTERED

Many problems were listed, but these should not be considered as a deterrent to future growth, nor should they be considered as roadblocks to ISS. Instead, they represent actual conditions that any relatively new service group probably will encounter to some degree. Also, many problems listed were essentially the same as those which farm manager/operators encounter daily and have learned to cope with to some degree. For example, soil variability is very real, and if a field is treated as a single homogene-

Table 2. REASONS CUSTOMERS GAVE FOR CONTINUING OR DISCONTINUING IRRIGATION SCHEDULING SERVICES

Reasons for	Frequency as listed by service groups: Commercial service for a "fee"	Frequency as listed by service groups: Agency service without direct fees
Continuing scheduling service:		
1. Improved water management	4	11
2. Increased yield and/or quality	7	5
3. Lower production costs including water	4	3
4. Satisfied, good service, etc.	3	--
5. Consultants available for other problems	2	--
6. Educational	1	1
7. Miscellaneous - curious, peace of mind, no charge, etc.	1	5
8. None	1	--
Discontinuing scheduling service:		
1. Believe no direct benefit or value, fee too high, or not reducing operating costs	4	2
2. Learned nothing new, confusing, poor service, or poor communications	3	3
3. Does not fit operations, water on turn basis, etc.	1	4
4. None requested to be discontinued yet	--	5
5. Can do as well without service, or do not have time to follow	--	4
6. Sold farm or lost lease	1	1
7. No longer in high-value crops	1	1
8. Poor yield due to other factors, like disease, etc.	1	1
9. Works only with sprinklers	--	1
10. Documenting water use for possible adverse action	--	1

Table 3. ADEQUACY OF CLIMATIC DATA FOR SCHEDULING PURPOSES.

Responses to "How can better climatic data be provided for you?"	Frequency as listed by service groups: Commercial service for a "fee"	Agency service without direct costs
Comments:		
1. No comment	3	9
2. Need more readily accessible data, perhaps on call, regularly mailed, in newspaper daily, or computer readout	3	3
3. Adequate	1	3
4. Need better solar radiation data	--	2
5. Need more, and alternative or localized stations	1	3
6. Need more comprehensive reports	1	1
7. Should purchase equipment and read own instruments	1	1
8. Expect local station to lose solar radiation site - concerned	--	1
9. Have station provide net radiation	--	1
10. Need more rain gauges	--	1
11. Need better forecasts related to irrigation needs.	--	1

Table 4. PRINCIPAL MODE OF COMMUNICATIONS USED, PERCENTAGE OF ALL GROUPS.

Nature of communication	Oral	Written	Telephone	Two-way radio	Via computer terminals
	percent				
To field technicians	81	42	48	13	10
To farmers	74	68	61	6	--
From farmers	81	23	68	3	--
To field offices	81	56	81	13	19

ous unit, irrigation scheduling recommendations must represent the best technical judgment for the situation. In some cases, the irrigation system might be operated so as to use only the upper increment of the available soil water storage capacity if large differences exist within a field. Many times the allowable depletion of soil water between irrigations is determined by the irrigation system's capacity to apply water, and the soil's water-holding characteristics have little to do with irrigation scheduling.

IMPROVEMENTS OR NEW DEVELOPMENTS NEEDED

Needed improved crop curves were listed as a high priority. Studies are now underway to adapt plant growth models and procedures that separate evaporation and transpiration in estimating evapotranspiration which will alleviate many of the problems associated with crop curves.

The need is urgent for an improved, rapid technique for assessing soil moisture content throughout the soil profile. Obviously, improved irrigation systems that apply known amounts of water also would help immensely to alleviate this problem.

FIELD MONITORING

None of the service groups currently use remote sensing or make visual observations of fields from aircraft. Because of the large travel requirement some commercial groups will probably begin using helicopters to rapidly scan the farm fields, initially perhaps only to make a visual overall appraisal of crop growth, uniformity, etc. The airplane or helicopter pilot, or an observer, could then either radio his observations to an irrigation technician operating from a land vehicle in the area to check portions of those fields that need immediate attention. If a helicopter is used, it could land and the pilot could make a first-hand appraisal of the situation. Eventually, remote sensor/recorders probably will be used in aircraft to evaluate soil surface and plant temperatures.

ATTITUDES TOWARD ADOPTING ISS

A comprehensive study of attitudes toward new water use practices also was conducted in 1974 by the University of Idaho with particular emphasis on the adoption of irrigation scheduling (Carlson, 1975). This research study was supported by the U. S. Bureau of Reclamation. A trained graduate student administered a questionnaire in an interview format to 187 farmers, or about 50% of the farmers in the A & B Irrigation District owning 20 ha (50 ac) or more. Attitudes toward the USBR's three levels of scheduling services (field-by-field, and farm and irrigation guide methods) were evaluated considering two groupings, farm and guide users. One result of this study that is of particular concern to ISS groups is the farmers source of new information or the best place for him to obtain irrigation advice. As their best source of new information, about 44% placed a high premium on peers (neighbors and friends), about 22% indicated the irrigation district, 15% the Extension Service, 14% the Agricultural Experiment Station, and only about 2% listed private consultants. The principal difference between the two types of service offered was that the guide user would likely tell a new farmer to see his neighbor and friends, while more farm users would tell a new farmer to see the irrigation district or the Agricultural Experiment Station. Most farmers (65%) preferred periodic workshops as a means of obtaining new farm information, with farm demonstrations listed next (18%), followed by trained personnel on the farm (11%).

A key element in accepting a technical service is in recognizing the need for such services. The survey showed that farmers who recognize their irrigation problems center around the amount and timing of water application are more likely to be more involved in an ISS program.

> "Thus, perception of the problem precedes adoption of techniques to alleviate the problem" (Carlson, 1975).

Another important issue is the ability to control water application and the adoption of a scheduling service. ISS seems to be more easily adapted to sprinkler irrigation since substantially more farm users have sprinkler systems than do guide users. This may have other significant implications, however. Service groups providing ISS will need to monitor the soil water level more closely on surface irrigated farms because it is more difficult to estimate the amount and uniformity of water applied with surface systems. Carlson (1975), in citing Crouch (1972), stressed another key element concerning the adoption of new practices. Many proposed new practices are not adopted because Research and Extension fail to recognize farmers' specific needs. Technology for ISS was developed because decades of experience had shown that the traditional recommendations for timing and scheduling irrigations were inadequate for the farmers' needs. Service groups must not lose sight of the fact that unless they continue to provide farmers' needs and improve their product (service), demand for their product will decline.

GENERAL COMMENTS

The more experienced ISS groups still encounter problems explaining the function, purpose, and need for an irrigation management service, especially in new areas. Some groups feel they must first convince employees of agricultural agencies that irrigation scheduling problems exist and that an ISS program is needed. Agency ISS groups particularly are concerned about documenting that ISS can result in increased net returns to the farmer; whereas, the increasing demand for ISS should be sufficient to gage the value of ISS to farm manager/operators. In some areas, action agency and Extension Service groups have taken the lead in promoting new technology and have readily recognized potential benefits. In other areas, individuals perhaps do not recognize the need and probably are not equipped to provide these services themselves with the intensity needed. Many individuals have too many other responsibilities, do not have the necessary training or support staff, and may be reluctant to take on the demands and responsibilities of making actual decisions and recommendations throughout the irrigation season. Commercial ISS groups must be "available" or on call at all times. In addition, the Extension Service in most states probably could never obtain adequate funding to secure the necessary staff to provide the needed ISS, but they can play a major role in aiding commercial and agency groups in becoming established and improving their services because they have access to experimental data, and soils and crop information, etc.

A very common problem encountered by many ISS groups is in finding and training qualified employees. As expected with a relatively new service, many potentially valuable employees do not have prior experience, and many current employees need more experience. Probably one of the most frustrating problems encountered, especially for the newcomer, is coping with nonuniform soils and water applications. Also, communicating essential technical information to the farmers each week is difficult. Better communication techniques are needed.

The more experienced groups believe that irrigation recommendations should be made while visiting the farmer, but only "after" thoroughly checking the fields that are serviced. This is especially important when the amount of water applied is unknown. Experienced personnel use estimates of past and expected evapotranspiration and irrigation intervals, along with observations of soil moisture in each field. This procedure limits the area that an employee can serve.

As previously stated, better crop curves, especially early in the season, are urgently needed. Also, these curves must reflect current growing conditions and not be based solely on time. Presently, several investigators are working on evaporation-transpiration models which greatly improve evaporation estimates, and changes in the transpiration component will be dependent on the current crop growth rate. These models should reduce or eliminate the early season crop curve problem. A closely related problem involves guidelines for determining or prescribing optimum soil moisture depletion levels at all growth stages and for various soil types. An ISS should emphasize increased net returns, not maximum yields. A commercial ISS group is primarily working for the farm manager/operator, and increased net returns is the primary reason he is seeking ISS.

Finally, implementing ISS for some 16 million irrigated ha (40 million ac) in western USA is a tremendous undertaking. Developing the technology plays a significant role, but it does not assure a viable ISS operation. Organizations with qualified and trained personnel will be playing a vital role in implementing better irrigation water management. The current capacity of existing ISS organizations could serve about 242,000 ha (600,000 ac) on a field-by-field basis in 1975. This represents a tremendous increase during the past 5 years, and represents the beginning of a new era in irrigation water management. Feedback from ISS groups also will greatly aid in improving ISS technology during the next 5 years.

SECTION VIII

EFFECTS OF IRRIGATION SCHEDULING ON SALINITY OF RETURN FLOWS

IRRIGATION WATER MANAGEMENT AND RETURN FLOW QUALITY

The average volume of irrigation water delivered annually to many irrigated farms on western USA irrigation projects, W_f, plus the average annual precipitation, P, or $(W_f + P)$ is greater than the annual volume of water used consumptively, W_{cu}. The prime justification water users and project management give for continuing this practice of $(W_f + P) >> W_{cu}$ is to maintain a salt balance in the soil. A favorable balance of the more soluble salts is necessary (except for carbonate and gypsum minerals) for sustained high crop production on irrigated lands. However, sustained crop production probably can be maintained with much less $(W_f + P)$ as compared with present practices (van Schilfgaarde, et al., 1974).

A current popular assumption is that since W_f is much greater than necessary to maintain a salt balance, the salt load of return flows could be reduced substantially with more efficient irrigation. This assumption also implies that increased long-term national economic benefits will accrue by reducing W_f to many existing projects on river systems where salinity problems now exist.

The leaching fraction (LF), or the water used for leaching, W_L, must be $\geq W_{LR}$, or the water needed to meet the "leaching requirement" (LR) to maintain a favorable salt balance in the soil. Recent lysimeter studies (Bernstein and Francois, 1973; and Bernstein, et al. 1975) suggest that the LF could be much less than previously recommended without an appreciable yield reduction. Achieving a very low LF, 0.05 to 0.1, will require sophisticated irrigation systems that assure very accurate control of the amount of water applied and very uniform water applications.

Most studies of low LF have concerned the salt and ion balance in the soil, the salt and ion concentration in the drainage water, and related plant response. Little attention to date has been directed toward practical methods of achieving a low LF, the increased costs, including the capital investment, operation and maintenance costs required, and the technical skills necessary to manage more complex systems to achieve a low LF. These requirements must be considered relative to economic benefits that may result from reducing water deliveries, or increasing irrigation management efficiency (E_{im}). There will be obvious benefits on some projects which require costly drainage facilities to remove several times more drainage water, W_D, than necessary to maintain a salt balance, and all other water that is not used consumptively. Pumping costs on some gravity irrigated projects could be reduced substantially by reducing W_f.

Return flows from irrigation projects normally are composites of water from deep percolation or drainage through the soil profile, seepage from canals, surface runoff, and direct spills of irrigation water into the drainage system which bypass the soil. Usually, the higher the proportion of steeply sloping and rolling land in a gravity irrigated project, the greater the proportion of surface runoff in the return flow. In some projects with level land and basin irrigation, little surface runoff occurs. Also, where the soils on sloping lands are sandy and have very high intake rates, there may be little surface runoff. Reducing the total water diverted into irrigation projects, W_I, which would increase the bypass flow in the river, may have little effect on the salt load in downstream waters depending on the sources of return flows from a project, the physical features, particularly the underlying strata, of the project and river system, and the relative flow rates from the project and in the river.

Another current popular assumption is that long-term national economic benefits will accrue from improving the "quality" of irrigation return flows. In its extreme case, there is little basis for attempting to reduce the salt concentration in river flows entering oceans. No one questions the fact that consumptive use or evapotranspiration concentrates the natural dissolved salts that are present when water is diverted from a river. But there are questions about the long-term national economic benefits from attempting to attain very low leaching fractions and operate farms with soil salinity near critical levels. Decreasing the quantity of water delivered to the farms, W_f, normally will reduce the quantity of return flow to the river, but the concentration of soluble salts in the drainage water may be greater. When combined with the bypass river flow, the net effect on downstream water users may not always be beneficial on some rivers since there may be little net reduction in the salt concentration, and there may be an increase in percentage of sodium and the chloride ions. The sodium hazard is normally represented by the sodium absorption ratio, SAR, ($SAR = Na/[Ca + Mg)/2]^{1/2}$, with concentrations expressed in milliequivalents per liter). Under special circumstances, decreasing return flows will result in lower direct costs and thus increase long-term national economic benefits. For example, an International Treaty with Mexico and Congressional Acts specify that return flows from the Wellton-Mohawk Project in Arizona must be desalinized to decrease the salt concentration in the lower Colorado River that flows to Mexico.

There are many facets to consider in arriving at long-term national economic benefits to be derived from alternatives for improving E_{im}. For example, where the water diversions to an irrigation project, W_I, are much greater than W_{cu}, the irrigated project and its underground aquifers may serve as a recharge area to an aquifer supplying water for other beneficial uses, or the project may serve as a temporary storage reservoir which stabilizes downstream flow. This occurs along the South Platte River in Colorado and Nebraska, and Silver Creek near Hailey, Idaho. Studies currently are underway in Idaho to evaluate the effects of converting gravity systems to sprinklers in the gravelly upper reaches of Silver Creek on the late season and total flow to downstream water users. There is no surface reservoir on the Big Wood River above Silver Creek and the aquifer is the principal means of retaining flood flows, regulating flow to the water users, and preserving a large trout fishing-based recreational industry. Under these conditions, an economic assessment of all benefits that may accrue from changing E_{im} in a recharge area of a project serving as a temporary storage and stabilizing reservoir must be considered. Some less apparent benefits have been mentioned, but there are also some long-term economic costs of erosion caused by excessive water use, soil salinization caused by poor drainage, larger pumping costs, higher initial and maintenance costs of larger distribution systems, and indirect drainage costs. Many water users also believe that if they improve E_{im} on their project or farm, the resulting decrease in W_f would be available to them for irrigating additional land in the area. This was very apparent to me based on questions asked of speakers at the National Conference on Managing Irrigated Agriculture to Improve Water Quality, Grand Junction, Colorado, May 16-18, 1972. If farm deliveries are reduced and the water savings are diverted to new land in the area, an increase in E_{im} on the original project may have detrimental effects on downstream users because it could significantly increase W_{cu}, reduce the river flow below the area, and increase the concentration of soluble salts because of more evapotranspiration. This apparent attitude of water users attending the Conference was not in harmony with those presenting papers, nor the theme of the Conference. Estimating long-term national economic benefits from different water management alternatives cannot be realistically approached in a simplistic manner because most systems are complex with many complicated interactions that have physical, biological, and social implications.

Some of the pros and cons concerning the goals of irrigation water management for salt control, particularly reducing the LF, can be found in recent articles by Christiansen (1973), and an article by van Schilfgaarde, et al. (1974), with discussions by Christiansen (1975), Olsen (1975), and Willardson (1975). Additional articles closely related to this subject are those by Rhoades, et al. (1973 and 1974).

When considering the practical ramifications of irrigation water management for salt control, the question of approaching the theoretical minimum leaching fraction may be academic for the next one or two decades for most western irrigated projects since most apparent leaching fractions now range from 0.3 to 0.6 based on recent use of water studies that have been conducted. However, large improvements in E_{im} are possible in most irrigated areas without being too concerned about the final acceptable minimum LF necessary to maintain a favorable salt balance in the soil profile over entire fields. Improving E_{im} will provide direct economic benefits from increased crop yield and quality and lower drainage costs. Also, reducing deep percolation should lower the salt load by reducing the soil mineral dissolution rate.

Basically, the minimum leaching fraction will be applicable to only that area that regularly receives the least water application, which may be < 10% of each field. The average LF for each field will be dependent on the actual average E_{im} for each field. Minimizing the salt load in the return flow will require a very efficient irrigation system to permit controlling the amount of irrigation water applied to each subarea of each field throughout the year so that, annually,

$$\frac{\Sigma (W_D)_j}{\sum_{j-1}^{m} [\sum_{i=1}^{n} (E_t)_i]_j} = \frac{\sum_{j=1}^{m} [I + P_e - \sum_{i=1}^{n} (E_t)_i]_j}{\sum_{j=1}^{m} [\sum_{i=1}^{n} (E_t)_i]_j} \simeq LF^* \qquad [17]$$

where the interval between successive irrigations is represented by the subscript j; I = the depth of irrigation water applied during the irrigation interval; P_e = the precipitation during the irrigation interval that does not run off the unit area; E_t = the daily evapotranspiration for each day, i, during the irrigation interval; W_D = the cumulative drainage during the irrigation interval; and LF* = the required annual minimum leaching fraction.

The main problem that will be encountered in attempting to approach the LF* over the entire field is the uniformity of water distribution along with nonuniform soils and nonuniform crop growth. Also, the quantity of rainfall after an irrigation must be considered as a stochastic process. In many areas, leaching caused by unexpected rainfall could make a LF < 0.1 very difficult to achieve. Probably the most difficult management problem that will be encountered in attempting to maintain a very low LF will be controlling irrigations needed to germinate small seeds, and irrigating shallow-rooted crops with gravity irrigation systems. Efficient germination irrigations can be achieved relatively easily with special sprinkler systems used only for germination purposes. Similarly, limiting the first irrigation applied to a shallow-rooted row crop when only a small amount of soil water has been depleted will be very difficult with irrigation systems that flood the entire soil surface. Under these conditions, a cropping sequence that schedules a deep-rooted crop to precede the shallow-rooted crop, and scheduling irrigations to allow the soil to be depleted before the end of the previous season, will reduce deep percolation.

ESTIMATING THE LEACHING REQUIREMENT

When planning for a favorable salt balance in a soil profile under steady-state conditions, it is commonly assumed that the salt uptake by crops is negligible, and that mineral dissolution and precipitation are 0, although with recent leaching models these assumptions are not necessary. The leaching requirement (LR) is the potential minimum leaching fraction (LF*) that will maintain the salinity near the bottom of the root zone below the maximum level for each specific crop in relation to the expected concentration of soluble salts in the applied water.

$$LR = LF^* = \frac{C_{aw}}{C_r} = \frac{C_{aw}}{\alpha C_{dw}} \qquad [18]$$

where C_{aw} is the concentration of salts in the applied water (irrigation and effective precipitation); C_r is the concentration of salts in the soil solution at the bottom of the root zone that can be tolerated by the specific crop without a significant yield reduction ($< 5\%$) when the soil water content is near field capacity, θ_{fc}, or when the rate of drainage is less than 0.1 mm/day; $\alpha = C_{dw}/C_r$, and C_{dw} is the average salt concentration in the drainage water. The ratio α is needed under some situations because the average salt concentration in the drainage water may be significantly less than the concentration in the soil as the drainage rate approaches 0. For example, immediately after a heavy irrigation of a shallow soil, the rate of drainage is very rapid and the salt concentration probably is less than C_r. Also, even within the smallest subarea, drainage may not be uniform. In addition, because of other uncertainties, the maximum value of C_r probably is not independent of environmental conditions, especially the evapotranspiration rate. Therefore, maximum C_r values for specific crops determined with steady-state lysimeters in greenhouses may need to be modified for field conditions. The acceptable maximum value of C_r for each crop also may vary with environmental conditions at different stages of crop growth. In practice, salt concentrations expressed in equation 18 are determined and reported as electrical conductivity (EC) in mmho/cm.

Since no irrigation system can apply water at 100% uniformity under ideal conditions, including some of the most sophisticated center-pivot and moving lateral sprinkler and drip systems, the average LF for a field, which will be used in designing, operating, and managing irrigated systems will be much larger than the LF* applied to that portion of each field that regularly receives the least depth of application. The average leaching fraction for the field is strongly dependent on the uniformity at which water can be applied if the entire field is to be leached with a $LF \geq LF^*$. The average LF for this condition could be estimated as follows:

$$LF = 1 - \alpha_d \, (1 - LF^*) \qquad [19]$$

where α_d = the expected distribution coefficient which is the ratio of the average depth of water applied to some agreed upon fraction of each field that receives the least amount of water, to the average applied to the entire field (Jensen, et al., 1967). The distribution coefficient as defined is not the same as that commonly used to describe the uniformity of water application by sprinkler systems, U_c. But α_d can be estimated from U_c as illustrated in the following example:

<u>Example</u>

Assume that the average depth of water applied in the 10% of a field regularly receiving the least amount of water is $(1 + LF^*)W_{cu}$; the application of water by a sprinkler system is normally distributed independent of the amount applied, and the uniformity coefficient, U_c, can be estimated with equation 21; the distribution coefficient, α_d, at 5% of the area (see Figure 61-1, Jensen, et al., 1967) represents the average depth of water applied to 10% of the area that regularly receives the least amount of water; irrigations are timed exactly so that only $LF^* W_{iw}$ drains through the soil; and W_{cu} is not affected by the soil salinity level. Under these conditions, the average LF for the field for various LF* and uniformity coefficients will be:

U_c	s[1/]	α_d	Average LF with a LF* of: 0.05	0.10	0.15
%	%				
100	0	1.00	0.05	0.10	0.15
95	6.25	.89	.15	.20	.24
90	12.50	.79	.25	.29	.33
85	18.75	.69	.34	.38	.41

1/ Estimated from equation 21 with $\bar{x}$ = 100%.

The data presented above clearly indicate that even with an irrigation system that has a uniformity coefficient of 90%, which is excellent with present equipment, the average LF for a field will be 2.2 LF* with LF* = 0.15; 2.9 LF* for LF* = 0.10; and 5 LF* for LF* = 0.05. When considering these data, the apparent fractions on western irrigated projects with salinity problems that are as high as 0.4 may not be unreasonable with present irrigation systems. However, many areas do not have salinity problems and there is no basis for large apparent leaching fractions if water could be put to other beneficial uses.

Areas within fields that receive the least water application can be predicted with gravity irrigation and some sprinkler systems. However, it is difficult to change the distribution pattern within a field with gravity or solid set sprinklers during the growing season.

In my opinion, since the apparent LF for many surface irrigated projects in the western USA is about 0.4 or greater, which may be five to ten times larger than LF*, substantial reductions can be made in the LF on many western irrigated projects without adverse salt balance effects in the soil if irrigations are scheduled (time and amounts), and water applied <u>much</u> <u>more</u> <u>accurately</u> and <u>uniformly</u> than is now being done. Improving irrigation water management efficiency will reduce the salt pickup in some projects and river systems.

ATTAINABLE IRRIGATION EFFICIENCY

The attainable irrigation efficiency must be considered in attempting to reduce the average LF. It depends on the potential water application efficiency, E_a^*, for an irrigation system and how the system is managed. E_a^* values are more predictable when the application rate is controlled primarily by the system, like with sprinkler systems, and is not influenced by soil characteristics. Even with sprinkler systems, E_a^* will be influenced by operating pressures, wear on the nozzles and heads, damaged heads, plugged nozzles, broken springs, windspeed and wind direction. Similar problems, except for wind, affect drip irrigation systems, but mechanical problems are different (no moving parts in the emitters). Clogged nozzles, both mechanically and chemically, and pressure variations probably are the principal factors affecting E_a^* for drip systems. The uniformity of water application is a major factor affecting E_a^*. For sprinkler systems, it is most commonly expressed by the Christiansen (1942) uniformity coefficient

$$U_c = 100 \left(1.0 - \frac{\Sigma|x - \bar{x}|}{N\bar{x}}\right) \quad [20]$$

where x = the amount of water applied per unit subarea; $\bar{x}$ = the mean for the entire area; and N = the number of subareas. The same uniformity coefficient also can be expressed as a function of the standard deviation, s, since most distribution patterns from operating sprinkler systems are normally distributed if U_c > 70% (Hart and Reynolds, 1965). Therefore,

$$U_c \doteq 100 \left(1 - \frac{0.8s}{\bar{x}}\right) \quad [21]$$

E_a^* can be calculated if the standard deviation of the amount applied by the overlapping laterals or from the moving laterals is known. A reasonable percentage of the area that is to receive the full irrigation must be considered to estimate E_a^* for sprinkler systems (Jensen, et al., 1967). For example, it would be uneconomical and impractical to operate systems until the last 1% of the area received the full desired amount while 99% was greatly overirrigated. No standard has been established for this purpose since the economic returns are related to the value and sensitivity of the crop to underirrigation and salinity. Also, because of changes in windspeed and direction, the seasonal uniformity coefficient tends to be greater than that for a single irrigation if the soil is not filled to the effective field capacity at each irrigation (Jensen and Erie, 1971). Also, moving laterals tend to apply water more uniformly than stationary operated laterals, since each sprinkler becomes a line source rather than a point source. However, if stationary operated sprinkler laterals are not set in identical positions at each irrigation, the areas receiving less than the average amount during one irrigation may receive an above-average amount the next irrigation. Solid set sprinklers usually are not moved during the season and the same areas tend to receive the same distribution all season. The uniformity of water application by sprinklers is not greatly influenced by the amount applied, i.e., very light or heavy irrigations have little effect on U_c

and E_a^*.

With basin irrigation, E_a^* largely depends on the accuracy to which the basins are leveled. Nonuniform intake rates throughout the basin, the stream size, and time required for spread of water throughout the basin also may significantly affect E_a^*. Basin irrigation requires the application of at least a minimum amount to cover high areas, or assure that all level furrows receive water from end to end if furrows are used in the basin. This amount may be more than the soil will hold early in the season.

Furrow irrigation on sloping fields can produce very uniform application of water if sufficiently large stream sizes are used. However, if runoff cannot be recirculated, E_a^* may not exceed 75 to 80%, and often it will be less than 75% because of surface runoff. Surface runoff normally does not directly influence the magnitude of W_D and leaching within the fields, since the runoff may either be returned to the canals, reused on the farm, or diverted to the drains. Therefore, a low E_a does not necessarily result in a high LF as is often assumed. Normally, furrow irrigated fields are uniformly graded, but fields leveled to a concave shape may improve the uniformity of water distribution and E_a^* (Powell, et al., 1972).

Graded borders can be very efficient if proper stream sizes are used for the slope, length of run, type of crop, and intake rates involved. Some surface runoff is common with borders, but usually runoff is less than with furrow systems if properly designed and managed. Where intake rates are high, the ends of low gradient borders are commonly diked; E_a^* for surface irrigation systems can be as high as for sprinkler systems.

In practice, E_a^* is seldom attained or approached as often with gravity systems as compared with sprinkler systems, because the actual efficiency, E_a, is influenced much more by management and other factors. For example, E_a for gravity systems is affected by initial and maintenance land leveling, the soil surface conditions, stream sizes, and other physical factors that affect overland or furrow flow, like crop density. U_c can easily be evaluated and calculated for drip systems similar to sprinkler systems. It can also be evaluated and calculated for gravity systems, but not as easily since the quantity of infiltration is more difficult to evaluate than the quantity being applied. A more detailed discussion of surface irrigation efficiency can be found in an article by Willardson and Bishop (1967).

ACTUAL WATER APPLICATION AND IRRIGATION EFFICIENCIES

O. W. Israelsen was one of several scientists who made some of the first detailed studies of irrigation practices. He assisted in studies of farm irrigation practices in California from 1913 to 1915, and conducted very detailed studies in Utah from 1937 to 1941. A total of 145 individual irrigations were evaluated in Utah County, and 28 irrigations were evaluated in Salt Lake County. The results of the Utah studies showed that the average water application efficiency for higher lands near the mountains was 38%, for lands of medium elevation 44%, and for low lands 34%. He found "that low irrigation efficiencies accompany abundant water supplies and that losses occur when irrigation water is applied to soils that already have plenty of moisture" (Israelsen, 1943). He also stated:

> "Every irrigation farmer knows that he cannot put a gallon of water into a quart cup, but unknowingly, many try to put 4 acre-inches of water into a soil which has capacity for only 1 acre-inch. Unfortunately, the excess 3 acre-inches flow away by deep percolation."

Willardson (1972) reported that the water application efficiency on a furrow-irrigated field of potatoes in 1959 averaged 46% for 11 irrigations with a standard deviation(s) of 20%. Tyler, et al. (1964) conducted a 5-yr study of 41 farms in southern Idaho using measured water deliveries, and estimated seasonal consumptive irrigation requirements made with the Blaney-Criddle procedure. The average seasonal irrigation efficiency for 203 farm-years was 50% with s = 9%. The U. S. Bureau of Reclamation (1971) made a detailed study of four farms in 1964 and six farms from 1965 to 1968 in the same general area and measured water deliveries, farm system losses, and surface runoff. Deep percolation was estimated, using spring and fall gravimetric soil samples, measured water applied to individual fields, and estimated consumptive use during the growing season. The mean irrigation efficiency was 42%, with s = 6%. The measured and estimated average losses expressed as percentage of the water delivered were:

Farm system losses	10.5%
Surface runoff	16.4%
Estimated deep percolation	31.8%

The USBR (1973) conducted a similar study of four gravity- and five sprinkler-irrigated farms in the Columbia Basin during 1970-72. Water was measured to each farm or area with weirs or line meters. Runoff from the gravity-irrigated areas was measured with Parshall and V-notch trapezoidal flumes. The average seasonal irrigation efficiencies for the various systems are summarized below:

System	Events	Average E_i %	s %
Furrow or rill	10	35	4
Sprinkler, side roll and squarematic	8	49	12
Center-pivot	4	58	8

A recent estimate of irrigation efficiencies for the years 1970 to 1972 in the Wellton-Mohawk Project in Arizona indicated the sandy mesa farms averaged 33% and the valley farms with mainly basin irrigation averaged 65%. The average was 56% for the entire project (Advisory Committee, 1974).

The data briefly summarized above clearly show remote prospects during the next decade of improving irrigation water management efficiency on 80% of the irrigated land that is now gravity-irrigated to such an extent that the recent theoretical minimum leaching fractions become the critical issue except on parts of fields that receive the least amount of water, and areas that have salinity problems. Drip irrigation can greatly improve efficiencies in some areas, but the total area of drip irrigation is not expected to be over 0.5% of the total irrigated area in the USA by 1980.

ROOM FOR IMPROVEMENT

One of the key issues that investigators of irrigation efficiencies have emphasized for over three decades is that the farm manager/operator is not aware of the amount of water a soil can hold, and often the total amount of water that is applied, or the distribution of applied water. This is the prime purpose of making scientific irrigation scheduling services available to as many irrigators as possible. Estimates of the response to suggested irrigation schedules obtained during the 1974 survey indicated the following expected density distribution:

Degree to which schedules are followed	Irrigators who respond to recommended irrigation dates
	%
Irrigate within ± 1 day	45
Irrigate within ± 2-3 days	33
Irrigate within ± 3-5 days	22

Nearly 80% irrigated within ± 3 days of the recommended irrigation dates. Most of the recommended irrigation dates consider the expected amount of water that is normally applied with the existing system so as to avoid very inefficient irrigations. The application of scientific irrigation scheduling technology, coupled with improved surface irrigation systems that are being developed and other irrigation practices, could result in average increases in irrigation efficiencies from the current average level of about 40% to about 50% during the next decade. At first this may not seem to be a large change, but it represents a 25% improvement in practices that have continued with little change for three decades. Conversion to sprinklers has been the main factor resulting in improved irrigation efficiency in many areas. But sprinkler irrigation requires much more energy than gravity irrigation. Significant improvements in gravity irrigation systems and practices are needed to avoid improving irrigation efficiencies by conversion to systems that have very high energy requirements.

POTENTIAL FOR SCIENTIFIC IRRIGATION SCHEDULING TO REDUCE SALINITY OF RETURN FLOWS

Reducing the average LF in each field can reduce the salinity of return flows by decreasing dissolution or weathering of soil minerals, and dissolution of salt deposits or displacing highly saline waters underlying irrigation projects. In addition, if the volume of water applied per unit area is closely controlled so that the LF on the parts of each field that receive the least amount of water approaches LF*, precipitation of carbonate and gypsum compounds in the soil would further reduce the salinity in return flows. However, as shown by the previous example, extremely uniform water applications will be needed along with very accurate control of the amount applied to a major part of each field to have a significant effect on return flow quality except where canal seepage and other easily avoidable water losses are involved. The material presented earlier indicates that scientific irrigation scheduling alone may result in direct net economic benefits to the farm manager/operator from increased crop yields and better quality. Scientific irrigation scheduling with some improvements in gravity irrigation systems probably could increase average irrigation efficiencies 10 percentage points during the next decade. However, this amount probably would have little effect on return flow quality. Similar conclusions were reached by Skogerboe, et al. (1974) in evaluating irrigation scheduling for salinity control in the Grand Valley.

Major improvements in gravity or low pressure surface irrigation systems and irrigation practices, along with changes in water delivery policies controlled by institutions and state organizations regulating water rights, will be needed to achieve sufficient increases in irrigation water management efficiencies to significantly reduce salt loads in irrigation return flows without large energy inputs. Scientific irrigation scheduling can significantly reduce the salt load in return flows with irrigation systems that enable uniform applications of known amounts of irrigation water. Potential efficiencies of new irrigation systems and potential reductions in salt loads probably could not be achieved without scientific irrigation scheduling. Scientific irrigation scheduling is economically feasible with most existing irrigation systems, but will be more effective with new and better irrigation systems. Major benefits to the farm manager/operator result from improved crop yields and quality, and general improvement of irrigated farm management.

SECTION IX

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SECTION X

APPENDIX

Table A1. COMMERCIAL IRRIGATION SCHEDULING SERVICES PROVIDED FOR A FEE IN 1974 IN WESTERN USA

Serv. Grp. No.	Exp. yrs.	Area Served	Main Services Provided: Irrig. sched.	Syst. oper.	Plt. nutr.	Pest mgmt.	Other	Summer Crops: Fields	Summer Crops: Area (ha)	Winter Crops: Fields	Winter Crops: Area (ha)
1	4	C. Ariz.	x	--	x	--	a	800	10,490	300	4,380
2	1	C. Calif.	x	x	x	--	--	60	2,400	100	4,050
3	2	Ida.	x	x	x	x	--	35	5,670	---	---
4	4	Ida.,Colo. and Wash.	x	x	x	x	--	1,000	28,330	---	---
5	2	Ida.	x	--	x	x	--	44	2,100	25	400
6	5	Ida.	x	x	x	x	b,c	43	2,020	---	---
7	6	Ida., Nev.	x	x	x	x	b,c	75	3,240	---	---
8	5	Neb., Kan., and Colo.	x	--	x	x	a,b	2,000	32,480	---	---
9	19	Wash.	x	--	x	--	--	180	7,280	20	800
10	9	Wash	x	x	x	x	--	240	8,090	---	---
Total or average use			100%	60%	100%	56%	--	4,447	102,100	445	9,630

a System design

b Cropping practices, tillage operations, etc.

c Farm or ranch management for absentee owners

Table A2. IRRIGATION SCHEDULING SERVICES PROVIDED BY STATE (S), FEDERAL AGENCY (U), COMPANY (C) OR PROJECT (P) IN 1974 IN WESTERN USA

Serv. Grp. No.	Exp. yrs.	Oper. or Dev.	Area Served	Main Services Provided: Irrig. sched.	Syst. oper.	Plt. nutr.	Pest mgmt.	Other	Summer Crops: Fields	Summer Crops: Area (ha)	Winter Crops: Fields	Winter Crops: Area (ha)
S-1	5	D	N.Dak.	x	--	x	x	--	21	660	---	---
S-2	5	D	Wyo.	x	--	--	--		50	1,010	---	---
U-1	1	D	Ariz.	x	--	--	--	--	82	1,210	14	200
U-2	1	D	Ariz.	x	--	--	--		57	1,140	69	1,380
U-3	2	D	Calif.	x	--	--	--	--	108	1,780	102	1,710
U-4	3	D	Calif.	x	x	--	--	--	133	8,170	26	2,010
U-5	2	D	Colo.	x	--	--	--	--	1	50	---	---
U-6	3	D	Colo.	x	--	--	--	--	502	2,800	---	---
U-7	2	D	Ida.	x	x	--	--	--	108[a]	1,010	---	---
U-8	5	D	Ida.	x	--	--	--	b	30	320	10	80
U-9	4	D	Kans.	x	--	--	--	--	306	3,600	---	---
U-10	1	D	Nebr.	x	--	--	--	--	6	120	---	---
U-11	1	D	N.Mex.	x[c]	--	--	--	--	---	---	---	---
U-12	2	D	N.Mex.	x	--	--	--	--	102	860	---	---
U-13	3	D	Tex.	x	--	--	--	--	135	1,400	---	---
U-14	2	D	Utah	x	--	--	--	--	313	1,850	5	20
U-15	1	D	Wash.	x	--	--	--	--	20	80	---	---
U-16	4	Wyo.		x	--	--	--	--	525	6,070	---	---
Sub. Tot.									2,499	32,130	226	5,400
C-1	1	D	Ida.	x	--	x	x	--	36	400	---	---
C-2	1	D	Ida.	x	--	x	x	--	50	1,620	---	---
C-3	1	D	Ida.	x	--	x	x	d	26	230	---	---
P-1	10	0	Ariz.	x	x	x	--	--	854	19,260	260	5,580
Total or % involved				100%	14%	23%	18%	--	3,465	53,640	486	10,980

a Periodic visits and weekly farm guides
b System improvement
c Computer services to State University
d Regular contracting services

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(Please read Instructions on the reverse before completing)

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16. ABSTRACT

A comprehensive review is presented of irrigation water management principles, factors to be considered in improving irrigation water management, leaching requirements, climatological approaches to irrigation scheduling, scope of irrigation scheduling services in 1974, basic concepts of scheduling services, and probable effects of scientific irrigation scheduling on salinity of return flows. A definition of irrigation water management efficiency is presented to evaluate the annual volume of irrigation water used relative to the optimum amount needed for maximum annual crop production or income. The term considers the minimum, but essential water needed for both consumptive and nonconsumptive uses. The lack of significant changes in irrigation efficiency during the past several decades is discussed and attributed to problems associated with the management of a complex soil-crop-environment system, a lack of economic incentives to make improvements, and ineffective traditional approaches to improve irrigation scheduling. New proposed minimal leaching practices are discussed. The author concludes that substantial improvements in irrigation efficiencies can be made before the proposed minimal LF are reached on most western irrigated projects.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
*Irrigation Irrigated land Leaching Salinity Management *Scheduling	*Irrigation efficiency *Irrigation scheduling Leaching fraction Return flow	2C
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