I R R I G A T I O N C O N F E R E N C E

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IRRIGATION MANAGEMENT FOR THE NEXT DECADE.

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SUMMARY

Irrigation water management is becoming more important as irrigation competes for limited water supplies and energy, and as lands throughout the world degrade and decline in productivity because of poor water management. This paper discusses the state-of-the-art of irrigation water management and its effects on water and energy conservation, current trends and new developments in on-farm irrigation systems, recent developments in water use-crop production technology, new irrigation scheduling technology, and lists expected changes in technology.

Effective irrigation water management is important for the success of individual farm units and is vital to the success and productivity of irrigation projects. Efficient and effective water management technology is a challenge. It must be developed concurrently with project works and must be upgraded continually.

Irrigation efficiency with older unimproved surface systems is usually much less than those attainable. The difference between actual and attainable efficiency with newer sprinkler systems is usually less. Surface irrigation systems can be modernized and operated just as effi-

cleanly as sprinkler systems and with less energy.

The area of irrigated land in the United States increased 17% during the past 5 years. Most of this increase occurred in the semiarid central and southern Great Plains and in the subhumid and humid southern and southeastern USA. Groundwater has been the principal source of water for these newly irrigated lands.

Center pivot sprinkler systems are now used on about 40% of the sprinkler irrigated USA lands. Most of these systems are used in semiarid central and southern Great Plains. Side roll and tow line laterals are next in popularity, and are replacing hand move laterals. Traveller and gun type systems are used mainly in subhumid and humid areas.

Recent water use-crop production studies showed that the yield of many crops is linearly related to seasonal evapotranspiration (ET) if limited water is distributed proportionally to ET rates. Controlled water stress on some crops can lower ET with little reduction in yield or quality, thus increasing water use efficiency.

New irrigation scheduling technology has stimulated commercial irrigation management services. In 1977, commercial firms provided field-by-field scheduling service on over 10,000 fields and 231,000 ha (571,000 ac.) of summer and winter crops. The U. S. Bureau of Reclamation (USBR) provided similar services to 63,000 ha (156,900 ac.), and the Salt River Project in Arizona provided services to 5,800 ha (14,400 ac.). General scheduling guides also are provided by the USBR, and ET rates for major crops are being printed twice weekly in many newspapers. Commercial and agency services for individual fields have grown from less than 40,000 ha in 1971 to an anticipated 300,000 ha for summer crops in 1978. Major changes in scheduling services include the use of neutron probes for scheduling and monitoring and some companies now offer aerial color and color infrared photography to supplement ground observations.

The role of consultants in providing management services is discussed. Consultants specializing in providing management services, including system improvements, for irrigated farms are becoming more common in modern irrigation projects.

INTRODUCTION

Development of irrigated land expanded rapidly during the past two decades, but not without problems and emerging challenges. Increases in irrigated lands have paralleled increases in world population. Shmueli (1973) estimated that the irrigated land increased from less than 10 million hectares in 1800 to about 40 million in 1900, 160 million in 1950, and 200 million in 1969. The Food and Agricultural Organization (FAO, 1977) estimated that in 1975 the total world irrigated area was 223 million hectares, and is expected to increase to about 273 million by 1990.

Development of modern automated sprinkler systems in developed countries has stimulated rapid expansion of irrigated lands and conversion of surface systems to sprinklers. Some lands previously considered unsuitable for irrigation because of soil or topography and high pumping lifts are now irrigated. Rapid expansion of irrigation in the USA is accelerating groundwater mining in some areas, increasing energy consumption, and increasing public concern for alternative uses of water resources. For example, in the Pacific Northwest, irrigation and hydroelectric power uses are now in conflict because further development of land for irrigation decreases the capacity to generate hydroelectric power. Increased concerns about environmental quality, particularly the quality of return flow from irrigation tracts, is placing new constraints on irrigated agriculture.

In developing countries, recent adverse publicity concerning large irrigation schemes has increased, while the main purpose of the project, increased crop production and living standards, are deemphasized by special interest groups (Worthington, 1977). Of major concern is the incidence of diseases transmitted by mosquitoes, simulium fly, tsetse fly, snails, and fresh water crustaceans (White, 1977). Public health precautions must assure potable drinking water supplies, adequate sanitation, and washing facilities in areas where population density increases with irrigation development.

Rapid expansion of irrigated agriculture and increasing size of farming units in developed countries; increasing farm costs, particularly for energy; and current low farm prices for farm products are creating

new water management challenges. Farm managers need flexibility in water deliveries to maximize net return for their investment in facilities, labor, and other agricultural inputs. Efficient water storage and distribution networks that minimize the constraints and provide this flexibility are needed. Efficient water management requires irrigation systems to uniformly apply the desired amount of water at the proper time.

On-farm water management is a daily or weekly decision-making process. Since the farm manager stands to gain or lose by his management decisions, it is very important that this decision-making process be retained as his option. It is highly doubtful that an irrigation association, or agency, can make better management decisions than the individual farm manager, provided of course, that he has access to data needed to make good decisions to maximize his management objectives.

The development of computer technology during the past two decades has provided the breakthrough needed to enable farm managers to apply the latest irrigation science and technology to irrigation water management. Aerial color and color infrared photography is another modern technological tool that is now being applied and made available to USA farm managers. This technology can enhance irrigation water management decisions and improve irrigation practices. It may enable detecting problems of plant nutrition, disease, and poor distribution of fertilizers and the effects of other cultural practices at early stages that would otherwise not be known except in terms of unexplainable low yields at the end of the growing season.

Various aspects of water management will be discussed in this paper. The primary emphasis will be on farm systems because success of the total irrigation scheme depends on the success of the individual farming units. Primary emphasis will be placed on techniques by which the farm manager can improve his daily decisions to achieve his management objectives. The primary management objective in most developed countries is to maximize net returns from the input of various soil and water resources, fertilizers, pesticides, labor, and related cultural practices.

Recent trends of current popular on-farm irrigation systems will be summarized. Emerging new technology in surface irrigation that will enable efficient irrigation with low labor and energy requirements along

with new technologies in sprinkler irrigation will be discussed.

Recent experimental studies indicated that we can control plant water stress during the growing season to optimize water use efficiency. This is becoming more important with increased water costs, due to high pumping lifts or limited water supplies.

Recent developments in irrigation technology that are enabling the application of irrigation science and remote sensing to individual fields will be described. Also, the current status of irrigation managment and related private consulting services in the USA will be presented.

IRRIGATION WATER MANAGEMENT

Water is essential for plant growth. Seeds need water to germinate and seedlings need water to emerge. Water provides the transport mechanism for plant nutrients and the products of photosynthesis. Irrigation is the application of water to the soil to supply water essential for plant growth that is not provided by natural precipitation. Yield responses to water applications occur only where soil water and precipitation are not adequate to prevent plant water stress. When enough water is provided to eliminate plant water stress, there is normally no benefit from applying greater amounts. Excessive water applications, may produce water logging, reduced crop production, and increased salt load in the return flow water. Irrigating a new land area with imported water causes a large change in the hydrology of the area. Limited natural subsurface drainage often must be increased just to handle unavoidable seepage and the minimum leaching requirement.

When irrigation is introduced in an area, agricultural production may be increased substantially. Continued production from irrigated agriculture is often much below that obtained by an optimum combination of irrigation and drainage, appropriate soil reclamation and management practices, and selection of crops best suited to local conditions (Gulhati and Smith, 1967). Gulhati (1967) also stated that successful irrigation projects involve much more than the "spectacular engineering feats involved in conserving natural waters and making them usable for irrigation, conveying these waters over long distances, and distributing them equitably among the farmers."

Traditionally, when water is first brought into a nonirrigated area and supplies are plentiful, overirrigation is the first and most common error made by farmers (Buffum, 1892). Negative effects of overirrigation caused by inefficient systems and poor management have developed on projects throughout the world. Houston (1977) indicated that degradation of land by water logging and salinity is a common by-product of irrigation. More than 70% of the 30 million hectares of irrigated land in Egypt, Iran, Iraq, and Pakistan are moderately to seriously affected. India has about 12 million hectares affected. Salty areas are found in northern and central Africa, central valleys and plains of Chile, Peru, Argentina, Venezuela, and Haiti, and more recently in the Far East in traditional rice areas.

After decades of irrigation development and similar experiences in many areas, problems like those mentioned by Houston go unsolved, even though in most cases, "we do know what to do about it from the scientific standpoint." These experiences clearly indicated that one of the greatest needs in improving irrigation technology is to improve irrigation water management. Levine (1977) stated that systems in developing countries are often inefficient because the importance of the management component and social constraints has been or is underestimated. He also cautioned that designs based on preconceived norms of efficiency often fail because the role of water as a factor substitute for other inputs, like labor, capital, and managerial skills, is not recognized. Likewise, public objectives for system performance are usually not congruent with farmer objectives, or even with irrigation bureaucracy.

History has clearly shown that good irrigation water management will not occur if left to chance. Without a dedicated water management program, a new scheme will encounter many of the same problems that have been encountered by other irrigation schemes throughout the world. Irrigation water management technology must be developed and implemented concurrently with the development of water storage and distribution works, and steps must be taken to assure continued application. Good irrigation management practices usually become more important in time as a project approaches a new hydrologic balance as large quantities of water are imported each year.

The success of an irrigation scheme depends first of all on the success of the individual farm units. The farm manager must be given the freedom to exercise decision-making to maximize his management objectives without creating adverse effects on his neighbors or downstream projects. The most common management objective is to maximize net profit by optimizing the inputs of all resources. When water supplies are scarce or very expensive, maximum net profit often coincides with the management objective of maximizing water use efficiency, which is the production of the marketable product per unit of water used in ET, or per unit of irrigation water applied (see Eq. 11). When land resources are scarce and water supplies are ample, the management objective may be maximum yield per unit area, although this may not be the most economical alternative.

With plentiful water supplies and low and often fixed water delivery costs, farmers try to eliminate water as a production variable. Accelerating energy costs and limited energy supplies may limit water applications. The management objective may still be to maximize net returns, but more emphasis will now be given to minimizing energy costs. Increasing energy costs are expected to cause substantial improvements in irrigation efficiencies where pumping is involved.

In the USA, problems of erosion on irrigated land and sediment in irrigation return flow have become critical issues in some areas of the Pacific Northwest and western Intermountain areas where land slopes are fairly steep. A major water quality problem that is receiving renewed attention is salt loading. For example, in the Grand Valley of western Colorado, groundwater from seepage and deep percolation dissolves and carries about 635,000 tonnes of salt per year to the Colorado River. This is about 22 tonnes for each irrigated hectare. This situation is unique because groundwater flow passes through marine shale that contains crystalline salts before returning to the river system (Duke et al., 1976).

Improving irrigation water management with most existing systems that do not have automatic controls so that small amounts of water are applied as needed requires a better understanding of factors controlling water stress and effects of controlled water stress on crop production. Planned optimum timing and amounts of water application should be developed before planting and then modified as needed during the growing season.

These decisions are made daily or weekly.

Long term management decisions affecting water use efficiency may involve alternating deep and shallow-rooted crops to maximize the recovery of water applied to deep soils. This is especially important when water is pumped because most irrigation pumping consumes energy that normally cannot be recovered. Excess water pumped from deep groundwater and applied to shallow rooted crops may not be lost, but the energy used in pumping this water is lost unless a deep rooted crop can be grown the next year to recover some of this water.

New challenges are facing irrigated agriculture. Efficient and effective water management offers a great challenge to farm managers. Improved irrigation water management is needed to maintain productivity of some irrigated areas and to increase productivity of many other projects.

IRRIGATION EFFICIENCY AND ITS EFFECT ON WATER AND ENERGY CONSERVATION

Irrigation Efficiency Terms

The basic concepts of irrigation efficiency have been described by Israelsen (1932, 1950) and used by irrigation specialists for many decades. However, the concept of irrigation efficiency is not well understood by many policy makers and nonagriculturalists. Proper use of irrigation efficiency terminology is essential in discussing irrigation water management. Therefore, several of the more important terms are defined and reviewed in this section.

Irrigation efficiency was defined by Israelsen (1950) as the ratio of water consumed by the crops of the agricultural farm or project to the water diverted from a river or natural source into the farm or project canals and laterals.

$$E_i = \frac{V_c}{V_w} \qquad [1]$$

where V_c is the volume of irrigation water consumed by the crops during their growth periods and V_w is the water diverted from a river or other natural source into the project canals or to farms during the same time period.

To further illustrate the full significance of this term and the

implications that changes in irrigation water management can have on the use of water resources, we can consider that the volume of water withdrawn from the stream or other natural source like groundwater is used consumptively (evaporated) or nonconsumptively, that is $V_w = V_c + V_{nc}$. With this notation, and assuming that consumptive waste is negligible, we can also define irrigation efficiency as

$$E_i = \frac{V_c}{V_w} = 1 - \frac{V_{nc}}{V_w} \qquad [2]$$

The net depletion of water within a river basin or groundwater system for irrigation, V_{dep}, is

$$V_{dep} = V_c + (1 - E_r)V_{nc} \qquad [3]$$

where E_r is the fraction of V_{nc} that is or can be removed (Jensen, 1977b). The net or effective irrigation efficiency E_e is

$$E_e = \frac{V_c}{V_w} + E_r \frac{V_{nc}}{V_w} \qquad [4]$$

which also can be expressed as

$$E_e = E_i + E_r(1 - E_i) \qquad [5]$$

These variations in efficiency terms are presented because the recovery of water that is diverted for irrigation and not consumed, $E_r(1 - E_i)$, is often ignored by the general public and sometimes by policy makers concerned with low farm or project efficiencies. The magnitude of this term can be ignored when E_r is very small or negligible, but this is often not the case in mountain valleys and in many river basins. For example, Sylvester and Seabloom (1963) showed that almost the entire Yakima River in Washington flow late in the season consisted of return flow.

Israelsen (1950) also defined water application efficiency as

$$E_a = \frac{V_s}{V_f} \qquad [6]$$

where V_s = the volume of water stored in the root zone of soil on a farm and V_f = the irrigation water delivered to the farm. The same definition can be applied to individual fields.

More recently, Bos and Nugteren (1974) presented an excellent summary

of a cooperative irrigation survey conducted early in the 1970's by the International Commission on Irrigation and Drainage (ICID), the University of Agriculture, and the International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. The water quantities defined were:

Water requirement (crop), $W - P_e = V_n$ = rainfall deficit

Field application, V_a

Farm supply, V_f

Project supply, V_t

The efficiency terms defined were:

Water conveyance efficiency = $e_c = \frac{V_f}{V_t}$

Farm ditch efficiency = $e_b = \frac{V_a}{V_f}$

Field application efficiency = $e_a = \frac{V_n}{V_a}$

Farm efficiency = $\frac{V_n}{V_f} = e_a e_b$

A much more detailed discussion of these terms and standards for calculating efficiencies was recently presented by the ICID Committee on Assembling Irrigation Efficiency Data (ICID) in 1978.

Similar discussions of efficiency terms can be found in other recent articles by Jensen et al. (1967), Jensen (1974), Kruse and Heermann (1977), and Shmueli (1973).

Observed Efficiency

The average calculated efficiency values reported by Bos and Nugteren (1974) for Group III projects (includes Australia and the USA), based on completed questionnaires for 32 irrigated areas, are presented in Table 1. The reported values of field application efficiency ranged from 40 to 75% and averaged 60%. Several items were denoted specifically:

- o sprinklers were more efficient for applications less than 60 mm
- o no correlation existed between farm size and farm application efficiency
- o highest field application efficiencies were obtained with flows of 30 to 50 l/s per field

Other observed field water application efficiencies (E_a) and farm

efficiencies (E_f) are presented in Table 1 along with estimated attainable efficiencies for various field systems (E_a^*), and for farms using these systems (E_f^*). Evaluations made in the 1960's showed little improvement in E_a as compared with studies made three decades earlier by Israelsen et al. (1944). Israelsen et al. (1944) made meticulous soil moisture measurements before and after irrigations using gravimetric techniques. The results of 145 tests on 11 Utah County farms over 3-year period ranged from 24 to 51%, with an average of 40%. Efficiencies for 28 tests on six Salt Lake County farms ranged from 18 to 58%, with an average of 35%. The greatest single factor contributing to low application efficiencies was excessive water applied during an irrigation.

The ability to uniformly distribute water over a field and to control the amount applied is a key factor in achieving efficient irrigation. Without this control, very low efficiencies are inevitable. This has been clearly shown by Clyma and Ali (1977) in Pakistan, even though, on the average, water supplies are inadequate for full cropping throughout the year. Very small basins are used in Pakistan because the farmer generally is not able to level his land and there are no surface drains. The farmer must apply water to cover the high spot in each basin at each irrigation to avoid salt problems. Most people have assumed this to amount to 57 to 100 mm, but Clyma and Ali (1977) found in 700 measurements that the amount applied varied from 25 to 330 mm. Over one-third of the basins had elevation differences greater than 12 cm and one-third had from 6 to 12 cm differences, which indicates why many irrigations are excessive.

Characteristics of Irrigation Systems that Influence Efficiencies

Values of E_a and E_i on individual fields or farms are near the attainable values when the amount of water applied is controlled and limited to the amount the soil can hold. For example, with a sprinkler system, the entire system is enclosed and the amount of water applied is not influenced by the soil characteristics or the rate of flow, like it is with borders or furrows.

Furrow irrigation on sloping fields can produce very uniform applications of water if sufficiently large streams are used. However, if the runoff cannot be recirculated the attainable efficiency may not exceed 75% and often it will be no more than 65%.

TABLE 1. Recent evaluation of field water application and farm irrigation efficiencies relative to estimated attainable values using good equipment and management.

Irrigation method	Field Efficiency: Attainable E_a^*	Field Efficiency: Observed (E_a) Range	Field Efficiency: Observed (E_a) Average	Farm Efficiency: Attainable E_f^*	Farm Efficiency: Observed (E_f) Range	Farm Efficiency: Observed (E_f) Average	Comments	Source
	percent			percent				
Surface								
Furrows and rills	70	--	--	65	--	--	Survey results, ICID	(1)
	70	--	--	65	31-55	42	5 Idaho farms, 5-yr. period	(12)
	70	--	--	65	29-41	35	5 Columbia Basin farms, 3-yr.	(13)
	70	57-73	65	65	--	--	Nebraska, experimental field	(6)
	70	24-77	46		--	--	Potatoes; Utah 1959	(14)
(with auto. cutback)	85	--	76	80	--	--	Experimental field	(8)
(with runoff reuse)	90	84-97	92	85	--	--	Nebraska, experimental field	(6)
(multiset)	80	--	--	75	--	--	Experimental field	(11,15)
(multiset and reuse)	90	--	--	85	--	--	Experimental field	(15)
(multiset and auto. reuse)	95	--	95	90	--	--	Experimental field	(15)
Graded borders	80	--	--	75	--	--	Survey results, ICID	(1)
Low gradient and level borders	90	56-100	83	85	--	--	Experimental borders	(9)
Basins	75	--	59	70	--	--	Survey results, ICID	(1)
Basins (small)	75	25-40	30	65	--	--	Canal + public wells (Pakistan)	(3)
		0-100	40	65	--	--	Canal + private wells (Pakistan)	(3)
		40-100	60	70	--	--	Canal water only (Pakistan)	(3)
Basins (level)	85	85-100	--	80	--	--		(5)
Basins (laser beam leveled)	90	--	--	85	--	--		(4)
Sprinkler								
Standard set and side roll	80	--	68	75	--	--	Survey results	(1)
	80	--	--	75	33-62	--	Columbia basin, 2 farms	(13)
	80	61-65	--	75	--	--	Experimental fields	(10)

(continued)

TABLE 1 (continued)

Center pivot	90	--	--	85	48-60	53	Columbia Basin	(13)
	90	--	--	90	--	--	Eastern Colorado	(7)
Trickle								
Row crops	95	--					Equivalent to best furrow systems	(2)

1. Bos and Nugteren (1974, Group III areas)
2. Bucks et al. (1974)
3. Clyma and Ali (1977)
4. Dedrick et al. (1978)
5. Erie (1968)
6. Fischbach and Somerhalder (1971)
7. Heerman et al. (1976)
8. Humpherys (1978)
9. Jensen and Howe (1965)
10. Pair (1963)
11. Rasmussen et al. (1973)
12. USBR (1971)
13. USBR (1973)
14. Willardson (1972)
15. Worstell (1976)

Graded borders can be very efficient if balanced 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 if border systems are properly managed, runoff usually is less than with furrow systems. Level or low gradient borders with diked ends can result in very high efficiencies.

With basin irrigation, the attainable water application efficiency largely depends on the levelness of the basins. Actually efficiencies also depend on the amount of water depletion before an irrigation. If shallow rooted crops are grown, only a small amount of soil water may be depleted before another irrigation is needed, but at each irrigation usually sufficient water must be applied to cover the high areas. This practice often causes extremely low water application efficiencies.

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 and irrigation scheduling. E_a^* may be limited by design constraints and water delivery policies, but uniformity of water application and evaporation and spray drift are the major factors affecting E_a^* (Jensen, 1975).

Moving sprinkler laterals tend to apply water more uniformly than stationary-operated laterals, since each sprinkler essentially becomes a line source rather than a point source. The uniformity of water application with stationary-operated laterals can be improved if they are placed in different positions at alternate irrigations. Solid set sprinklers usually are not moved during the entire growing season and the distribution tends to be the same all season. The uniformity of water application by sprinklers is not greatly influenced by the amount applied, whereas with some of the surface irrigation systems it is difficult to achieve uniform application if one attempts to apply a small or a large amount.

Center pivot systems can be fully automated, the amount of water applied per revolution can easily be set, and they can apply water very uniformly. Also, they can be used on fairly rough topography and sandy soils, and they can be used to apply fertilizers and herbicides. Most current systems, however, require more energy to operate than standard

sprinkler systems.

Factors affecting E_a for trickle systems are similar to those for sprinkler systems, except for wind, but mechanical problems are different. These consist of clogged nozzles, by mechanical, biological, and chemical processes, and pressure variations. Both trickle and sprinkler systems which control the rate of application tend to result in higher actual efficiencies than the other systems because they are less subject to mismanagement.

Irrigation Water Management and Efficiency

The relative magnitude of present water application and irrigation efficiencies as compared with the attainable efficiencies for a given irrigation method can be considered as an index of the level of irrigation water management, (I_{mo})

$$I_{mo} = \frac{E_a}{(E_a^*)_o} = \frac{E_i}{(E_i^*)_o} \qquad [7]$$

the management index when considering a potential change of water distribution and irrigation methods is

$$I_m = \frac{E_i}{(E_i^*)_n} \qquad [8]$$

where $(E_i^*)_o$ is the attainable efficiency using the present distribution and application method, and $(E_i^*)_n$ is the attainable efficiency with a new or modified system. Low values of I_{mo} and I_m may be acceptable where water supplies are abundant, crop yields are acceptable, irrigation energy requirements are low or negligible, and natural drainage is ample, so that water-logging and salinity problems have stabilized at a minimum level; and a high proportion of the water not used consumptively (V_{nc}) is being recovered for other beneficial uses without high pumping lifts. When one or more of these stipulations is not achieved and substantial water and crop production losses or indirect costs are encountered, then the management index must be improved. However, the economic analyses required often can become very complex.

Irrigation Efficiency, and Energy Requirements and Costs

Irrigation efficiency significantly affects the energy requirements for irrigation when water is pumped from a river or groundwater supplies,

or applied under pressure. Any improvement in irrigation efficiency will reduce the net energy required for most irrigation projects and farms because there usually is not significant recovery of this energy (Jensen, 1977b). The energy required per unit area, Q_e, is

$$Q_e = (Q_q + Q_p) - Q_r \quad [9]$$

where Q_w = the energy required to withdraw water from a river or groundwater aquifer, Q_p = the energy required to apply water under pressure, and Q_r = the energy that can be recovered within the distribution network or by running the surface return flow through hydroelectric plants before returning it to the river if a significant fall is involved. If $Q_r = 0$,

$$Q_e = (Q_w + Q_p) = 0.0272 \frac{V_c \cdot H_D}{E_i E_p} \quad [10]$$

where $(Q_w + Q_p)$ is the total pumping energy required per hectare to withdraw and provide operating pressure in kWh/ha; V_c is the net depth of irrigation water used consumptively in mm; H_D is the total dynamic head (TDH) consisting of the sum of the pumping lift, pressure head for sprinkler systems or pressure delivery, and friction losses; and E_i and E_p are the irrigation and pumping efficiencies, respectively. If both E_i and E_p are between 0.70 and 0.75, the energy required to apply 10 m^3 (1 mm depth) of water per meter of TDH would be about 0.05 kWh/ha.

Two examples illustrate the effects of different irrigation methods on energy requirements. The first situation exists in southern Idaho where very high lifts (about 180 m) are required in pumping from the Snake River. If the values of the variables in Eq. 10 are:

V_c = 700 mm (net annual irrigation water requirement)

H_D = 180 m lift + 50 m for sprinkler systems or 180 m + 10 m for a pressure distribution to surface systems

E_p = 0.70

E_i = 0.75 for sprinkler systems and 0.60 for surface systems,

then the annual energy requirements will be:

	Sprinkler systems	Surface systems
Annual energy (kWh/ha)	8,340	10,430

In this particular case, irrigation water could alternatively be diverted from the river by gravity at some distance upstream and delivered to the area by gravity although enlargement of a major canal and at least one inverted siphon would be needed. The annual energy requirement for the

two irrigation methods used for gravity diversion and delivery would be

	Sprinkler system	Surface systems
kWh/ha	1,810	450

Unfortunately, the evapotranspiration of 7,000 m^3/ha (ET = 700 mm) from each new hectare of land irrigated reduces the annual potential for generating hydroelectric power in downstream plants by about 10,200 kWh. The cost of energy should take into account both the present cost of hydroelectric energy for pumping and the replacement cost of the loss in potential hydroelectric power generation which is considerably higher (about $0.03 vs. 0.007/kWh).

The second example developed by Eisenhauer and Fischbach (1977), illustrates the fixed and operating costs to be considered with and without an energy escalation factor. The cost of energy in the USA has been escalating 9 to 11% per year. The example summarized in Table 2 illustrates the relative costs of improved surface irrigation systems and a center pivot system, each capable of achieving a 75% or better irrigation efficiency. The fixed costs include the depreciation of the well, pumps, and motors. The operating costs are based on a 30-m pumping lift from groundwater and a fuel oil energy source, except for the reuse system which uses electricity.

This example clearly indicates several important characteristics. First, improving the irrigation system generally will increase the total annual fixed and operating costs. Second, the example also clearly indicates that energy costs are rapidly becoming a greater component of annual irrigation costs. As irrigation costs increase, farm managers should place greater emphasis on maximizing net returns per hectare and less emphasis on maximizing yield. The relative effects will be amplified with greater pumping lifts.

Improving the Irrigation Water Management Index

After completing a study of five irrigation farms in the southern Idaho area from 1964 through 1968, the U. S. Bureau of Reclamation (1971) made a very detailed analysis of attainable efficiencies with additional labor, and with improvements in management and existing irrigation systems. Most fields were irrigated from unlined ditches, or from concrete lined ditches and using siphon tubes. Some fields were still being irri-

TABLE 2. Typical initial and annual costs for several common irrigation systems in Nebraska and relative labor and power costs. Assumed pumping lift = 30 m. (Source: Eisenhauer and Fischbach, 1977.)

	Gated pipe		
	With reuse system	Automated with reuse system	Center pivot
Area, ha	61	61	54
Initial cost, $/ha	512	853	887
E_i, percent	75	85	85
Annual cost, $/ha			
Fixed costs	66.70	108.70	118.10
Operating costs:			
Without escalation factor	36.00	29.10	49.00
With energy escalation factor	51.70	43.30	76.70
Total annual costs, $/ha			
Without escalation factor	102.00	137.80	167.10
With energy escalation factor	118.40	152.00	194.80
Labor and power costs, percent of total annual costs			
Labor	9.9	3.6	3.0
Power; Without escalation factor	18.6	11.9	20.2
With energy escalation factor	29.3	19.6	31.5

gated using cuts in a head ditch. The average results for the five farms are summarized in Table 3. The entire 5484 hectare project is supplied with water by a set of pumps on the Snake River. The 2070 kWh/ha annual energy requirement included losses in the canals and laterals. The USBR estimated that by more carefully examining soil moisture before irrigating, using cleaner ditches, and using furrow slickers to make smooth and uniform furrows, the farm efficiency could have been increased to 51.5% (Level 1). With an increase in labor, the farm efficiency could be increased to 58.2%. Providing concrete lined head ditches, land planing, reshaping fields, and irrigation scheduling services could increase the farm efficiency to 64.2%. The energy requirement for Levels 1, 2, and 3 would be 1730, 1570, and 1460 kWh/ha, respectively. These changes would have resulted in a change in irrigation management index from 64% with the present system to 79, 90, and 99% for Levels 1, 2, and 3, respectively. I estimated that if a system to recover surface runoff were used in addition to Level 3, assuming that 80% of the surface runoff be returned for reuse, the farm efficiency could be increased to 73.6%, and the annual energy requirement reduced to 1370 kWh/ha. Similarly, if each farm were converted to a sprinkler system and achieved a farm efficiency of 75%, the quantity of water pumped from the river would be reduced, but the energy requirement would be increased to 2470 kWh/ha.

In this particular project, part of the surface return flow is now being relifted to the canal system. There are no drainage problems, and sediment in return flow could be controlled if each farm or group of farms installed return flow systems. Thus, there would be little justification to convert from surface irrigation with reuse systems to a sprinkler system which would nearly double the energy requirement, unless there were other benefits to be derived by farm managers. Drainage wells now used for disposal of surface runoff, for example, may be prohibited in the future.

Currently many surface irrigation systems are being converted to sprinkler systems largely because of reduced labor requirements. Side roll lateral sprinkler systems, which can be used on most short crops, are popular in southern Idaho. The side roll laterals are either moved with a central power source using a gasoline engine, or an end-drive system powered by an electric motor and generator system mounted on a tractor.

TABLE 3 (continued)

Level 3 - Level 2, plus concrete lined head ditches, land planing, reshaped fields, and irrigation scheduling services

2/ Estimates for Level 3 by the USBR, plus an assumed 80% recovery of surface runoff for reuse. Also, water delivery assumed reduced by the same amount.

3/ Approximate values if each farmer converted his surface system to a side roll sprinkler system, and assuming an irrigation efficiency of 75%, of which 10% would be deep percolation, 10% evaporation loss, and 5% miscellaneous losses.

4/ Based on actual pumping volumes for 1966-68 for the entire 5485-ha project, a 51 m total dynamic pumping head (TDH), and an 80% pumping plant efficiency. Total water delivered to farms = 994 mm, total pumped = 1195 mm.

5/ Assuming a return flow TDH of 15 m, a sprinkler TDH of 55 m, and farm pumping plant efficiencies of 70%.

TABLE 3. Estimated losses and attainable efficiencies for the five-farm study area in southern Idaho (Source: USBR, 1971), and estimated effects of system improvements on energy requirements.

	Present system 1964-68	Improved management, additional labor and improved system[1/]			Level 3 plus return flow system[2/]	Estimate for sprinkler[3/]
		Level 1	Level 2	Level 3		
Average losses (percent)						
Evaporation	--	--	--	--	--	10
Farm system	10.5	7.7	7.1	6.1	7.0	3
Surface runoff	16.4	23.7	19.0	16.0	3.7	2
Deep percolation	31.8	17.1	15.7	13.7	15.7	10
T O T A L	58.7	48.5	41.8	35.8	26.4	25
Farm efficiency	41.3	51.3	58.2	64.2	73.6	75
Annual energy requirements (kWh/ha)						
Project[4/]	2070	1730	1570	1460	1320	1300
On-farm[5/]	0	0	0	0	50	1170
T O T A L	2070	1730	1570	1460	1370	2470

1/ Estimated attainable efficiencies with various levels of increased input as described by the USBR (1971)

Level 1 - Examining soil moisture, cleaner ditches, furrow slicking, etc.

Level 2 - Level 1, plus additional labor

(continued)

Water Use Efficiency (U_e)

When water supplies are scarce and the management objective for the farmer and the nation is to maximize food and fiber production per unit of water used in ET, the term water use efficiency (U_e) is used to evaluate the production under various irrigation practices. Water use efficiency has been defined in terms of the marketable crop produced per unit of water used in ET (Haise and Viets, 1957). Viets (1962, 1965) also defined water use efficiency as the ratio of dry weight of crop to depth of ET.

$$U_e = \frac{Y_m}{ET}, \text{ or } U_e = \frac{DM}{ET} \qquad [11]$$

where Y_m = the marketable yield, DM = dry matter produced, and ET is the total depth of water used in ET. The ET for a given crop in a climatic region is very similar from year to year, thus the major emphasis in increasing U_e has been to increase the production of either dry matter or the marketable product per unit area which increases the numerator of Eq. 11. More recently, Shmueli (1973) described an optimization approach to maximize water use efficiencies by maximizing both yield per unit area and minimizing ET for the amount of irrigation water applied. He cautioned, however, that there may be hazards in attempting to minimize the denominator of Eq. 11, such as reduced financial return from the investment in the irrigation system and increased soil salinity from continued partial wetting of the root zone.

Irrigation Water Storage and Distribution Systems

The development of optimum water storage and distribution systems to maximize the use of water supplies for energy production and agriculture is a major subject in itself. I will not deal with this aspect of irrigation water management, other than to indicate that a good water distribution system should allow the farmer to obtain water when he needs it at a rate sufficiently large so that he can utilize the stream efficiently with a minimum or reasonable amount of labor. The irrigation distribution system should also permit the farm manager to reject water when it in not needed or as soon as irrigations are completed, rather than at arbitrary time intervals, like 24-hour periods. In some countries, a continuous flow of water cannot be rejected or disposed of through a surface drainage system. The water must be applied whether needed or not. This situation exists in Pakistan and has been one of several factors contrib-

uting to high water tables and salinity problems. Many farmers in California now use overnight storage reservoirs to permit larger deliveries to individual fields and greater flexibility in the rate and duration of irrigation sets (Merriam, 1977).

The current general methods of delivering water to farms consist of: (1) the continuous flow system where each water user receives his share of water throughout the irrigation season; (2) the rotation system where rotations at fixed time intervals are made between two or more water users or groups of water users under one or more laterals or segments of a project canal system; and (3) the demand system which is capable of delivering water to the farm at any time and in any quantity as required by the water user. The third type is ideal from the manager's standpoint, since it allows him to plan his other farm operations knowing that he can obtain water when it is needed and he can reject water when it is not needed. Because unlimited capacity cannot be built into the entire system, the demand system sometimes must be modified during the period of peak water use. When this occurs, the system is changed to a modified demand system and a rotation process may be used for a period of time.

ON-FARM IRRIGATION SYSTEMS

Current Irrigation Trends in the United States

The extent, distribution, and changes that have occurred in irrigation systems during the past five years are summarized in Table 4 by climatic and physiographic regions. Also shown is the proportion of irrigation water obtained from ground and surface sources. Several major trends are apparent.

1. The areas irrigated in the arid Southwest, the arid Pacific Northwest and the semiarid Central Mountain regions have remained nearly static.
2. Surface systems are used on 83 to 84% of the irrigated lands in Regions 1 and 3. About 50% of the irrigation water is withdrawn from surface sources in Region 1 and 83% in Region 3.
3. Recent major expansion of irrigated land has occurred in semiarid, subhumid, and humid areas (Regions 4, 5, and 6). Sprinkler irrigation has increased more rapidly than surface irrigation in these areas and 61 to 77% of the water sources is from groundwater.

TABLE 4 (continued)

1/ Murray and Reeves (1977)
2/ Irrigation Journal (1977)
3/ Percent of the total 1977 irrigated area that is sprinkler irrigated

TABLE 4. General characteristics of irrigation development in the United States from 1972 to 1977 by regions.

Region	Source of water[1]		Total area irrigated[2]			Sprinkler irrigated[2]			Percent of total[3]
	Ground	Surface	1972	1977	Change	1972	1977	Change	
	percent		10^3 ha						
1. Arid Southwest (AZ and CA)	50	50	3977	3779	-198 (-4.9%)	611	605	-6 (-0.9%)	16
2. Arid Pacific Northwest (ID, OR, and WA)	17	83	2910	3015	105 (+3.6%)	482	1373	892 (+185%)	46
3. Semiarid Central Mountains (CO, MT, NV, UT, and WY)	12	88	4440	4521	81 (+1.8%)	403	669	+267 (+83.5%)	15
4. Semiarid Central and Southern Plains (KS, NB, NM, OK, and TX)	77	23	6791	8666	1875 (+27.6%)	1440	2628	1188 (+83.5%)	30
5. Subhumid Cornbelt (IL, IA, MN, MO, and WI)	77	23	202	466	264 (+131%)	128	375	247 (+193%)	80
6. Subhumid and humid South and Southeast (AR, FL, GA, LA, MS, NC, and SC)	61	39	1747	2602	855 (+48.9%)	384	999	615 (+160%)	38
All states (including others in addition to those listed above)	40	60	20,215	23,658	3443 (+17.0%)	4068	7122	3054 (+75.1%)	30

(continued)

4. The older, semiarid mountain irrigated areas (Regions 2 and 3) have the highest proportion of surface irrigation. From 83 to 88% of the irrigation water is from surface sources.
5. The Pacific Northwest (Region 2) has the highest portion of sprinkler irrigation (46%) of the arid and semiarid regions. This is associated with the large increase in sprinkler irrigation during the past 5 years (185%). However, 83% of the irrigation water is from surface supplies. Since the total irrigated area increased only 3.6%, this increase represents a large conversion from surface systems, mainly furrows and rills to sprinkler systems. Several factors have influenced these changes. Ample, low cost hydroelectric power has been readily available until the last 2 years, and the rolling, highly erodible lands have not been suitable to level for efficient surface systems.

The energy used per hectare to apply the irrigation water varies with the quantity applied and the pumping lift. The Mountain States (Region 3) use the least energy per unit area (Dvoskin and Heady, 1976). The Southern Plains (Region 4) and the arid Southwest (Region 1) use the most energy per hectare because of high pumping lifts from groundwater.

The current distribution of various sprinkler methods in these regions is summarized in Table 5. Because of the tremendous increase in center pivot systems, it now represents the major sprinkler irrigation method (39%) in the U.S. Towline and side roll laterals and hand move systems are next (21% each). Side roll systems, however, cannot be used on tall crops, like corn. (The traveller and gun type sprinklers are becoming more popular than the large boom type irrigators in Europe (Butterworth, 1978), even though large boom systems have smaller droplets desired for many soils.)

Three major improvements in surface irrigation have been implemented on a large scale. These are gated aluminum pipe for water distribution to furrows, underground concrete and plastic pipe for on-farm water distribution, and concrete-lined ditches with siphon tubes for water distribution to furrows. Large concrete-lined ditches with single or multiple turnouts to level basins are used in Arizona.

TABLE 5. Estimated distribution of various sprinkler systems in 1977 in the United States by general regions (Source: Irrigation Journal, 1977)

Region	1977 sprinkler irrigated area	Center pivot	Tow line and side roll	Hand move	Traveller and gun types	Solid set	Not classified or other
	10^3 ha	percent					
1. Arid Southwest	605	2	10	69	--	19	--
2. Arid Pacific Northwest	1373	19	36	40	1	4	--
3. Semiarid Central Mountains	669	46	23	12	--	2	17
4. Semiarid Central and Southern Plains	2628	62	25	10	2	--	1
5. Subhumid Cornbelt	375	61	4	2	30	2	1
6. Subhumid and humid South and Southeast	999	12	--	8	31	8	41
Total and averages for these regions	6649	39	21	21	7	4	8

Many return-flow systems are being installed to recover surface runoff, especially where groundwater is pumped. Desilting basins, vegetated strips, and other devices are being installed to remove sediment from irrigation return flows where soil erosion is a problem.

Trickle or drip irrigation systems are only used on a very small part of the irrigated land in the U. S. The 1976 survey (Gustafsen, 1977) indicated only 74,000 ha of trickle-irrigated land, which is 0.3% of the total 1977 irrigated land.

Trends in sprinkler and surface irrigation similar to those in the U. S. are occurring in other countries. In the USSR, for example, nearly one-third of the irrigated land was sprinkler irrigated in 1975 (USSR National Committee of ICID, 1977).

Will these trends continue? Will most of the irrigated area eventually be sprinkler irrigated? Because of the larger annual operating costs with sprinklers, escalating energy costs, and the much larger energy requirements for sprinkler systems, I predict a slow down in the rate of expansion of sprinkler irrigated land during the next decade.

Efficient irrigation is currently easier to achieve with sprinkler irrigation systems. With the modern controls, they provide good control of water applications, except under high wind conditions. The investment in research and development of sprinkler irrigation since World War II has been staggering, and the impact on sprinkler sales for both new land and for converting obsolete systems on existing irrigated lands has been phenomenal, as shown in Table 4. Unfortunately, we have seen only a token research and development effort on improving surface irrigation systems. There is now a renewed interest in low energy, low pressure systems which should stimulate innovative new technology for surface systems using lined ditches or low pressure distribution systems. We are now beginning to modernize surface irrigation techniques, but we are much behind the development of modern sprinkler systems. Until October, 1976 we did not have an organization in the U.S. concerned specifically with surface systems. At the 27th Annual Convention of the Sprinkler Irrigation Association in 1976, the name of the organization was officially changed to "The Irrigation Association." The Association decided to adopt a broader name because of the development of new types of "closed" irrigation systems.

New Developments in Surface Irrigation Technology

During the past two decades much of the limited surface irrigation research has been on the hydrodynamics of surface systems. When combined with modern computer technology, we now have the capability for utilizing fundamental mathematical relationships that describe the dynamic nature of overland flow, infiltration, and distribution of water in the soil profile to improve irrigation management (Katopodes and Strelkoff, 1977a, 1977b). The greatest limitation in applying these mathematical relationships in the design and operation of irrigation systems will be in predicting the infiltration capacity of soils and the surface hydraulic roughness. Both of these variables change with time, crop, and growth stage. However, I do not anticipate significant problems with these variables for future efficient surface irrigation systems because, where land slopes are small, we will be seeing much greater use of large basins that are annually smoothed with laser-beam controlled land leveling equipment. For systems on sloping fields, water controls will incorporate feedback mechanisms and microprocessor electronics to regulate flow rates to borders and groups of furrows to achieve efficient irrigation. We soon will have fully automated surface systems that can apply small water applications as needed to maintain an optimum available soil water level in the root zone during each growth stage.

Level-basin irrigation, using large 2- to 4-ha (5- to 10-ac) basins, has become popular in one project in Arizona where slopes are flat; large flows are available, intake rates are low, and surface drainage normally is not needed. Provisions for surface drainage should be provided in case of overirrigation or excess precipitation. High efficiencies (70 to 90%) can be obtained when using laser plane technology to level and annually smooth the basins (Dedrick et al., 1978). Automated large gate and pipe turnouts and volumetric water control systems are being developed for level basin systems (Haise et al., 1970; Dedrick and Erie, 1977, 1978; and Erie and Dedrick, 1978[3/]). Erosion control turnout structures are needed to handle the large flows at a single location to each basin.

[3/] H. R. Duke, Fort Collins, Colorado, will be presenting a paper on an automated volumetric flow measurement and control system at the December 1978 meeting of the American Society of Agricultural Engineers.

Cutback irrigation, where furrow flow is reduced after the water advances to the ends of the furrows, has been advocated for decades. However, because of the increased labor required with manually operated systems and problems associated with handling a constant flow, this technology has not been implemented. With automation, these problems no longer need constrain this system. The high initial flows are usually provided in one of two ways:

1. A return flow system is used to boost the flow during the advance of the streams in the furrows; and
2. The set is split after the water has advanced to the ends.

Fischbach and Somerhalder (1971) reported application efficiencies up to 92% using the first method (Table 1). Design criteria for return flow systems have been provided by Bondurant (1969), and Stringham and Hamad (1975).

With the development of automatic valves for pipe (Humpherys, 1978, and Humpherys and Stacey, 1975), and their availability commercially, we can expect greater use of the second method. With this method, one-half of the total set is irrigated with the full stream until the water reaches the end of the furrows. The flow is then directed to the second half for the same time period. Then the flow is distributed over the full set for the balance of the irrigation period providing a 50% cutback in the furrow stream size. Humpherys and Worstell[4/] obtained a seasonal irrigation efficiency of 78% in 1977 with a semiautomatic split-set cutback system using gated pipe on furrow irrigated beans. Only 57% efficiency was obtained on the control.

A third method of achieving better application efficiencies with furrow irrigation is to reduce the length of run for the furrows by using multiple water distributors. Because of increased labor with manual systems, this technique generally has not been used. Actually, run lengths have increased to reduce labor and farming costs. The multiset technique can be achieved with gated pipe on the surface, but more labor is required to place and move the pipe for cultivation and other operations (Rasmussen et al., 1973). A buried multiset system, which eliminates some of these disadvantages is being evaluated in southern Idaho (Worstell, 1976). Humpherys and Worstell[4/] obtained a seasonal irriga-

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[4/] Unpublished data from 1977 experiments.

tion efficiency of 89% with a semiautomatic experimental multiset system on a bean field in 1977.

A fourth method using the bubbler concept, but with low cost corrugated plastic tubing, has been developed for an orange grove (Rawlins, 1977). Corrugated 100-mm diameter plastic tubing is buried between every other tree row. Smooth 9-mm tubing is inserted into the main tubing to deliver water to each tree at a rate of 0.06 ℓ/s (1 gal/min). The flow rate is controlled by the elevation of the outlet stapled to each tree. When using a simple calibration technique, a 90% emission uniformity is achieved. With a simple dynamic readjustment, a 98% uniformity can be obtained.

Improving Farm Surface Irrigation Systems by Automation

Most water distribution systems on older projects were not designed to provide water on demand or to allow farmers to reject water when not needed. Many project systems need improvement. This can be done by more automation and by providing storage within distribution networks. Open-channel delivery systems without automation now limit the extent to which farm systems can be significantly improved and automated. Until project systems can be improved, on-farm reservoirs can be used. On-farm reservoirs provide greater flexibility in water flows and enable farmers to use automated farm irrigation systems, and they reduce trash problems associated with direct deliveries from open, unlined channels. On-farm water distribution systems are being improved by replacing open ditches with buried pipelines.

Automation is extremely important in achieving the kind of control needed with surface systems to achieve efficient irrigation. Automation can reduce labor to 10 to 30% of that required with nonautomated systems, depending on the systems involved. Automated border-dike systems used in New Zealand have greatly reduced the labor requirement. Previously, 1 ha required one man-hour of labor, but now 60 ha can be irrigated per man-hour.[5/] Pipeline systems generally are easier to automate, especially if gated pipe is used. Commercial, low-cost valves that do not require separate power supplies are now available for pipelines. One of these

5/ A. R. Taylor. Personal communication.

valves, known as the Snake River Automated Irrigation Valve, was developed at our Research Center (Humpherys and Stacey, 197).

Pneumatic valves for pipe turnouts and alfalfa valves have also been developed and are available commercially (Haise et al., 1965; Haise and Fischbach, 1970; and Fischbach and Somerhalder, 1971).

Automating on-farm surface irrigation systems has progressed sporadically. There are several very modern essentially fully automated systems operating in California and Arizona. Typically, low labor automated surface irrigation systems require fairly large flow rates. Stream sizes up to 0.4 to 0.6 m^3/s (15 to 20 cfs) are used in Arizona. Automated border-dike systems are used extensively on pasture lands in New Zealand (Stoker, 1978). The system at the Winchmore Irrigation Station uses a flow rate of 0.23 m^3/s (8 cfs). Four border strips are irrigated at one time with a timer- or sensor-controlled drop gate automatically sequencing the system upstream.

Recent Developments in Sprinkler Irrigation Systems

Perhaps the newest development in automatic agricultural sprinkler equipment is the "linear move" system. Problems encountered with center pivot systems have involved the system hydraulics, water application rates, and physically fitting common square or rectangular farm fields. Water is supplied at the pivot, but most of the water is applied near the outer end of the lateral, causing high friction losses in the lateral. Large gun sprinklers are needed at the outer end to extend the area covered and these require either a high pressure for the entire system (much greater than necessary closer to the pivot), or a booster pump. The rate of water application varies throughout the system with rates often so high near the outer end that runoff occurs.

The new linear move systems use some of the standard reliable pivot components and new electronic controls to minimize problems encountered with earlier linear move systems. The pressure at the end of the lateral can be as low as 140 kPa (20 psi), and water is applied at about the same rate throughout the entire lateral. The Valley "Rainger"[6/] and the

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6/ Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.

Gifford-Hill "Curve-A-Linear"[6/] both pump from an open ditch as the systems move across the field. With the Gifford-Hill system, a flexible hose connection can be made to a pipe system. An electronic guidance system controls the alignment of the system with the field.

Clues to Future Trends

We can learn much from the past three decades of experience with irrigation systems and practices. First, recommending that farmers adopt practices like using cutback flows and shorter run lengths is a waste of time, unless we provide the technology to accomplish these practices with less labor and less inconvenience through coordinated agency and industry research and development. Research and other professional irrigation specialists have underestimated the farmers' willingness to adopt complex technical equipment that usually require services of skilled technicians. Fully automatic center pivot systems with complex corner devices and routine use of laser-controlled land leveling are two examples.

If we can develop dependable equipment and methods to predict or control the amount of water needed to maximize net returns, and enable farm managers to conveniently and economically apply water uniformly, they will adopt the technology.

RECENT DEVELOPMENTS IN WATER USE-CROP PRODUCTION TECHNOLOGY

During the past three decades, many experiments have been conducted to determine optimum irrigation practices for most farm crops. Traditionally, these studies attempted to delineate critical stages of growth, the maximum allowable depletion of soil water before irrigation, and the response to irrigation. Today, because automated systems can apply light uniform irrigations, new irrigation studies have been initiated to refine optimum water amounts and frequencies to achieve the farmer's management objective (MO). The MO may be to maximize production per unit of limited water supplies, but most often it is to maximize net returns when considering all variable inputs.

There are many publications on critical crop growth periods when plant water stress is apt to produce large reductions in crop yield and/or quality. The reasons for these yield reductions are not clear (Vaadia and Waisel, 1967). Viets (1972) indicated that reduced mineral nutrition

under decreasing water availability cannot be closely related to reduced growth. Some experimental results can be attributed to the ET rate which determines the rate at which plant water stress is imposed without plant conditioning, and the severity of the water deficit or stress index (ET demand vs. available soil water supply during a critical period) as defined by Nix and Fitzpatrick (1969). Recently, scientists have determined that, for many crops, plant "conditioning" lessens yield reduction and quality caused by a period of limited available soil water. Some sensitive crops, like potatoes, growing on sandy soil, require maintaining a lower soil water tension to avoid tuber growth problems that do not occur in finer textured soils with high ET rates. Sufficient root shrinkage also may trigger severe plant water stress. Recent studies by Huck et al. (1970), and Herkelrath et al. (1977a, 1977b), indicated that root shrinkage can cause a significantly large increased resistance to water flow from soil to the plant roots to reduce water extraction.

Today, effective irrigation water management requires distributing limited water supplies or reducing high pumping costs, while maintaining crop yield and quality. This is being accomplished by irrigating to condition the plants to water stress and to reduce ET. We are learning how to control soil water levels on more crops to regulate unnecessary plant growth and to improve crop quality by controlling plant water stress and by curtailing undesired nutrient uptake at certain growth stages.

Production - Evapotranspiration Relationships

Most scientists have observed and reported curvilinear relationships between ET and the yield of the marketable product of a farm crop when approaching maximum yields. Typical examples for alfalfa, cabbage, corn, cotton, grain sorghum, and winter wheat are illustrated in publications by Jensen and Musick (1960), Musick et al. (1963), Stewart and Hagan (1969), Thomas et al. (1970), Stewart et al. (1973), Fitzgerald et al. (1971), and Grimes and Dickens (1977). As minimum or zero yield of the marketable product, like grain, is approached, most studies show that the relationship is essentially linear and intersects the ET axis between 100 and 150 mm (Staple and Lehane, 1954; Leggett, 1959; and Musick et al., 1963). Relationships for dry matter production vs. transpiration are essentially linear, and those for dry matter production vs. ET are nearly linear.

Yield vs. total irrigation water applied is generally curvilinear, though for some crops yield responses can be approximated by linear relationships. Typically, the return from increasing increments of irrigation water diminishes as maximum yields are approached. An excellent compilation of about 20 years of experimental results of yield vs. water application for eight field crops, four orchard crops, and four special crops in Israel has been presented by Shalhevet et al. (1976).

Stewart et al. (1977) recently summarized the results of a comprehensive four-state study of optimizing crop production through control of water and salinity in the soil. All studies were conducted with a hybrid corn variety adapted for each area and all experiments used a sprinkler line continuous variable design (Hanks et al., 1974). The results showed that, if a deficit in ET is caused by limited irrigation and the limited water is distributed proportional to the ET rate, the grain yield vs. ET relationship becomes nearly linear on a deep soil in an arid area. Most previous studies involved delaying irrigations until various levels of soil water depletion occurred before irrigating. Linear regression analyses relating yield to ET showed high linear correlation coefficients. ET ranged from a low of about 60% of the maximum ET to 100% and the intercepts of the ET axis were near zero. However, all other data indicated that grain yield should approach zero with an ET of 100 to 150 mm. Thus, the near linear relationships presented could be misleading if ET is reduced to less than about 50% of the maximum by limiting irrigations because the intercept does not agree with the other data as $Y \rightarrow 0$. At Davis, California, normally ET would not be reduced to less than 60% of the maximum because corn can extract about 400 mm from that soil when thoroughly irrigated before planting. When plotting the means of grain yield and ET for Davis within water levels, curvilinear trends (decreasing yield response as $ET \rightarrow ET_{max}$) are apparent for the treatment irrigated throughout the season (III) as shown in Table 6. Results from Fort Collins, Colorado and Logan, Utah showed more curvilinear relationships. The corn treatment not irrigated during the vegetative stage (OII) produced as much grain as that irrigated all season. The response was essentially linear and it intercepted the ET axis at 190 mm. The more linear response is probably due to a smaller evaporation component, since no irrigations were applied during the vegetative growth stage. This practice may not be advisable in all areas, however, since stress may delay the date of maturity and increase the risk of frost damage.

TABLE 6. Yield of corn grain at Davis, California, and evapotranspiration as irrigation is limited. (From Stewart et al., 1977.)

Year and treatment[1/]	Water level[2/] 1	2	3	4	5	6
			Grain yield, kg/ha			
1974-III	6900	8220	9 920	11 000	11 650	11 550
1975-III	8180	9080	9 900	10 650	11 700	11 950
1974-OII	7800	8850	10 350	10 700	11 200	11 600
			ET, mm			
1974-III	435[3/]	485	553	636	673	674
1975-III	410	450	498	514	599	612
1974-OII	440	496	525	553	559	571

[1/] III - Irrigated throughout the growing season
OII - Not irrigated during the vegetative stage, but in the pollination and maturation stages.

[2/] Zones adjacent to the sprinkler line source (6 is next to the line).

[3/] Maximum water extracted from the soil by corn = 404 mm.

Controlling Growth and ET by Water Stress

When imposing a controlled stress period, ET is reduced, yields are usually less than when watered throughout the season, but amount of irrigation water applied during the growing season may be reduced substantially. We are beginning to see more irrigation practices in arid areas to control plant water stress and limit undesired plant growth during some stages, or to enhance partitioning of photosynthate to the marketable product. Miller (1977) summarized a series of experiments in which daily sprinkler irrigation was used (Table 7). The amounts applied ranged from slightly in excess of daily ET down to 50% of pan evaporation. The treatments began after sufficient growth occurred to provide canopy closure. Typically, available soil moisture was generally depleted on the 50 and 75% treatments during the season. More important, ET was reduced with little change in marketable yield, and production per unit of water used increased. Additional details on the sugarbeet experiments were presented

TABLE 7. Effect of deficit irrigation on water use and sugar percentage and yield of sugarbeets, and grain yields of dry beans and wheat (from Miller and Aarstad, 1976; and Miller, 1977).

Crop and daily irrigation treatment[1]	Sucrose %	Sugar yield kg/ha	Water use mm	Total water applied mm
SUGARBEETS (1974 sugar yield)				
100%	15.7	13 200	718	760
75%	15.8	12 900	670	615
50%	17.6	13 000	485	356
50% after 16 July	16.7	12 500	570	477
50% after 15 August	15.5	12 300	660	600
50% after 13 September	15.8	12 900	743	708
NUGAINES WINTER WHEAT				
100%	--	6 640	732	607
75%	--	6 950	670	510
50% to flower (6 June), then 75%	--	6 990	536	444
75% to early boot (19 May) then 100%	--	6 910	721	632
50% to flower (6 June) then 100%	--	7 110	597	521
50% to early boot (19 May) then 75%	--	6 470	615	503
DRY BEANS				
100%	--	4 350	345	340
75%	--	4 390	302	264
50%	--	4 290	292	211
100% to 6 Aug., then 50%	--	4 360	353	387
50% to 6 Aug., then 75%	--	4 910	277	231
50% to 6 Aug., then 100%	--	4 360	315	251

[1] Irrigated daily after canopy closure, based on evaporation from a USWS Class A pan.

by Miller and Aarstad (1976). Similar results on sugarbeets were obtained by Carter[7/]. Irrigations were terminated early in an experiment in 1977 to evaluate the effects of drought and limited water supplies on sugarbeet yield and sucrose production. The last irrigation was applied on one treatment on July 16, another on August 1, while the control was irrigated all season. Only a few light rains occurred after September 15 before mid-October harvest. Root yields were reduced to 82 and 93% of the control which was irrigated all season. However, since sucrose percentage increased with plant water stress, and as soil nitrogen uptake was reduced, sucrose yields were 91 and 98% of the control for the July 16 and August 1 cutoff dates, respectively. The reduction in irrigation water applied during August and early September was about 30% for the season.

Other crops, like alfalfa grown for seed, typically produce more with some controlled plant water stress. A thorough irrigation early in May at Kimberly, Idaho with no other irrigations the remainder of the season produced the largest seed yields in 1969 and 1970 (Kohl and Kolar, 1976; and Kolar and Kohl, 1976). Similarly, Krogman and Hobbs (1977) reported that over a 6-year period in southern Alberta, there was no advantage to irrigating after alfalfa was in the bud to early bloom stage (June to early July).

These studies indicated that when gradual plant water stress is imposed and some soil water is available, some crops adapt to these conditions. Cutler and Rains (1977) studied the effects of irrigation history on response of cotton to subsequent water stress. They concluded that cotton subjected to water stress during development is less sensitive to tissue water deficits.

Most observed yield vs. ET curvilinear relationships may be associated with the manner in which ET reductions are imposed. Typically ET was reduced when irrigations were delayed, allowing greater levels of soil water depletion before irrigating. Musick et al. (1976) found a distinct curvilinear relative yield vs. the lowest observed soil water level for 12 crop years of data at Bushland, Texas, on grain sorghum,

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7/ Carter, J. N. Unpublished data.

soybeans, and winter wheat. In these experiments, the maximum stress period usually occurred during panicle development and grain filling for grain sorghum and winter wheat, and during flowering through pod filling for soybeans. These results indicated that a single maximum stress period may determine the bulk of the decrease in yield, thus causing more of a curvilinear response since ET may not be reduced proportionally the entire season. Also, the lack of significant yield reductions, obtained by Miller and Aarstad (1976), by daily deficit irrigation indicated that preventing severe stress for at least part of each day may be a significant factor increasing water use efficiency.

Increasing Irrigation Water Use Efficiency

Most of the studies previously mentioned generally considered crop production per unit of irrigation water applied only during the growing season. The four-state, 2-year corn study (Stewart et al., 1977) required that the initial soil water content be brought to field capacity before or at the time of planting. From an irrigation standpoint, when water supplies are either limited or expensive, production from irrigation both before and during the season must be considered.

When irrigation was just beginning to expand in the southern High Plains of Texas, preseason irrigation to fill the subsoil was considered an efficient use of water. However, Musick et al. (1971) in a 4-year study showed that irrigation water use efficiency (the increase in production of grain per unit of irrigation water) was always less when part of the irrigation water was applied preseason. Average storage efficiency (soil water stored relative to amount applied) of 20 preseason irrigations plus rainfall from fall to mid-May ranged from 41 to 49%. Also, preseason fall irrigation decreased subsequent spring rainfall storage to about one-half of that on nonirrigated treatments. Similar results were reported by Jensen and Sletten (1965a, 1965b), where preseason irrigation plus rainfall storage efficiency was 26 to 33% for spring irrigations for grain sorghum and about 40% for summer rainfall plus the preplant irrigation for fall-planted winter wheat.

Crop Growth Modeling

A tremendous effort has been devoted to modeling plant growth and crop production during the past decade. Space does not permit a thorough review of this subject in this paper. We can expect many crop models to

varying complexities to be described in the literature during the next few years. The less complex models requiring daily climatic data as input will be incorporated into computerized irrigation scheduling programs.

IRRIGATION SCHEDULING TECHNOLOGY

Israelsen (1950) stated that uniform distribution of irrigation water and adequate depth of water penetration into the soil would be much easier to obtain if the irrigator could see by simple inspection how deeply into the soil his irrigation water penetrates and to directly estimate the depth of water stored in each foot of soil.

This statement is still applicable today for most farm managers. The neutron probe, now used by several irrigation service groups and some farmers, permits direct determinations of soil water with depth at sites where access tubes have been installed. Surface moisture probes generally still are not used by service groups.

Irrigation scheduling is predicting the time and amount of the next one or more irrigations, taking into account expected precipitation. The most common management objective, where water is not limited and its cost is either very, very low or not based on volume, is to eliminate water as a production-limiting variable. Negative effects of excess water application are avoided by delaying irrigation until soil water depletion is sufficient to permit efficient irrigation with the existing system. Plant water stress effects are avoided by irrigating before crop yield and/or quality are reduced because of inadequate available soil water. Irrigation scheduling technology considers rainfall and ET since the last irrigation, the allowable soil water depletion at the present growth stage, and the expected rainfall before the next irrigation. Irrigation scheduling is a decision-making process that farm managers encounter daily or weekly. They can make better decisions if more specific information about ET and the current soil water status are available. The type of scheduling information desired by farm managers depends on their mode of operation. Many farmers prefer to obtain this information from a reliable source rather than to determine it themselves. This is where irrigation consultants have a role. The information currently provided by consultants or irrigation management groups can be adapted to any of the following management options.

1. High frequency irrigation with constant or declining soil water during the growing season and a targeted leaching fraction (LF).

2. Normal periodic irrigation to bring the soil to field capacity and a targeted LF using constant or variable amounts per irrigation and fixed or variable intervals.
3. Normal periodic irrigations, but with planned gradual depletion of soil water during the crop season with the targeted LF planned during the noncrop or some other crop season.
4. Limited or supplemental irrigation to optimize production or net returns per unit of water, and alternating, well watered, shallow rooted crops with nonirrigated, or partially irrigated deep rooted crops.
5. Combinations of the above.

Farmers often want more than data. They want field inspections by qualified professionals or technicians. Periodic field monitoring is an essential component of a successful scheduling service to reduce the uncertainty of the predicted soil water status caused by unknown irrigation or precipitation amounts and nonuniform irrigations, and to observe other factors that may be limiting crop growth (Jensen and Wright, 1978).

Current Scheduling Practices in the United States

Many standard procedures and guides for irrigation scheduling have been advocated for decades. Most depend on soil probing, using soil moisture blocks and tensiometers, and evaporation pan data. I have labeled all of these methods traditional because they have one thing in common--the farm manager must use or apply some technique and develop some degree of skill to get the information he wants. Although tensiometers and soil moisture blocks are valuable tools for irrigation scientists and technicians, they generally have not been adopted by most farmers for various reasons even though they have been available commercially for three decades (Jensen, 1975). We have overemphasized the traditional approaches and not adequately considered alternative procedures to provide vital decision-making data that are needed by farm managers to achieve efficient and economical irrigation. Irrigation scheduling requires current information on trends and probable effects of alternative actions. As Jensen (1972) stated, 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 also could use predictions of adverse effects, like delaying an irrigation for several days or perhaps terminating irrigations, on the yield of marketable products.

The most widely used general procedure for providing irrigation scheduling services in the United States is the climatic data based approach. Most current service groups use or have adapted the USDA-ARS computer program for scheduling. We developed this program in southern Idaho from 1966 to 1969 to supplement a detailed use of water study conducted by the USBR (1971). The program was evaluated in 1968 and 1969 in Idaho and on the Salt River Project in Arizona (Jensen, 1969; and Jensen et al. 1970). The computer program was released in 1970 and modified slightly in 1971 (Jensen et al., 1971), and has been described in several publications (Jensen, 1972, 1975, and 1977b; and Lord and Jensen, 1975). The program has been revised for small desk type computers by Kincaid and Heermann (1974) and specifically adapted for center pivot systems by Heermann et al. (1976). A comparison of six nonscheduled and 11 adjacent scheduled center pivot systems on corn in 1977 showed over a 25% reduction in water pumped from 740 to 530 mm, respectively (Heermann and Duke, 1978).

The Kincaid-Heermann version of the USDA-ARS program was used by the University of Nebraska in developing its scheduling program for its AGNET (Agricultural Computer Network) system (Thompson and Fischbach, 1977; and Tscheschke et al., 1978). The AGNET scheduling program uses soil moisture block readings as an optional input for its Method 2 and requires these readings for the Method 1. An estimated 20,000 to 40,000 ha were scheduled in 1977 using the AGNET program.

A more detailed program has been developed by the USBR for its Irrigation Management Service (IMS) program (Buchheim and Ploss, 1977). The program also has been used to develop optimizing techniques (Trava et al., 1977), and the USBR IMS program has been modified in cooperation with the Extension Service to provide weekly general estimates of ET for various crops in Idaho. These estimates are printed in local newspapers (Larsen, 1978). Irrigation scheduling technology also is being used to reduce peak electrical loads and to limit rachet-type electrical rates that are based on the maximum electrical demand for the peak 15- to 30-minute use period during the year (Schleicher, 1977). A current summary of electrical load management practices in relation to water management and scheduling to avoid significant reductions in crop yields was presented by Heermann and Duke (1978).

Woodruff (1968) and Woodruff et al. (1972) developed an irrigation scheduling guide for Missouri based on the expected average ET rate for corn. Wilcox and Sly (1974) described irrigation scheduling procedures for British Columbia using pan evaporation. Similar procedures using pan evaporation were described for the Columbia Basin (Jensen et al., 1961, and Hagood, 1964). Brosz and Wiersma described procedures based on average expected ET rates for corn and alfalfa. Other methods and procedures were described by Jensen (1975).

Kanemasu et al. (1978) developed procedures for estimating water requirements of corn using a "pocket" calculator. The program is oriented toward conditions in Kansas and is based on an earlier ET model (Kanemasu et al., 1976; and Rosenthal et al., 1977).

Current Status of Commercial and Agency Scheduling Services in the USA

I recently contacted 10 commercial consulting firms that are providing scheduling as part of their services. They estimated that they had provided field-by-field scheduling services to 231,000 ha (571,000 ac) of summer and winter crops in 1977. They estimated they would serve 232,600 ha (575,000 ac) of summer crops in 1978. The USBR provided field-by-field IMS to 63,500 ha (156,900 ac) in 25 different districts. The Salt River Project provided scheduling services to 5,800 ha (14,400 ac) on the project in 1977. These two groups expect to provide service to 69,600 ha (172,000 ac) of summer crops in 1978. The USBR also provided irrigation "guide" information to about 35,000 ha (87,200 ac). The USBR is now placing emphasis on scheduling irrigation system operations.

Commercial and agency scheduling service for individual fields has grown from less than 40,000 ha (100,000 ac) in 1971 to about 302,000 ha (746,000 ac) in 1977. Including the Nebraska AGNET program, the total would be over 325,000 ha (> 800,000 ac). The commercial firms employed about 250 specialists, technicians, and other support staff and the agencies employed 60 in 1977.

All of the commercial firms provided plant nutrition (petiole and soil sample analyses) services, and most provide pest management services. Many commercial firms supplement these services with aerial color, color infrared, and black and white photographs or transparencies of scheduled

fields, cost accounting, and system evaluation and improvement engineering. Of the 10 commercial groups contacted, seven had 5 to 10 years experience, one had over 10, and two had less than 5 years. Each technician, or professional staff member generally monitors from 1,000 to 1,500 ha (2,500 to 3,700 ac) but some handle 2,600 to 3,600 ha (6,500 to 9,000 ac). Fees for irrigation scheduling vary from about $8 to $15 per ha ($3 to $6/ac) depending on the service provided. With other services included, they may range from $12 to $30 per ha ($5 to $12/ac). In some cases a flat fee of $175 to $300 per field is charged, depending on the type of service provided. One commerical firm specializes only in aerial color infrared services on a weekly basis. Their results are made available within 24 hours to enable customers to assess system operations and various problems affecting crop growth, like water and fertilizer uniformity, disease, stands, pesticide applications, etc. Fees are negotiated based on the number of photographs provided, but range from about $2 to $3.75/ha ($0.75 to $1.50/ac). These fees also depend on the size and number of fields.

The Salt River Project charges $7.60/ha ($3.10/ac) for a year. This includes irrigation scheduling and weekly field inspections, two petiole samples per field and crop, and one soil sample for N, P, K, TSS and SAR analyses.

Recent Developments in Irrigation Scheduling Services

Probably, the major change that has occurred during the past 2 years with service groups is that they are now beginning to use neutron probes to measure soil moisture. Two small firms schedule irrigations using neutron probe data and a large firm uses the probe to calibrate and assist technicians to monitor soil moisture by the "probe and feel" method. The USBR uses the probe to adjust computed soil water levels. The other major change is the addition of aerial photography to aid in detecting crop growth problems at an early stage. Also, aerial photography often clearly reveals water distribution problems associated with the design and operation of automatic sprinkler irrigation systems, and plant stress areas within fields caused by soil compaction areas due to vehicle traffic, fertilizer application uniformity, pesticide and herbicide equipment malfunctions, etc.

Role of Agricultural Consultants

The private consultant has an important role in providing irrigation management and related services. Private consultants stimulate competition and new innovations in irrigation services. Also, since not all farm managers will want the same degree of service, agency groups should consider providing optional services for a fee to those who want them, as is done in the Salt River Project in Arizona.

Agricultural consultants must work in the best interest of their customers--the farm managers. Therefore, they should not sell or receive commissions on products they recommend, and their recommendations must be based on valid experimental data if they are to maintain the confidence of the farm managers they serve. Sometimes traditional practices and pressures from fertilizer dealers are difficult to combat. For example, Carter et al. (1975, 1976) showed that 70% of sugarbeet fields studied in southern Idaho had excess nitrogen fertilizer applied in 1971. If these fields were representative of general practices, and if the farmers had used soil tests and better fertilizer prediction methods, they would have gained about $19 million on 69,200 ha (1974 prices) because of the higher sugar content, root yields and lower N fertilizer costs. Sugarbeet quality is adversely affected by excess N uptake, and root yield may be limited by inadequate N and sometimes excess N.

A sugar company in southern Idaho conducted four detailed experiments in 1977 using fertilizer rates based on laboratory analyses and recommendations made by three commercial laboratories, the sugar company, and the University of Idaho (Kerbs, 1978). The soil samples were collected and split into four parts by the company, but they were submitted by the farmers as routine requests for fertilizer recommendations. The results are summarized in Table 8. The important point in these data is that applying a wide range in fertilizer elements to avoid all possible risk of deficiencies, even though soil tests did not show deficiencies, did not maximize net returns to the farmers. One important conclusion is that there is still room for consultants who are working for the farmers and not the fertilizer industry. Also, a small investment in soil analyses and obtaining a valid fertilizer recommendation is probably one of the best investments a farmer can make.

Table 8. Average fertilizer recommendations and yield of sugarbeets at four locations in southern Idaho (from Kerbs, 1978).

Laboratory making soil test and recommendations	Recommended fertilizer amounts							
	N	P_2O_5	K_2O	S	Zn	Mn	B	Cu
	kg/ha							
Lab. 1	344	254	194	29	13	7	3	0.8
Lab. 2	300	384	40	0	13	0	2	0.6
Lab. 3	386	231	88	386	0	0	1	0
TASCO[1/]	119	0	0	0	11	0	0	0
Univ. of Idaho	0	0	0	0	11	0	0	0

	Average yields, quality, costs and returns					
	Root	Sucrose	Price[2/]	Gross	Fert. Cost	Net
	t/ha	percent	$/t	$/ha		
Lab. 1	59.5	14.7	24.96	1485	195	1290
Lab. 2	59.1	14.8	25.08	1482	166	1316
Lab. 3	61.2	14.8	25.11	1536	185	1351
TASCO	59.7	15.4	26.29	1570	40	1530
Univ. of Idaho	58.5	15.5	26.52	1551	10	1541

[1/] Twin Falls Amalgamated Sugar Company

[2/] Price is based on beet quality

Irrigation recommendations likewise must be based on valid experimental data and recommendations must be targeted to maximize net returns to the farmer or to conserve his resources. Irrigation management services will become even more important as irrigation costs, like labor and energy increase. Where high pumping lifts are involved, energy now represents a major part of the total annual irrigation costs and it will increase.

Monitoring Crops and Soil Water

Periodic monitoring of fields by irrigation service groups is an essential element of a managment service, but it also represents a major part of the costs. One technician or specialist can inspect 1,000 to 1500 ha once or twice a week. This usually requires much travel, since customer fields are not always located in a concentrated area. Once a

field has been checked, the climate-based computer program can estimate and predict further depletion with sufficient accuracy for several weeks (standard ET error of $1/\sqrt{\Delta t}$ in mm/day where Δt is the time period in days), or until the next irrigation that is applied (Jensen and Wright, 1978). With some irrigation systems that uniformly apply specific known amounts of water, monitoring for soil water may not be needed all season (Heermann et al., 1976). What is often overlooked by inexperienced groups is that visits to the fields and with the farmers mean much more than checking the soil water status and uniformity. Each field technician or professional with a successful commercial firm serves as an advisor on many crop production problems. Questions he can not answer himself are relayed to the home office by radio or radio-telephone to obtain an immediate qualified answer. Thus, remote sensing using aerial methods or even satellites may increase a service company's capability and may reduce the costs of monitoring fields, but it will not replace field specialists.

Satellite data and aerial techniques have been used to estimate leaf area index (Kanemasu et al., 1977). Other studies have shown that remotely sensed canopy temperature relative to air temperature in mid-afternoon can result in a "stress degree day" (SDD) whose sum starting at day 100, or the head growth period, was inversely related to yield of durum wheat (Idso et al., 1977). Data also indicated that albedo measurements could be used to determine the period to begin summing the SDD parameter; i.e., from the first appearance of awns until heads produce no more dry matter. Albedo increases dramatically as plants approach maturity. These techniques are expected to be adopted by irrigation management service groups to supplement, but not replace, computer computations using crop growth models. These models relate growth and soil water depletion to ET. They are very economical to use and there are good yield-ET relationships available. The SDD parameter will be most effective where uniform climate and predominantly clear skies prevail. Obviously, this technique would be valuable in predicting crop yields over large areas.

Remote sensing can increase the capability of groups providing management services. One company operating in Manitoba, Canada (The Furrow, 1978) charges $40 to take an infrared photograph, and $6/print per 260 ha (1 sq. mi.). These are used for working with farm managers in assessing crop production problems caused by nonuniform fertilizer and herbicide distribution, drainage, insect damage, and weeds. Microwave

techniques are being evaluated for remotely observing surface soil moisture (Schmugge et al., 1978). Currently, the method may permit assessing the water content in the upper few centimeters of soil from aircraft or satellites, but the method will not be operational for a few years.

NEW IRRIGATION MANAGEMENT TECHNOLOGY

Changes in irrigation management technology that require major modifications or complete replacement of existing facilities will occur slowly during the next decade because of manufacturing, distribution, installation, and construction problems. Design and construction or manufacture of ready-to-use equipment for large irrigated areas will not occur suddenly. For example, consider the current status of center pivot irrigation systems some 25 years after the first one was built. Management techniques can change more rapidly. Modern irrigation scheduling could be implemented on a project-wide basis in 2 to 3 years. Adoption of new concepts of timing or applying specific amounts of water can occur over large areas within 1 to 2 years.

Major management goals will be to improve the ability to control the amount of water applied and to distribute it uniformly over the fields. After achieving this capability, we will require better knowledge of optimum irrigation amounts and timing. Some changes in irrigation technology expected during the next decade are listed below:

A. Water Storage and Distribution
   1. More automation and closed pipe delivery systems to provide water as needed with automatic adjustments when irrigations are completed.
   2. Automatic volumetric measurement or control of water deliveries.
   3. More combined use of surface and subsurface storage by all users within a basin or project.
   4. More regulating surface reservoirs to increase water delivery flexibility and reduce operating wastes.

B. On-Farm Systems
   1. Substantial increases in the use of automated controls or remotely controlled facilities to reduce labor and increase water application efficiencies.
   2. Greater use of soil water and/or salinity sensors in automated systems will occur.
   3. Irrigation controllers or sensing-readout devices (powered by

solar radiation or wind in remote locations) will measure incoming solar or net radiation, air temperature, and, possibly, humidity and windspeed which will be processed by self-contained microprocessor units.

4. Output from climatic sensors will be used with ET and crop models to control or indicate the need for the irrigation. Sensors mentioned in item 2 will provide feedback. For controllers, manual programming will be used for semiautomatic systems.
5. Remote read-out devices will enable irrigators to determine the status of water controllers from a central location as is now done with canals and laterals.
6. Gated pipe will be equipped with gates that permit automatic opening and closing of groups of gates and pressure regulation.
7. Other surface systems will have computerized controllers to optimize flow rate and volume delivered to achieve maximum irrigation efficiencies.
8. Sprinkler systems will operate at lower pressure to reduce energy requirements.
9. More moving systems, both sprinklers and other types, will be used to increase water application uniformity.
10. More on-farm reservoirs will be used where delivery flows are small and constant, or small wells are used.
11. Return flow systems for reusing surface runoff will become more common.
12. New, innovative water application systems will be developed.
13. More closed conduit on-farm systems will be used with greater use of plastics.

C. Water Use-Crop Production Technology

1. Plant growth and crop production models that have soil water and ET variables will be available for planning before the irrigation season, and they will be incorporated into computerized irrigation scheduling programs to enable better dynamic or real time decisions to be made in managing irrigations throughout the growing season.
2. The models mentioned in item 1 will include crop yield and quality aspects, plant nutrition relative to soil and fertilizer nutrient supplies, and will be coupled with models of plant pests and diseases.

3. Improved guides will be available for regulating plant water stress to optimize the yield and quality of marketable crop products while reducing water and energy requirements.
4. Plant breeding efforts will be geared more specifically to developing crops under controlled soil, water, and plant stress regimes.
5. New techniques will be developed to stimulate root development to fully utilize the full potential rooting depth in arid soils where crops now have severely restricted root systems.

D. Irrigation Scheduling Technology

1. Improved crop growth-ET models will be incorporated in private and agency programs providing irrigation scheduling services. Improved estimates of daily ET for major crops, including forecasts, will be printed twice a week in many newspapers serving irrigated areas.
2. ET estimates and computer scheduling programs will be made more accessible to consultants and farm managers through computer networks using telephones.
3. Improved techniques for monitoring soil water status, both on the ground and from aircraft will become readily available for commercial use.
4. Plant nutrition subroutines will be incorporated in computer programs used for real time estimates and predictions of water requirements.
5. Automatic irrigation systems will utilize either output from climatic or soil water sensors and microprocessors to turn systems on and off, or light irrigations may be applied in pulses to maintain specified soil water levels. Fields may still be monitored by consultants or agency specialists.

E. Social and Institutional Aspects

1. Some water laws and policies will be changed to stimulate water and energy conservation. This will accelerate the implementation of new technology.
2. Water users in developing countries will have a greater input in irrigation water delivery policies to reduce yield losses caused by arbitrary changes in water deliveries or unscheduled system maintenance.

REFERENCES

Bondurant, J. A. 1969. Design of recirculating irrigation systems. Am. Soc. Agr. Eng. Trans. 12:195-198.

Bos, M. G, and J. Nugteren. 1974. On irrigation efficiencies. Int. Inst. for Land Reclam. Improve. Pub. 19, Wageningen, Neth., 95 p. (Note: 2nd edition 1978, 142 p.)

Buffum, B. C. 1892. Irrigation and duty of water. Wyo. Agr. Exp. Stn. Bull. No. 8, Oct.

Buchheim, J. T., and L. F. Ploss. 1977. Computerized irrigation scheduling using neutron probes. Am. Soc. Agr. Eng. Paper No. 77-2004, 14 p.

Bucks, D. A., L. J. Erie, and O. F. French. 1974. Quantity and frequency of trickle irrigation for efficient cabbage production. Agron. J. 66(1):53-57.

Butterworth, B. 1978. Reel boom in Europe. Irrig. J. 28(1):27.

Carter, J. N., D. T. Westermann, and M. E. Jensen. 1976. Sugarbeet yield and quality affected by nitrogen fertilizer. Agron. J. 68: 49-55.

Carter, J. N., D. T. Westermann, M. E. Jensen, and S. M. Bosma. 1975. Predicting nitrogen fertilizer needs for sugarbeets from residual nitrate and mineralizable nitrogen. J. Am. Soc. Sugar Beet Technol. 18(3):232-244.

Clyma, W., and A. Ali. 1977. Traditional and improved irrigation practices in Pakistan. Am. Soc. Civ. Eng., Irrig. Drain. Div. Spec. Conf. Proc. 1:201-216.

Cutler, J. M., and D. W. Raine. 1977. Effects of irrigation history on responses of cotton to subsequent water stress. Crop. Sci. 17:329-335.

Dedrick, A. R., and L. J. Erie. 1977. Irrigating on the dead level. Agr. Res. 26(1):8-11.

Dedrick, A. R., and L. J. Erie. 1978. Automation of on-farm irrigation turnouts utilizing jack-gates. Am. Soc. Agr. Eng. Trans. 21(1):92-96.

Dedrick, A. R., J. A. Replogle, and L. J. Erie. 1978. On-farm level-basin irrigation-save water and energy. Civ. Eng., 48(1):60-65.

Duke, H. R., E. G. Kruse, S. R. Olsen, D. F. Champion, and D. C. Kincaid. 1976. Irrigation return flow water quality as affected by irrigation water management in the Grand Valley of Colorado. Final Rep. to Environ. Prot. Agency. U. S. Dep. Agr., Agr. Res. Serv., Fort Collins, CO.

Dvoskin, D. K., and E. O. Heady. 1976. Energy requirements of irrigated crops in the western United States. Misc. Rep., The Center for Agr. and Rural Develop., Iowa State Univ., Ames, 33 p.

Eisenhauer, D. E., and P. E. Fischbach. 1977. Comparing costs of conventional and improved irrigation systems. Irrig. Age 11(8):36-37.

Erie, L. J. 1968. Management: A key to irrigation efficiency. Proc. Am. Soc. Civ. Eng., J. Irrig. Drain. Div. 94(IR3):285-293.

Erie, L. J., and A. R. Dedrick. 1978. Automation of an open-ditch irrigation conveyance system using tile outlets. Am. Soc. Agr. Eng. Trans. 21(1):119-123.

FAO. 1977. Water for agriculture. Food and Agr. Organ. of the UN, UN Water Conf. Mar del Plata, Mar., 26 p.

Fischbach, P. E., and B. R. Somerhalder. 1971. Efficiencies of an automated surface irrigation with and without a runoff reuse system. Am. Soc. Agr. Eng. Trans. 14(4):717-719.

Fitzgerald, P. D., T. L. Knight, and C. G. Janson. 1977. Lucerne irrigation on light soils. N.Z. J. Exp. Agr. 5:23-27.

Furrow, The, (Can. Issue). 1978. Aerial infrared is working. 83(1): 27-28.

Grimes, D. W., and W. L. Dickens. 1977. Cotton responses to irrigation. Calif. Agr. 31(5):16-17.

Gulhati, N. D., and W. C. Smith. 1967. Irrigated agriculture: An historical review, p. 3-11. *In:* Irrigation of agricultural lands, R. M. Hagan et al. (Eds.). Am. Soc. Agron., Mono. 11, Madison.

Gustafson, C. D. 1977. Drip irrigation. Irrig. J. 27(3):37.

Hagood, M. A. 1964. Irrigation scheduling from evaporation reports. Wash. State Univ. Ext. Ser. Cir. No. 341.

Haise, H. R., and P. E. Fischbach. 1970. Auto-mechanization of pipe distribution systems. Nat. Irrig. Symp. Proc., Lincoln, Nebr., p. M1-M15.

Haise, H. R., E. G. Kruse, and N. A. Dimick. 1965. Pneumatic valves for automation of irrigation systems. U. S. Dep. Agr. ARS 41-104, 21 p.

Haise, H. R., E. G. Kruse, M. L. Payne, and L. J. Erie. 1970. Automated pipe-valves for surface irrigation. Am. Soc. Agr. Eng. Paper No. 70-745.

Haise, H. R. and F. G. Viets. 1957. Water requirements as influenced by fertilizer use. Int. Comm. Irrig. Drain. 3rd Congr. Proc. R25, Q8, 8.497-8.508.

Hanks, R. J., J. Keller, and J. W. Bauder. 1974. Line source sprinkler plot irrigation for continuous variable water and fertilizer studies on small areas. CUSUSWASH 211(d)-7, Utah State Univ., 13 p.

Heermann, D. F., and H. R. Duke. 1978. Electrical load and water management. Irrig. Assoc. Conf. Proc., Feb., p. 60-67.

Heermann, D. F., H. R. Haise, and R. H. Mickelson. 1976. Scheduling center pivot sprinkler irrigation systems for corn production in eastern Colorado. Am. Soc. Agr. Eng. Trans. 19(2):284-293.

Herkelrath, W. N., E. E. Miller, and W. R. Gardner. 1977a. Water uptake by plants: I. Divided root experiments. Soil Sci. Soc. Am. J. 41:1033-1038

Herkelrath, W. N., E. E. Miller, and W. R. Gardner. 1977b. Water uptake by plants: II. The root contact model. Soil Sci. Soc. Am. J. 41: 1039-1043.

Houston, C. E. 1977. Irrigation development in the World. p. 425-432. *In:* Arid land irrigation in developing countries: Environmental problems and effects. E. B. Worthington (Ed.), Pergamon Press, New York.

Huck, M. G., B. Klepper, and H. M. Taylor. 1970. Diurnal variations in root diameter. Plant Physiol. 45:529-530.

Humpherys, A. S. 1978. Improving farm irrigation systems by automation Int. Comm. Irrig. Drain., 10th Congr. Proc. R5, Q35, p. 35.89-35.98.

Humpherys, A. S., and R. L. Stacey. 1975. Automated valves for surface irrigation pipelines. Proc. Am. Soc. Civ. Eng., J. Irrig. Drain. Div. 101(IR2):95-109.

Idso, S. B., R. D. Jackson, and R. J. Reginato. 1977. Remote-sensing of crop yields. Science 196:19-25.

International Commission of Irrigation and Drainage. 1978. Standards for calculations of irrigation efficiency. Int. Comm. Irrig. Drain. Bull. 27(1):91-101.

Irrigation Journal. 1977. The 1977 irrigation survey. Irrig. J. 27(6): 19-26.

Israelsen, O. W. 1932. Irrigation principles and practices. John Wiley and Sons, Inc. (1st ed.), New York.

Israelsen, O. W. 1950. Irrigation principles and practices. John Wiley and Sons, Inc. (2nd ed.), New York. 405 p.

Israelsen, O. W., W. D. Criddle, D. K. Fuhriman, and V. E. Hansen. 1944. Water-application efficiencies in irrigation. Utah Agr. Exp. Sta.

Levine, G. 1977. Management components in irrigation system design and operation. Agr. Admin. 4(1):37-48.

Lord, J. M., Jr., and M. E. Jensen. 1975. Irrigation scheduling for optimum water management. Int. Comm. Irrig. Drain. 9th Congr., Q32.1, R46, p. 32.1.705-32.1.733.

Merriam, J. L. 1977. Level top canals for semi-automation of on-farm irrigation and supply systems. Am. Soc. Civ. Eng., Irrig. Drain. Div. Spec. Conf. Proc. 1:217-224.

Miller, D. E. 1977. Deficit high frequency irrigation of sugarbeets, wheat, and beans. Am. Soc. Civ. Eng., Irrig. Drain. Div. Spec. Conf. Proc. 1:269-282.

Murray, R. C., and E. C. Reeves. 1977. Estimated use of water in the United States in 1975. U. S. Geol. Surv. Circ. 765, 45 p.

Musick, J. T., D. W. Grimes, and G. M. Herron. 1963. Water management consumptive use, and nitrogen fertilization of irrigated winter wheat in western Kansas. U. S. Dep. Agr. Prod. Res. Rep. 75, 37 p.

Musick, J. T., L. L. New, and D. A. Dusek. 1976. Soil water depletion-yield relationships of irrigated sorghum, wheat and soybeans. Am. Soc. Agr. Eng. Trans. 19:489-493.

Musick, J. T., W. H. Sletten, and D. A. Dusek. 1971. Preseason irrigation of grain sorghum in the Southern High Plains. Am. Soc. Agr. Eng. Trans. 14(1):93-97.

Nix, H. A., and E. A. Fitzpatrick. 1969. An index of crop water stress related to wheat and grain sorghum yields. Agr. Meteorol. 6:321-337.

Pair, C. H. 1963. Effect of irrigation methods and systems management on water application efficiency. Int. Comm. Irrig. Drain., 5th Congr. Q16, R10, p. 16.146-16.159.

Rasmussen, W. W., J. A. Bondurant, and R. D. Berg. 1973. Multiset surface irrigation system. Int. Comm. Irrig. Drain. Bull. p. 48-52.

Rawlins, S. L. 1977. Uniform irrigation with a low-head bubbler system. Agr. Water Manage. 1:167-178.

Rosenthal, D. W., E. T. Kanemasu, R. J. Raney, and L. R. Stone. 1977. Evaluation of an evapotranspiration model for corn. Agron. J. 69: 461-464.

Schleicher, J. 1977. Ripple system cuts power costs for irrigation. Irrig. Age 12(1):29-32.

Schmugge, T., F. T. Ulaby, and E. G. Njoku. 1978. Microwave observa-

tions of soil moisture: Review and prognosis. Goddard Space Flt. Ctr. 28 p.

Shalhevet, J., A. Mantel, H. Bielorai, and D. Shimshi. 1976. Irrigation of field and orchard crops under semi-arid conditions. Int. Irrig. Inform. Ctr. Publ. No. 1, 115 p.

Shmueli, E. 1973. Efficient utilization of water in irrigation. p. 411-423. *In:* Arid zone irrigation, Yaron, Danfors, and Vaadia (Eds.), Springer-Verlag, New York.

Staple, W. J., and J. J. Lehane. 1954. Wheat yield and use of moisture on substations in southern Saskatchewan, Can. J. Agr. Sci. 34: 400-468.

Stewart, J. I., et al. 1977. Optimizing crop production through control of water and salinity levels in the soil. Utah Water Res. Lab., Logan, PRWG 151-1, 106 p.

Stewart, J. I., and R. M. Hagan. 1969. Development of evapotranspiration crop yield functions for managing limited water supplies. Int. Comm. Irrig. Drain. 7th Congr. Trans. Q23, R32, p. 23.505-23.530.

Stewart, J. I., R. M. Hagan, and W. O. Pruitt. 1973. Functions to predict optimal irrigation programs. Proc. Am. Soc. Civ. Eng., J. Irrig. Drain. Div. 100(IR2):179-199.

Stoker, R. 1978. Simple, efficient, automatic irrigation. Irrig. Age 12(6):76-77.

Stringham, G. E., and S. N. Hamad. 1975. Design of irrigation recovery systems. Proc. Am. Soc. Civ. Eng., J. Irrig. Drain. Div. 101(IR): 209-219.

Sylvester, R. O., and R. W. Seabloom, Jr. 1963. Quality and significance of irrigation flow. Proc. Am. Soc. Civ. Eng., J. Irrig. Drain. Div. 89(IR3):1-28.

Thomas, J. R., L. N. Namken, and R. G. Brown. 1970. Yield of cabbage in relation to nitrogen and water supply. J. Am. Soc. Hort. Sci. 95(6):732-735.

Thompson, T. L., and P. Fischbach. 1977. Irrigation scheduling saves time and money. Univ. Neb., Farm, Ranch and Home Qtrly, Spring.

Trava, J., D. F. Heermann, and J. W. Labadie. 1977. Optimal on-farm allocation of irrigation water. Am. Soc. Agr. Eng. Trans. 20(1): 85-88, 95.

Tscheschke, P., J. R. Gilley, T. Thompson, and P. Fischbach. 1978. IRRIGATE - A scheduling model. Agr. Eng. 59(1):45-46.

U. S. Bureau of Reclamation. 1971. Use of water on federal irrigation

Bull. 311, 55 p.

Jensen, M. C., J. E. Middleton, and W. O. Pruitt. 1961. Scheduling irrigation from pan evaporation. Wash. Agr. Exp. Stn. Circ. 386, 14 p.

Jensen, M. E. 1969. Scheduling irrigations with computers. J. Soil Water Conserv. 24:193-195.

Jensen, M. E. 1972. Programming irrigation for greater efficiency, p. 113-162. *In:* Optimizing the soil physical environment toward greater crop yields, D. Hillel (Ed.), Academic Press, New York.

Jensen, M. E. (Ed.). 1974. Consumptive use of water and irrigation water requirements. Rep. Tech. Com. on Irrig. Water Requirements, Am. Soc. Civ. Eng., Irrig. Drain. Div., 215 p.

Jensen, M. E. 1975. Scientific irrigation scheduling for salinity control of irrigation return flows. Environ. Prot. Agency Rep. (Technol. Ser.), EPA-600/2-75-064, 92 p.

Jensen, M. E. 1977a. Scientific irrigation scheduling for salinity control of irrigation return flow. Environ. Prot. Agency Nat. Conf. Irrig. Return Flow Qual. Manage. Proc., p. 133-139.

Jensen, M. E. 1977b. Water conservation and irrigation systems. Climate-Technology Seminar Proc., Columbia, MO, Oct. 25-26, p. 208-250.

Jensen, M. E., and O. W. Howe. 1965. Performance and design of border checks on a sandy soil. Am. Soc. Agr. Eng. Trans. 8:141-145.

Jensen, M. E., and J. T. Musick. 1960. The effect of irrigation treatments on evapotranspiration and production of sorghum and wheat in the southern Great Plains. Int. Soil Sci. Soc. 7th Congr. Trans. Vol. I, p. 386-393.

Jensen, M. E., D. C. N. Robb, and C. E. Franzoy. 1970. Scheduling irrigations using climate-crop-soil data. Proc. Am. Soc. Civ. Eng., J. Irrig. Drain. Div. 96(IR1):25-38.

Jensen, M. E., L. Swarner, and J. T. Phelan. 1967. Improving irrigation efficiencies, p. 1120-1142. *In:* Irrigation of agricultural lands. R. M. Hagan et al. (Eds.), Agron. Mono. 11, Madison.

Jensen, M. E., and W. H. Sletten. 1965a. Evapotranspiration and soil moisture fertilizer interrelations with irrigated winter wheat in the Southern High Plains. U. S. Dep. Agr., Agr. Res. Serv. Conserv. Res. Rep. 4, 26 p.

Jensen, M. E. and W. H. Sletten. 1965b. Evapotranspiration and soil moisture fertilizer interrelations with irrigated grain sorghum in the southern high plains. U. S. Dep. Agr., Agr. Res. Serv.,

Conserv. Res. Rep. 5, 27 p.

Jensen, M. E., and J. L. Wright. 1978. The role of evapotranspiration models in irrigation scheduling. Am. Soc. Agr. Eng. Trans. 21(1): 82-87.

Jensen, M. E., J. L. Wright, and B. J. Pratt. 1971. Estimating soil moisture depletion from climate, crop and soil data. Am. Soc. Agr. Eng. Trans. 14(5):954-959.

Kanemasu, E. T., J. J. Heilman, J. O. Bagley, and W. L. Power. 1977. Using Landsat data to estimate evapotranspiration of wheat. Environ. Manage. 1:515-520.

Kanemasu, E. T., V. P. Rasmussen, and J. O. Bagley. 1978. Estimating water requirements for corn with a "pocket" calculator. Kan. Agr. Exp. Stn. Bull. 615, 24 p.

Kanemasu, E. T., L. R. Stone, and W. L. Power. 1976. Evapotranspiration model tested for soybean and sorghum. Agron. J. 68:569-572.

Katopodes, N. D., and T. Strelkoff. 1977a. Hydrodynamics of border irrigation--A complete model. Proc. Am. Soc. Civ. Eng., J. Irrig. Drain. Div. 103(IR3):309-324.

Katopodes, N. D., and T. Strelkoff. 1977b. Dimensionless solutions of border irrigation advance. Proc. Am. Soc. Civ. Eng., J. Irrig. Drain. Div. 103(IR4):401-417.

Kerbs, L., 1978. Special Report: Results on comparison studies of fertilizer recommendations. The Sugarbeet, No. 89:8-11.

Kincaid, D. C. and D. F. Heermann. 1974. Scheduling irrigations using a programmable calculator. U. S. Dep. Agr., Agr. Res. Serv. Publ. ARS-NC-12, 55p.

Kohl, R. A., and J. J. Kolar. 1976. Soil water uptake by alfalfa. Agron. J. 68:356-358.

Kolar, J. J., and R. A. Kohl. 1976. Irrigating alfalfa for seed production. Univ. Ida. Current Inform. Ser. 357, 3 p.

Krogman, K. K., and E. H. Hobbs. 1977. Irrigation management of alfalfa for seed. Can. J. Plant Sci. 57:891-896.

Kruse, E. G., and D. F. Heermann. 1977. Implications of irrigation system efficiencies. J. Soil and Water Conserv. 32(6):265-270.

Larsen, D. C. 1978. Scheduling is best irrigation tool. Idaho Farmer-Stockman 96(6):68-71.

Leggett, G. E. 1959. Relationships between wheat yield, available moisture, and available nitrogen in eastern Washington dry land areas. Wash. Agr. Exp. Stn. Bull. 609, 16 p.

projects, Minidoka Project, North Side Pumping Division, Unit A. Crop and Irrigation Data, 1964-1968, Vol. 1, Summ. Rep., 154 p.

U. S. Bureau of Reclamation. 1973. Use of water on federal irrigation projects, Columbia Basin Project, Washington, Crop and Irrigation Data, 1970-1972, Summ. Rep., 85 p.

USSR National Committee, ICID. 1977. Land reclamation for enhancement of agricultural production in the USSR. Int. Comm. Irrig. Drain., Spec. Sess. Proc., Tehran, Rep. 15, p. 203-209.

Vaadia Y., and Y. Waisel. 1967. Physiological processes as affected by water balance. p. 354-372. *In:* Irrigation of agricultural lands. R. M. Hagan et al. (Eds.), Agron. Mono. 11., Madison.

Viets, F. G., Jr. 1962. Fertilizers and efficient use of waste. Adv. Agron. 14:223-264.

White, G. 1977. The main effects and problems of irrigation. p. 1-72. *In:* Arid land irrigation in developing countries: Environmental problems and effects. E. B. Worthington (Ed.), Pergamon Press, New York.

Wilcox, J. C., and W. K. Sly. 1974. A weather-based irrigation scheduling procedure. Canada Dep. Agr. Tech. Bull. 83, 23 p.

Willardson, L. S. 1972. Attainable irrigation efficiencies. Proc. Am. Soc. Civ. Eng., J. Irrig. Drain. Div. 98(IR2):177-246.

Woodruff, C. M. 1968. Irrigating corn on claypan soils in Missouri. Univ. MO UMC Guide 4137, 6 p.

Woodruff, C. M., M. R. Peterson, D. H. Schnarre, and C. F. Cromwell. 1972. Irrigation scheduling with planned soil moisture depletion. Paper No. 72-772, Am. Soc. Agr. Eng., 9 p.

Worstell, R. V. 1976. An experimental buried multiset irrigation system. Am. Soc. Agr. Eng. Trans. 19:1122-1128.

Worthington, E. B. (Ed.) 1977. Arid land irrigation in developing countries: Environmental problems and effects. Pergamon Press, New York, 463 p.