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Irrigation Scheduling Research And Its Impact on Water Use

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ABSTRACT

Future demands on the world's limited water resources and the demands to adequately feed and clothe an expanding population require that irrigation efficiency and crop productivity from irrigated lands improve. Irrigation scheduling is an important element in improving water use efficiency. Several new plant and soil water sensor technologies have direct implications for improving irrigation management. Irrigation scheduling research priorities are recommended to focus on evapotranspiration (ET) estimation methods, on improved understanding of spatial variation of ET and irrigation applications, on identifying the water balance components in typical irrigated agriculture, on integrating various sensing technologies into irrigation scheduling models and controls, on new and improved sensor technology, and on integrating water quality constraints into irrigation scheduling and control. Technology transfer of irrigation scheduling information to producers needs to consider producers' behavior and their actual on-farm needs.

Keywords: Drainage, Evaporation, Irrigation control/automation, Plant water status, Models, Runoff, Soil water, Transpiration

INTRODUCTION

Irrigation scheduling was defined by Jensen (1981) as *a planning and decision-making activity that the farm manager or operator of an irrigated farm is involved in before and during most of the growing season for each crop that is grown*. This basic definition remains the typical view of irrigation scheduling today. He further indicated four types of data needed for irrigation decision making:

- 1) *current level and expected change in available soil water for each field over the next 5 to 10 days;*

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- 2) *current estimates of the probable latest date of the next irrigation on each field to avoid adverse effects of plant water stress; and the earliest date that the next irrigation can be given to permit efficient irrigation with existing system;*
- 3) *the amount of water that should be applied to each field, if the irrigator is able to control or measure that amount, which will achieve high irrigation efficiency and the targeted soil water level; and*
- 4) *some indication of the adverse effects of irrigating a few days early or late, of applying too little or too much water, or perhaps terminating the irrigations for the season.*

Other information or data needed to supplement the above are water costs, water supply capacity, soil salinity levels, agronomic or field management schedules, etc. A perusal of ASAE irrigation scheduling and evapotranspiration conference proceedings from 1966 through this one demonstrates both the breadth of technology adapted to irrigation scheduling and the emphasis on understanding the many interrelationships and complexities affecting crop water. But most emphasis has been placed on field soil water status and earliest and latest irrigation dates (items #1 and #2) and sometimes the adverse effects of early or postponed irrigation are considered (item #4). However, the efficient irrigation depth to apply (item #3) is often not considered to be an irrigation scheduling decision but rather part of irrigation system design and operation. Neglect of the importance of this irrigation amount *window* (range in the efficient application amounts or item #3) can lead to problems or failures in irrigation scheduling and control systems.

Since the early use of computers in modern scientific irrigation management (Jensen, 1969; Jensen et al., 1970 & 1971) and now with the myriad of ways available to measure many differing soil-water-plant-atmosphere parameters (Hanks and Brown, 1987; and Phene et al., 1990), most of us have not fully utilized all the elements of this possible information to guide our irrigation decision making nor have many individuals developed the expertise and competency with this diverse range of instrumentation. Often, reliance is placed on only one system (such as a soil water balance model, soil water tension, soil water content, leaf water potential, canopy temperature, etc.) with little feedback on the range of other state variables in the soil-water-crop-atmosphere continuum. Irrigation scheduling, as outlined above, requires an extensive information gathering system, data integration scheme, and a means to successfully implement the irrigation management plan (Fig. 1). Irrigation scheduling itself is simply determining when and how much water to apply to meet a specified management objective. Yet the implementation of irrigation scheduling information into an operational irrigation plan is far more entailed than the above statement because many outside factors (labor, harvesting, crop culture, system maintenance, etc.) must be considered as well.

I want to focus this paper on the state of the on-farm irrigation scheduling knowledge and where we have come in the past 25 years or so, and then to discuss the impact that irrigation scheduling can have on irrigation water use. Then, I will emphasize some areas to consider for future research and technology transfer of irrigation scheduling information.

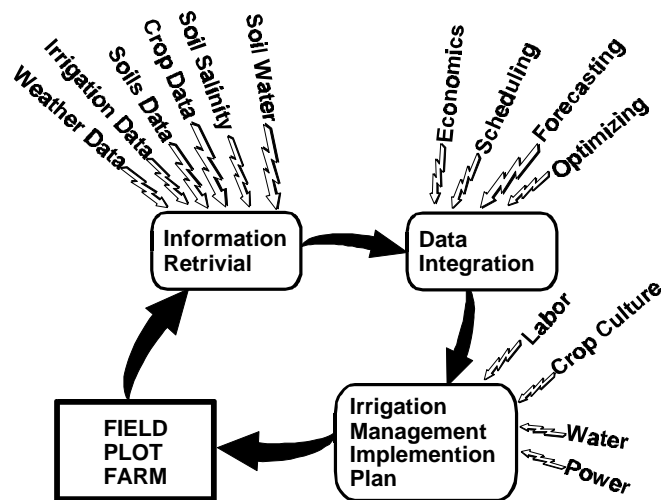


Figure 1. Irrigation Management Cycle.

STATE OF KNOWLEDGE

Although much information on irrigation scheduling has been published in the past 25 years, few new fundamental theories to enhance our understanding of water management have been presented. In fact, the diversity of information types and quality now available may lead to greater confusion rather than greater understanding unless advanced training or diverse experience enables one to discern minor, but important, differences in data. But in 1996, especially where I work the Texas High Plains water conservation and irrigation management have never held more promise or preeminence in common everyday lives.

Weather Data and Reference Evapotranspiration (ET)

Weather station networks, like CIMIS (Snyder, 1983) in California and many others including new ones like the Oklahoma Mesonet (Brock et al., 1995) provide direct information that can be used by media outlets (print, audio, and visual) which reach a broad grower network. Unfortunately, understanding and assimilating this information and formulating implementation strategies to actually use the data remain major challenges to scientists, extension specialists, action agency personnel, and consultants.

ET_p information [potential evapotranspiration; the ET_p terminology has largely been replaced by ET_r for reference evapotranspiration] was routinely broadcast on radio and television stations and published in the newspaper several years ago in California (and I m sure many other local media markets). Even now in the Texas High Plains, a region with not nearly enough water to make many choices about what to do with it, we have radio and television broadcasts and newspaper columns about PET [potential evapotranspiration] and grass lawn water use estimates. ASAE spearheaded efforts a few years ago to provide grass (lawn) evapotranspiration (ET) values for urban irrigation scheduling on The Weather Channel® for national broadcasts (Hoffman, 1994).

We can install an automated weather station, collect data, and be computing ET in a relatively short time (depending mainly on equipment delivery). Twenty-five years ago, it was a major task to compute what we call reference ET (ET_r) today (i.e., Kincaid and Heermann, 1974). Weather station siting remains critical to acquiring high quality, representative data for computing ET (Brown and Ley, 1993; Allen and Pruitt, 1986), and data verification methods and algorithms (see Allen, 1996; Meek and Hatfield, 1994) have improved substantially. Weather instruments must be maintained properly because erroneous data are difficult to detect even with good data screening techniques. Data measurement bias (either high or low) due to instrument calibrations are more difficult to detect and are more serious than random errors.

Despite almost 15 years of fairly robust and simple automated weather station use, little has been accomplished to standardize measurements, station siting, programming, data processing, or data quality checking (Ley et al., 1994) despite repeated attempts by many groups. We know that it is best to site a station far from vertical obstructions, over irrigated grass whenever possible, and in an area of adequate fetch, although how much fetch is still debated (Allen, 1996).

We know that solar radiation, air temperature, relative humidity, and wind speed data along with rainfall should be reported for daily periods, and hourly data are now preferred. But this knowledge has existed for almost 50 years (Penman, 1948). Van Bavel (1966) pointed out 30 years ago out that the combination equation was better suited to instantaneous data (hourly or shorter periods) than for daily averaged data.

Since the 1980s (Burman et al., 1980), the preferred terminology is reference ET rather than potential ET. ASCE Manual No. 70 (Jensen et al., 1990) provides one of the best systematic discussions of ET and presents standardized methods for computing ET_r for common reference crops of grass and alfalfa according to Allen et al. (1989). A complete description of methods to standardize the computation of grass reference ET is given by Allen et al. (1994b). However, the theory on which the best and most robust ET calculations rests the Penman-Monteith equation (Monteith, 1965) was published 30 years ago, and more often it is simply adapted rather than rigorously evaluated. However, the Penman-Monteith equation has been generally the most stable form of the Penman combination ET equation used around the world.

Major advances have occurred in measuring, calculating, and estimating ET using various methods. ET measurement should never be confused with ET calculation however. Only lysimeters and eddy correlation methods actually measure ET while the other methods estimate ET as a residual term. Although not the central focus of my paper, these advances in using eddy correlation systems, Bowen ratio energy balance systems, sap flow gauges to actually measure plant transpiration, and time domain reflectometry (TDR) systems along with neutron probes to accurately determine the soil water balance have all, except the neutron probe, become commercially available and far more reliable in the past quarter century. These advances have had a major impact on quality, availability, and costs for collecting the data for irrigation scheduling models.

Water Balance Modeling

Evapotranspiration calculated using water balance models provided the first computer applications for irrigation scheduling. Although many types of irrigation scheduling models are available (see Heermann, 1985; Heermann et al., 1990; Hill, 1991; Martin et al., 1990), many have features similar to the one described by Harrington and Heermann (1981) that compute ET as:

$$ET = K_c ET_r \quad (1)$$

$$K_c = (K_{cb} K_w) + K_s \quad (2)$$

and where the soil water balance between two dates (I-1 and I) is defined as

$$SW_i = SW_{(i-1)} - (ET + DP) + (IRR_n + P_n) \quad (3)$$

where ET is in mm, K_c is the crop coefficient, ET_r is the in mm, K_{cb} is the basal crop coefficient (Wright, 1982), K_w is a water deficit parameter (depends on SW), K_s is a soil wetness coefficient (depends on IRR_n and P_n), SW is soil water in mm, DP is deep percolation in mm beneath the root zone (essentially depends on SW; note DP can be negative when ground water uptake occurs), IRR_n is net irrigation in mm (*net* implies gross application less any field runoff and interception by canopy or residue covers), and P_n is net rainfall in mm (*net* implies gross received less any runoff and interception by canopy or residue covers). This water balance is one dimensional, and ET_r is generally computed with a Penman combination equation or a Penman-Monteith equation (Allen et al., 1989). K_{cb} is defined by ET from a crop with a dry soil surface (one or more days after irrigation or rain depending on soil type) yet fully supplied with water. SW must be computed over some root zone or soil profile depth. Several methods can be used to forecast ET based either on long-term climate data or extrapolations of current ET rates (Heermann et al., 1990).

Crop growth models calculate ET using methods similar to those outlined above, but often compute soil water evaporation (E) and crop transpiration (T) separately (Ritchie, 1972) for daily periods using leaf area index (LAI) to partition ET in the T and E components. Hanks (1991) demonstrated the development of K_c values based on more detailed crop water-use models. Crop growth models simulate the crop biomass and phenological developments along with its water use (Jones and Ritchie, 1991), hence they have daily LAI values available for computing daily E and T. Although some rather significant differences exist in the simpler K_c and the crop growth model approaches to estimating ET, essentially both are based on similar fundamental methodologies. One main difference is the time scaling of K_c values versus the more dynamic E and T procedures in the crop growth models based on LAI. LAI in many crop growth models is based on leaf expansion rates mainly derived from thermal units based on air temperatures (Ritchie and Johnson, 1990). Most K_c values are scaled by percent of time to full cover and then days after full cover, percent of total growing season length (days), polynomial equations based on time (either per cent or days), or growing degree days (GDDs). K_c values based on GDD scaling remove some seasonal environmental effects on crop development when compared with K_c values based solely on time or percent of normal growing season length (Amos et al., 1989). Since most crop growth models essentially utilize the GDD concept in crop development, K_c values based on the GDD approach become similar to crop growth model dynamics based on the individual growing season environment. Another difference between the simpler K_c and crop model approach is the computation of K_w . Many crop growth models consider irrigation as a water balance input, but few models utilize realistic irrigation constraints (like irrigation capacity or irrigation delivery schedules). In addition, many crop growth models simply consider irrigations as extra rainfall without considering the unique application differences for different forms of irrigation.

Both of these types of water balance models (irrigation scheduling and crop growth) are well suited for irrigation scheduling since they provide a daily accounting of water and can project several days forward to determine the earliest date to irrigate so the available soil water storage can efficiently store the irrigation amount and the latest date that an irrigation can be applied and still avoid crop-water shortages. Of course, since these models are single point water balance estimates, several model sets must be run simultaneously to simulate the field conditions of the leading and trailing irrigation sets (i.e. the starting and stopping points on a pivot or the first and last surface set for furrow irrigation) (Martin et al., 1990; Hill, 1991; Heermann et al., 1990). The next irrigation date forecast can consider rainfall probabilities as well as anticipate larger ET rates as the crop develops. However, irrigation scheduling using either ET or crop growth models in very coarse soils where the available water holding capacity in the root zone is low, and therefore irrigations must be applied frequently, are less useful than direct soil or plant measurements. Nevertheless, even in these cases, models can show longer-term trends not immediately apparent from manually observed parameters (soil or plant water status). Equally important to tactical decisions within a season, ET and crop growth models can be used to study longer-term situations (Hill, 1991) to fine-tune irrigation management strategies and to examine alternate economic scenarios. Both ET models and crop growth models are typically one dimensional so they don't consider the two-dimensional nature of irrigation and rainfall spatial variability, which can be more easily examined directly using either soil or plant water status observations.

Soil Water Status

We can measure soil water status (content and potential) and even salinity levels at points in fields using electronic sensors which can be utilized with automated data acquisition methods and integrated into irrigation control systems. Soil water measurement methods have been widely reviewed (see Holmes et al., 1967; Haise and Hagan, 1967; Campbell and Mulla, 1990; Campbell and Campbell, 1982; Gardner, 1986; Schmutge et al., 1980; Stafford, 1988; and Phene et al., 1990). Four methods dominate irrigation management gravimetric sampling, neutron scattering, electrical resistance/capacitance, and soil water pressure (tensiometers). Gravimetric sampling and the feel method remain the soil-water-measurement methods most widely used by growers and consultants. Neutron scattering has remained mainly a research tool but has found some use by action agencies and consultants (Gear et al., 1977) for irrigation management. Electrical resistance/granular matrix type sensors have remained one of the least expensive soil water measurement technologies applicable to producer use (Eldredge et al., 1993; and Thompson and Armstrong, 1987). These and other types of soil water sensors have wide application for irrigation scheduling and have been used successfully in automated control systems (see Youngner et al., 1981; Phene et al., 1989; and Phene and Howell, 1984; for a few examples). Time domain reflectometry (TDR) (Topp et al., 1980) provides a portable means to measure soil water contents and bulk electrical conductivity. Topp and Davis (1985) discuss the application of TDR to irrigation management and even present an idea for using TDR to control irrigation; however, TDR remains expensive, making it mainly suitable for research or use by trained consultants. Soil water measurements are useful for verifying ET models and for triggering or halting irrigations, but they are not extremely useful in forecasting the near future need for irrigation. The scheduler or controller must activate the irrigation based on the current soil water state, so this activation point or control level must permit irrigation in time to avoid yield affecting water deficits. Soil water sensors are effective in triggering demand irrigations or over-riding pre-set irrigations (i.e. when the soil may be sufficiently wet from prior irrigations and/or recent rains).

Soil water measurements are necessary for feedback information on irrigation scheduling based on ET. Since practically all models are unreliable in predicting many water balance components (and some components may even be ignored), it is desirable that field samples or measurements of soil water be periodically acquired to adjust model output for irrigation application and rainfall infiltration differences. Soil water sensor measurements made near the bottom of the root zone can be useful in indicating when irrigations are resulting in excessive deep percolation above salinity management requirements.

Plant Water Status

Plant water status has remained one of the more difficult parameters to measure electronically. Phene et al. (1990) describes many of the more widely used plant water status measurements. Sap flow measurements of transpiration using both steady state heat flux (Sakuratani, 1981 and Baker and van Bavel, 1987) or heat-pulse technology (Cohen et al., 1981) remain a promising method for automating irrigation control based on direct physical plant measurements. Yet, many problems such as sampling, range of instruments needed for a complete crop season (differing stem sizes), or sensor movement from plant to plant, besides the physical problems of instrumentation, remain to make sap flow gauges mainly useful for research at this time. In the 1980s, widespread optimism developed with a new technology to remotely sense crop (or plant) temperature (Jackson et al., 1980). Infrared thermometers (IRTs) became

commercially available that were portable, stable in a wide range of ambient temperatures, and easy to use. These devices and their use in detecting crop water deficits were widely studied in the 1980s and 1990s. Yet, precise measurement of crop temperature by itself was not useful without supplementary environmental data rendering the technique difficult to apply from satellites as originally envisioned. But simple crop temperature measurements using IRTs with some reliance on environmental data for irrigation control (Wanjura et al., 1995) can be used directly in control methods. Measurements of plant water status often do not provide sufficient lead time to schedule irrigations while avoiding yield-affecting crop water deficits and often do not respond quick enough to terminate irrigations.

Direct measures of plant water status can be used like soil water measurements in conjunction with ET models to provide feedback data on crop water deficits. They can also be particularly useful in irrigation scheduling where salinity in the ground water may cause sudden crop water deficits despite having near adequate root zone soil water amounts. However, crop water measurements are more useful in the drier range where crop water deficits begin to reduce yield than in the wetter range where over-irrigation cause excessive DP. They can also be useful in locating parts of a field that may be suffering from water shortages caused by irrigation operation or by soil differences.

Irrigation Control/Automation

Automated control of irrigation requires the use of either soil, crop, or environmental sensors to determine the need for irrigation (see Youngner et al., 1981; Phene et al., 1990; Zazueta and Smajstrala, 1992; Singh et al., 1995; or Wanjura et al., 1995 for some examples) and then either a logic-type controller or a computer to control the irrigation sequence. The controller may need to use various control modules to properly manage the irrigation system. These control modules might measure pressure and/or flow or other parameters at selected points and control pumps, filters, chemical injectors, etc. (Duke et al., 1990). It is important for controllers to have fall-back or safety shut down modes as well. Most control systems are designed for unattended operation with periodic operator intervention. Irrigation control using soil or plant water sensors suffers from sensor location and field placement limitations.

Irrigation management automation can reduce peak electric loads (Stetson et al., 1975) in addition to just making irrigation decisions. Since in many areas power costs are the main costs for irrigation, they represent one way to impact irrigation costs directly. Duke et al. (1984), Buchleiter et al. (1984), and Heermann et al. (1984) described an integrated center pivot control system that utilized radio communication between pivots, pumps, and the controller to reduce energy and water use. The system was evaluated for three years (Buchleiter and Heermann, 1986) on a farm in north central Oregon with over 4,000 ha and 15 center pivots with four pumping stations. It was effective in controlling irrigations, pivots, and pumps to the satisfaction of the producer. They reported that for two years of the three-year test the producer participated in a load control program and received a 14% reduction in power cost and had an annual savings of \$1,000.

IMPACT OF WATER MANAGEMENT ON WATER USE

Irrigation management, by its very definition, must affect or control water use as it relates to irrigation. However, direct comparisons of management systems are seldom without bias. One of the most critical biases can occur when selecting the base for comparison. Typically, the base

may be a historical one determined by the past use of water on a particular farm, field, or larger scale entity (district, basin, etc.) or one that is deemed the standard for a concurrent (side-by-side) comparison. It remains challenging to determine influences from annual and longer term climatic influences on water use and to separate or account for them in the historical base water use. The concurrent trial method compares some improved water management system with another standard water management system which is judged to be a fair level of comparison. Seldom do many studies use similar standards since these are locally dependent on crop and soil conditions. Since the application of irrigation management technology is an education and extension activity, it is also difficult to isolate the grower from knowing or seeing what the trial method may be doing. Often these observations can confuse and bias any comparisons. Although irrigation management comparisons can be made for a wide range of systems, it is often difficult to separate management decision effects from those of actual irrigation system operation decisions that affect uniformity and application efficiency. Common irrigation scheduling comparisons involve crop yield and/or economics as well. It is important to recognize that yield is influenced by many factors besides irrigation management.

Sources of Water Savings

Irrigation scheduling can reduce irrigation water use only by reducing runoff from either irrigation or rainfall, by decreasing percolation of water beneath the root zone in excess of any required leaching for salinity management, by reducing soil water evaporation after an irrigation, or by controlling soil water depletion in a manner that reduces ET during known non-sensitive crop growth stages. In some cases, irrigation scheduling may actually increase irrigation water use, while concurrently increasing crop yield by avoiding critical soil water deficits that reduce crop yield or by supplying both water and nutrients needed by the crop at a more optimum time for the particular crop. Essentially, these savings or increases in water use can be examined in terms of the water balance presented by Eq. (3). In fact, it is more illustrative to separate ET into its components and express the seasonal irrigation requirement as follows:

$$IRR_g = \frac{SW_{ps} - SW_{ph} + E + T - P_n}{IRR_e} + L \quad (4)$$

where IRR_g is gross irrigation amount in mm, SW_{ps} is pre-season soil water in mm (i.e. before any pre-plant irrigations), SW_{ph} is post-harvest soil water in mm, P_n here is the growing season effective net precipitation in mm, IRR_e is the mean application efficiency (fraction), and L represents deep percolation required for salinity management in mm (i.e. L includes any DP from irrigation and/or rainfall). Equation 4 illustrates areas where water savings can occur. Obviously, IRR_e must high in order to minimize IRR_g ; however, IRR_e will vary considerably from irrigation to irrigation and is highly dependent on the irrigation method. Irrigation scheduling attempts to maintain SW above some critical level, below which yields may be decreased, and below some threshold level, above which rainfall capture is reduced by increased runoff (maximizing storage for P_n) or above which DP is increased (above that necessary for salinity management) such that $SW_t \geq SW \geq SW_c$ where SW_t and SW_c are the threshold and critical soil water depletion levels. The allowable soil water depletion ($SW_t - SW_c$) is called *management allowed depletion* (MAD) and is a function of soil type and crop. The MAD concept requires that MAD be considerably larger than the maximum daily ET rate. In areas with coarse soils and limited root zone water holding capacity, the MAD concept is not extremely useful. The goal of irrigation scheduling and irrigation management is usually to maximize T , since T is so closely

associated with dry matter production and thereby economic yield, subject to water supply and other economic constraints. If T is maximized subject to the water supply and economic constraints, then it is likely that water use efficiency (yield per unit ET or yield per unit T) will also be near maximum too. It is common for yield per unit T (or ET) to remain nearly constant for a wide range of T; i.e. yield is nearly proportional to T (or ET).

Irrigation scheduling cannot achieve significant water savings by reducing T without reducing yield and thereby, perhaps, reducing profit too. Irrigation scheduling effects on water savings by reducing E are less straight forward. E can be reduced by extending periods between soil wetting. However, in humid and sub-humid climates and even in many semi-arid climates this dry period length is often determined by rainfall more than irrigation interval. Since rainfall can't be controlled and neither can it be forecast very accurately, it remains difficult to see where substantial savings can be made in E simply by scheduling alone (application methods may be a larger factor on E). Perhaps in more arid areas with Mediterranean type climates (low summer rainfall), irrigation scheduling (irrigation frequency and irrigation application depth) might affect E more consistently. E can be minimized by increasing the maximum irrigation interval constrained by the maximum efficient application amount and by the irrigation capacity. It is obvious that irrigation delivery schedules that are too frequent or rigidly constrained (e.g. fixed rotations) can result in inefficient use of water. Small savings in water may be possible by staggering the irrigations in slightly uneven day periods (12-h offsets) so that the same area of the field is not irrigated at exactly the same time of day on each irrigation cycle. This is more common with center pivots where rotations are set for a time period not evenly divisible by 24 h.

Any significant savings in water must come from maximizing P_n while reducing DP to only that necessary for leaching. The importance of P capture and DP reduction will depend on the specific hydrology of the site. In the Great Plains, P is highly erratic and unpredictable, but P can be a substantial component of total T while DP is of less concern in many cases. So, in this region, irrigation scheduling attempts to maximize P_n to achieve a high T, amount while reducing IRR_g . In more arid climates, DP becomes the over-riding parameter because P is relatively minor. In sub-humid and humid climates, both P_n and DP are more important for irrigation management decisions. As water quality issues become increasingly important constraints, both DP and runoff must be recognized and managed to avoid agro-chemical, sediment, and nutrient transport from the field to any water body (either ground water or surface water).

RECOMMENDATIONS FOR FUTURE RESEARCH

Before anyone considers new extensive irrigation management or irrigation scheduling research, the article by Marvin Shearer and James Vomocil (Shearer and Vomocil, 1981) should be required reading. They stated, *behavioral patterns and value judgements of growers may have been the dominant cause for lack of sustained adoption of modern irrigation scheduling*, as they surveyed educational efforts at technology transfer in irrigation scheduling in Oregon over a 25-year period. They recommend that successful (long-term and self-sustaining) technology transfer must consider the human behavior aspects since the behavioral patterns and attitudes of people were more important than having convenient, accurate, or reliable irrigation scheduling methods. World-wide irrigation expansion has slowed considerably (Higgins et al., 1988), and in the U.S., trends are for decreased number of irrigated farms and irrigated area (Franklin and Narayanan, 1988). Conversion from less efficient to more efficient systems does not always result in decreased water consumption (Vaux et al., 1990). Van Schilfgaarde (1990) restated the question

of sustainability of irrigated agriculture as *Do we want to maintain irrigation agriculture indefinitely?* He prodded the research community to supply the *facts in a comprehensible form* so political decisions could be made using *facts and the perception of facts*. Irrigation management and irrigation scheduling research can provide facts to guide both the U.S. and the world into better use of limited and declining irrigation water and land resources. Pereira et al. (1996) proposed a research agenda for the sustainability of irrigated agriculture based on a North Atlantic Treaty Organization (NATO) workshop conducted in 1994. Interestingly, irrigation scheduling and irrigation management were each mentioned only once in a list of 62 research topics although several topics implied connections to both. Clothier (1989) identified six areas of current irrigation science and two understudied areas. Most of his identified research topics relate to irrigation scheduling.

My outline for research needs is biased towards the world I work in and around. Acknowledging this bias, I offer the following areas for fruitful irrigation scheduling research and for technology transfer (list is not in any order of priority):

ET Estimation

Although much research has been conducted on crop water use, considerable gaps in knowledge still exist. Many of these were outlined by others in prior ASAE ET conferences and this one, and they still remain challenges for practitioners today. The diversity of measurements methods and computation methods for various parameters need standardization; however, I am firmly convinced this will never occur! However, I recommend that ET_r methods be compared with the ASCE methods (Penman-Monteith) whenever possible. Allen et al. (1994b) laid out a complete guide for using this standard ET_r method. Although, alfalfa ET_r is widely used in the U.S. and around the world, grass ET_r (Allen et al., 1994a) has an important advantage of providing urban clientele useful information too, with the disadvantage of having peak K_c values above 1.0 for many crops. Grass and alfalfa ET_r comparisons seem appropriate in a few locations to permit greater K_c cross use from previously published values.

Spatial Aspects of ET and Irrigation

Most ET theories apply to uniform landscape forms that differ greatly from many irrigated sites with mixed crops, variable soils, known spatial weather patterns, and fields that are in various states of irrigation. Existing theories of the boundary layer need to be examined in light of spatial patterns of crop development and yield across irrigated fields. Irrigation systems apply water nonuniformly to a crop due to hydraulics, environment (wind in the case of sprinklers and diurnal evaporation differences), and soil properties. Advanced irrigation application systems may have the capability to apply water and agrochemicals at precisely controlled spots and rates, but do we know the correct spatial needs for water? Realistic and accurate two- and three-dimensional crop growth and water-use models are needed to address these advanced questions. In addition, few data bases for spatially variations of crop yields from irrigated fields are known to currently exist.

Irrigation Water Balance

Most irrigation scheduling research has been conducted under controlled and regulated circumstances that don't always match real-world constraints. Although off-station and demonstration-type applied research is difficult, it seems apparent that fluxes of water and nutrients for irrigated agriculture need to be determined across a much wider spectrum than has been studied. Seasonal values for selected important crops—perhaps the list might begin with cotton, wheat, corn, rice, and alfalfa—for the various water flux components in the various regions in the U.S. and world would be interesting. Certainly, this data base has many uses related to many important water quality issues as well.

Integrated Irrigation Scheduling and Feedback Control

Too often we have used one method to schedule irrigations and have not utilized multiple information resources. Irrigation scheduling needs to integrate several sources of state variable information and formulate more robust recommendations. Many information systems exist now to use this broader flow of data to both make decisions and to control or automate irrigation systems. Few integrated irrigation scheduling systems have used redundancy in feedback information (more than one type of feedback sensor).

Sensor and Information Technology

Major advances have been made in making and automating environmental measurements that are critical for irrigation scheduling. Few attempts have been made to totally close this loop with detailed irrigation system and crop performance data too. Satellite or aircraft remotely sensed information can provide some periodic feedback information on spatial crop development that is difficult to observe from the ground. It is said we are in the *Information Age* now. Certainly, this conference demonstrates the bandwidth [an internet term implying speed and capacity] of irrigation scheduling information and delivery mechanisms to the producer. This conference and subsequent activities should address the matter of less than enthusiastic adoption of irrigation management systems and determine the information needs of the producers.

Water Quality Constraints

Water quality issues have plagued irrigation projects for centuries. Clearly, salinity and nitrate leaching will continue to receive high research priority in irrigated agriculture, particularly in areas with known problems. Irrigation application methods and irrigation operation must be more fully integrated into irrigation management decisions. Although management may be simpler in arid areas without large rainfall events to consider, drainage regulation is difficult in many situations. Drainage water disposal is increasingly more difficult and expensive and more often even prohibited. In humid and semi-arid areas, nitrogen movement (and movement of other agro-chemicals) into shallow aquifers must consider irrigation scheduling as one of the main mechanisms to avoid excessive application amounts and water quality degradation.

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