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Envisioning The Next Generation Of Irrigation Schedulers

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Abstract. *Many regions in North America are experiencing water shortages, and these conditions are expected to worsen. The next generation of irrigation scheduling applications must therefore be capable of providing operational advice in support of deficit irrigation strategies. However, the theoretical, technical, and practical challenges associated with deficit irrigation scheduling are far more complex than conventional (full) irrigation. This paper will outline key challenges that the next generation of schedulers must overcome in order to meet the needs of agricultural irrigation in an increasingly water short future. In addition, the paper will discuss how irrigation advisory programs will need to operate differently in terms of what they do and how they do it.*

Keywords. Irrigation Scheduling, Deficit Irrigation, Irrigation Optimization, Survey.

Introduction

The potential for using computers to schedule irrigation has been recognized for at least 40 years (Jensen, 1969; Jensen et al., 1970). Yet, as of 2008, less than 2% of irrigated farms use computer simulation models to schedule irrigation (USDA, 2009). Demand for water and pressure to conserve have been increasing for some time however, 'Condition of crop' and 'Feel of soil' have been and still are the dominant methods for deciding when to irrigate.

Over the past decade, several new irrigation schedulers have been developed and new ones are still being developed. In addition, several new technologies have become available to irrigators over the last decade. These new technologies present an opportunity for new irrigation schedulers to be tools that are more robust. The increasing demand for water will necessitate that the next generation consider a broader range of management options. The objective of this paper is to initiate a discussion about what the next generation of irrigation schedulers will need to do to be successful in the next decade. We begin by describing some of the challenges that new schedulers will face. This is followed by a proposed list of requirements for the next generation of scheduling tools.

Table 1. Methods Used in Deciding When to Irrigate (USDA, 1995, 1999, 2004, 2009)

Reported Method	***1988***	***1994***	***1998***	***2003***	***2008***
All farms	223,943	198,115	223,932	210,106	206,834
Any method	93.6%	94.9%	98.6%	100.0%	100.0%
Condition of crop	71.9%	68.2%	72.9%	79.4%	77.7%
Feel of soil	36.1%	39.5%	40.4%	34.8%	42.6%
Personal calendar schedule	15.4%	16.7%	18.0%	19.3%	25.1%
Scheduled by water delivery organization	10.6%	14.1%	10.1%	12.5%	11.8%
Soil moisture sensing device	7.5%	9.6%	8.0%	6.8%	8.6%
Reports on daily crop-water evapotranspiration	4.3%	4.4%	4.8%	7.2%	9.1%
Commercial or government scheduling service	4.5%	4.9%	3.2%	6.4%	8.0%
When neighbors begin to irrigate	NA	NA	NA	6.7%	6.9%
Computer simulation models	NA	2.3%	1.0%	0.6%	1.4%
Plant moisture sensing device	NA	NA	NA	1.5%	1.7%
Other	5.4%	8.7%	7.0%	8.9%	8.7%

Challenges for Irrigation Schedulers

Irrigation Optimization

Scientific Irrigation Scheduling (SIS) can be generally defined as the process of determining when and how much to irrigate (Cuenca, 1989). Conventional irrigation practices are predicated on achieving full production potential. The National Engineering Handbook (NRCS, 1997) recommends that soil moisture be maintained above a management-defined level based on crop stress. Similarly, FAO 24 (Doorenbos and Pruitt, 1992) defines irrigation water requirements in terms of full production potential. Both of these recommendations are based on an underlying goal of maximizing production: a biological objective. Consequently, soil moisture status tends to weigh most heavily on the decision process. Irrigation Optimization is a different task which seeks to allocate water according to one or more goals rather than simply maximizing production (English et al., 2002).Optimizing an irrigation schedule can have a variety of goals, including (Martin et al., 1990):

- maximizing net return,
- minimizing irrigation costs,
- maximizing yield,
- optimally distributing a limited water supply,
- minimizing groundwater pollution or
- optimizing the production from a limited irrigation system capacity.

Shortage of surface or ground water accounted for 63% of the farms that reported diminished crop yield from interrupted irrigation (USDA 2009, Table 26). Most farms have more than one field; when water supply and delivery is not limited, each field can be managed independently. When the quantity of water is limited, this constraint generally applies to all fields in the farm. When delivery capacity is limited, the shortages may apply to individual fields. In either case, the manager must consider all of the fields and the marginal value of water in each field; this is a non-trivial task. Martin and van Brocklin (1989) demonstrated some of the complexities of multi-field scheduling by using dynamic programming to schedule irrigations for a mix of crops. Lamacq et al. (1996) used a model of farmer behavior to simulate allocation of water to a group of surface irrigated fields using a network of irrigation ditches and demonstrated that decision-making must occur at the whole farm level. Bernardo (1987) used a whole farm simulation to demonstrate how, for center pivots, improved labor practices, and deficit irrigation were important adjustments for dealing with reduced water supplies.

Deficit Irrigation

Deficit Irrigation (DI) has been demonstrated as an optimal way to maximize net returns from water and has also been demonstrated as an effective irrigation strategy when water supplies are limited (English, 1990; English and Raja, 1996). Readers are referred to (Fereres and Soriano, 2006) and (Geerts and Raes, 2009) for reviews of DI and its appropriate use on a variety of crops. Methods for implementing DI include delaying irrigation, cancelling certain events, partial root zone drying, and reduced set times or application rates. These last two options present an important challenge for irrigation scheduling because irrigation efficiency is linked to irrigation intensity. This relationship means that the efficiency estimated at design time cannot be used to estimate application depths in water balance calculations; instead, efficiency must be simulated. The feasibility of DI also has a strong dependence on irrigation system performance, particularly on the low quarter efficiency (Rodrigues and Pereira, 2009).

DI strategies also have implications for the accuracy of the irrigation scheduler's calculations. The NRCS National Engineering Handbook recommends that "an irrigation scheduling tool needs only be accurate enough to make the decision when and how much to irrigate" (NRCS, 1997 p. 9-22). When implementing a deficit schedule irrigators can wipe out any of the potential crop yield or net return benefit through errors in timing or application amounts (Dudek et al., 1981). One of the basic assumptions built into most water balance models is that an irrigation event will fill the soil to field capacity. Filling the soil minimizes the spatial variability and uncertainty about the current soil moisture status. This assumption is not valid for DI when the strategy involves only partially refilling the soil. Implementing DI requires precision irrigation that in turn requires improved spatial and temporal resolution (Sadler et al., 2005).

The sensitivity of DI to timing errors also increases risk. Events beyond the manager's control (e.g. broken equipment, delivery delays) make implementing DI more vulnerable to events that damage yield. Despite this, DI has been demonstrated as effective even when delivery of water supply is uncertain (Perry and Narayanamurthy, 1998). Spatial non-uniformity is also a significant source of risk (Bernardo, 1988). Bernardo demonstrated that the variability of net returns increased when non-uniformity is considered and that risk efficient strategies incorporating non-uniformity will apply more water than under uniform conditions. Because the necessity to reach a prescribed level of yield reduction (for net economic returns) and the increased risk, irrigation schedulers must include yield estimates alongside their recommendations. Hornbaker and Mapp (1988) demonstrated that daily plant models allow a more careful analysis of the value of timing irrigation. Raes et al.(2006) developed a coupled water balance model with a model of yield decline that uses different yield decline rates during various growth stages. The authors concluded that their model would be useful for developing irrigation strategies under deficit conditions. These two papers, Raes et al., and Hornbaker & Mapp) demonstrate the utility and necessity of incorporating yield estimates.

Each of the risk sources described (externalities, spatial variability, excess yield reduction) can be managed through careful monitoring. Growers have differing levels of risk preference and will value irrigation schedulers recommendations differently based on their risk preference (Bosch and Eidman, 1987). Explicit consideration of growers risk preferences will help irrigation schedulers provide a schedule that is commensurate with the grower's preferences.

Management Information Systems

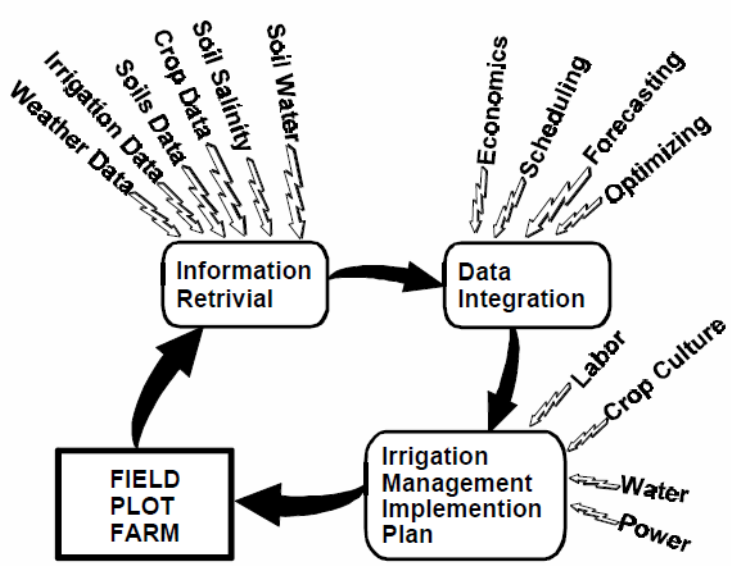

Figure 1 Irrigation Management Cycle (from Howell 1996)

Howell (1996, Figure 1) described the irrigation management cycle using the diagram shown in Figure 2. He identified 'sensor and Information Technology' as one potential area of research for irrigation scheduling and noted that not all of these sources of information have been fully utilized to facilitate irrigation decision making. Much has changed in Information Technology since 1996. Web based technologies for information exchange have matured. The availability of online databases for soils (NRCS, 2010), weather (NOAA, 2010), and crop information has expanded. Online delivery of data from on farm instrumentation is becoming commonplace. Perhaps the most encouraging development is the Department of Agriculture recent initiative to bring high-speed internet access to rural areas (USDA, 2010). Each of these factors presents opportunities for facilitating the "Information Retrieval" and "Data Integration" phases shown in

Figure 2. Building robust management information systems may lie more in the realm of computer science than in irrigation science however, dependence of irrigation scheduling on information means that developers of scheduling tools must have knowledge of both realms.

These technological advances are not necessarily improving grower confidence. In a survey of growers in the Hawkesbury-Nepean Catchment NSW, Maheshwari et al. (2003) found that while growers where interested in knowing more about scheduling they were not confident about what technologies were appropriate. In addition, when asked about soil moisture monitoring systems for paddock management, some growers said there was no use for it or considered it a waste of time.

NOAA has been offering weather forecasts online for many years. However, quantitative precipitation forecasts (expected depth), and the data necessary to calculate Penman based ET estimates have only been available for a few years. The National Weather Service has recently started providing point forecasts available in an XML format (NOAA, 2010). Wang and Cai (2009) demonstrated that using weather forecasts could have a positive impact on water use. They found that, using seven day forecasts in conjunction with the SPAW model, growers would have lower water use during normal years and higher profit during dry years when compared to scheduling based only on current soil moisture status. Although weather data is increasingly available online, not all weather networks are providing data in forms readily useable by web based applications. For example, the Agricultural Water Conservation Clearinghouse has a list of weather stations and ET networks (Agricultural Water Conservation Clearinghouse, 2010). Of the 14 networks listed there only one (CIMIS) provided weather data in an XML format. Nearly all of the networks provide their data in a 'csv' format that is readily useable by spreadsheet applications.

Data acquisition is only one part of the scheduling process shown in Figure 2. Making data easy to obtain and presenting it in clear ways is a valuable feature but the real power of irrigation schedulers lies in the potential for using the information to drive calculations. In this sense, an irrigation scheduler is also a decision support system. Mohan and Arumugam (1997) indicated that Expert Systems are viable and effective tools for irrigation management and stressed the need to include other aspects of irrigation management such as canal and reservoir operation. This need was also indicated by Clyma (1996) who concluded that scheduling services are not adequately integrated with other farm operations that hold greater importance than irrigation decisions. The need for combining irrigation tools with crop growth models has been emphasized in the past (Wolfe, 1990) and continues to be emphasized more recently (Woodward et al., 2008). Woodward also emphasized that user participation in each step of the development process is important for success of the program.

Table 1 indicates that 'condition of the crop' is the most commonly used indicator for scheduling irrigation. This implies that an irrigation scheduler that uses plant-based measurements would be more compatible with grower's current thinking. However, scheduling via plant-based measurements is not without problems (Jones, 2004). Using plant based measurements coupled with a mechanistic model has been demonstrated to be effective (Steppe et al., 2008) but the authors point out that the lack of parameter values for different crop is a serious limitation at present.

Wireless sensor networks are gaining feasibility and sophistication (Wang et al., 2006) and have the potential to significantly increase and simplify on farm data collection. Feasibility of field data acquisition using in-place and handheld devices connected via GSM-SMS communication was evaluated in Taiwan (Tseng et al., 2006). This system was found to be acceptable because of the availability of GSM in Taiwan; something still not universally available in rural North America. An expert system intended for use on a PDA has been developed specifically for implementing deficit irrigation in China (Lin et al., 2009). Mobile web devices and online information management systems have also been demonstrated as an effective tool for collecting management information and sharing that with retailers who want to know about pesticide use (Thysen et al., 2005). Making use of mobile devices for irrigation scheduling does involve technical challenges unrelated to irrigation management. However, the constrained nature (small display area) of the PDA interface does require that developers re-evaluate the importance of the information required to drive these systems.

Service Oriented Scheduling

Nearly every region in the western US has a scheduling tool available and a weather network that can supply data needed to perform SIS calculations. The tools may have varying features and the weather networks varying measurement densities but all of the tools require some effort to setup and use. Even when SIS services are free and 'self service' there is still a cost embedded in the time required to use them. The success of irrigation scheduling applications depends on more than their accuracy, ease of use, or cost. Shearer and Vomocil (1981) described the challenges and obstacles that they faced over 25 years of promoting irrigation scheduling in Oregon. They emphasized that if irrigation services are not supported externally to the farm then the growers will stop using the service. In other words, growers are willing to use irrigation scheduling but other farm activities are considered a better use of their time.

Two examples of successful scheduling services are the IASA in La Mancha Spain (Rodriguez et al., 2002; Manas et al., 1999; Smith and Muñoz, 2002) and the El Dorado Irrigation District in northern California (Taylor, 2009). IASA, the Irrigation Advisory Service of Albacete, provides irrigation scheduling advice and decision support to growers in the Castilla-La Mancha region of Spain and has been providing this service for more than 15 years. IASA staff visit participating farms on a weekly basis, collect information for the advisory service, and disseminate scheduling information through various mediums, and provide site-specific scheduling recommendations to the participating farms. The El Dorado Irrigation District (EID) in northern California is another example of how service can make irrigation scheduling successful. The EID uses TrueISM software (TruePoint Solutions, 2008) that was custom built for their district. Automated weather stations, permanently installed soil moisture monitoring sites, and regular visits by the EID staff all reduce the effort required for the grower. The service has been operating long enough to establish accurate system characterizations and positive relationships with the growers.

Both IASA and EID are providing scheduling services, that is, the irrigation schedule is produced by applying SIS but the schedule is delivered to the grower as a product of the organization. In both cases, the service involves significant hands on work by the service personnel and this time investment reduces the burden on the irrigator. Additionally, a reputation for the accuracy of the service has been established over time. This model of an irrigation scheduler does have limitations, particularly the need for continued funding, however as Shearer & Vomocil argued it does motivate the use of irrigation scheduling.

The federal government also has a role in motivating irrigation scheduling. The Natural Resources Conservation Service (NRCS) is the lead agency of the United States Department of Agriculture charged with carrying out the Department's conservation mission on private lands. Among the 160 plus NRCS conservation practices is the "irrigation water management" practice. Irrigation scheduling and irrigation water management are among the preferred tools NRCS has for assisting a landowner in mitigating the inefficient use of irrigation water.

In 2009, NRCS applied the Irrigation Water Management Conservation Practice on 1,091,582 acres nationwide (NRCS, 2009). The NRCS has encouraged the use of irrigation scheduling software through both technical and financial assistance to landowners. In addition, some developers of irrigation schedulers have received financial assistance from the agency. Other developers have received indirect assistance through the encouragement or requirement of using a specific irrigation scheduler.

Features of The Next Generation (NG)

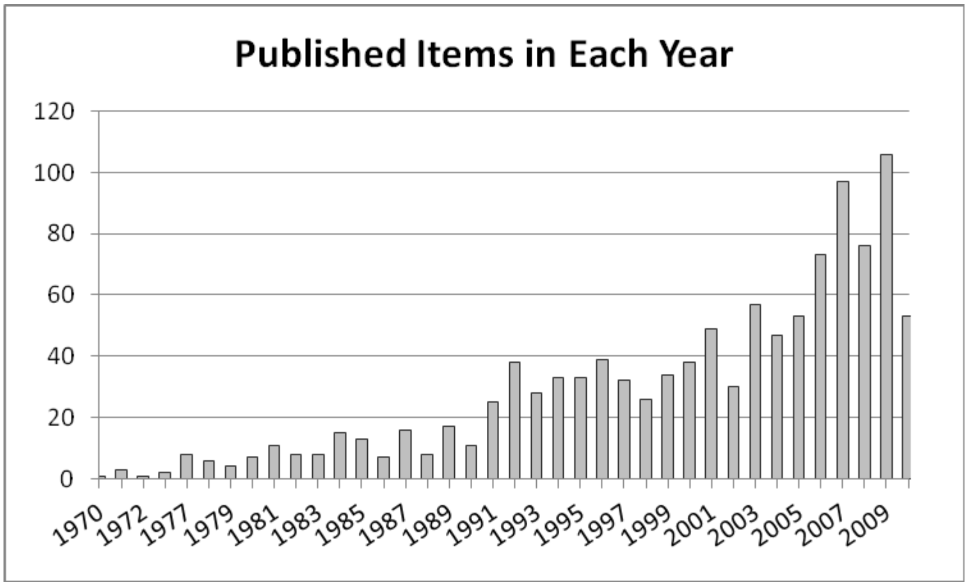

Figure 2 Search results from ISI Web of Knowledge using 'Topic=("irrigation scheduling")'

Figure 3 shows the number of papers published over the last 40 year that match the topic 'irrigation scheduling' as reported by ISI Web of Knowledge (http://apps.isiknowledge.com). Given the level of research activity relating to irrigation scheduling we can expect that development of irrigation schedulers will continue. As a starting point and motivator for discussion, we present several suggestions on what the NG should be in order to be successful. These statements are not intended to be speculations about the future; rather they are a proposed set of requirements that we hope will stimulate discussion about the NG.

The NG will be irrigation optimization tools. As such, they will provide the following features:

- *Explicit consideration of farm level constraints*. Limitations in water allocations apply to the whole farm and should be included in the analysis as such. Limitations in supply capacity can affect at the farm or field level (either demand exceeds pumping capacity or canal flow is less than ordered). Temporal limitations on both of these (e.g. midseason changes in allocation, and restrictions on delivery timing) will also be considered.
- *Conjunctive scheduling of all fields in a farm* (or management unit). Irrigators make decisions at the farm level so a scheduler will facilitate that decision process.
- *Alternative or unconventional scheduling strategies.* These strategies would include reduced adequacy, partial season irrigation, critical growth stage scheduling.
- *Full Season forecasting*. This feature will allow growers to evaluate different irrigation strategies and for planning under different water use scenarios.
- *Consideration of economic consequences*. The impact of management recommendations will be expressed in economic terms as well as agronomic terms.

The NG will support Deficit Irrigation (DI). Supporting DI necessitates including the following features:

- *Explicit analysis of irrigation efficiency*. Implementing DI often involves manipulating irrigation intensity. Irrigation efficiency is linked to irrigation intensity and cannot be assume a priori. Successful implementation of DI is dependent on system uniformity and efficiency.
- *Estimation of yields and potential yield losses*. DI involves some level of yield reduction relative to full production potential. Furthermore, when DI is used to maximize net economic returns, yields are an explicit part of the objective function. For both of these reasons, consideration of yields is an essential part of implementing deficit irrigation strategies.
- *Consideration of irrigator's risk preferences*. DI implies an increased risk of yield loss. People have different preferences for risk and financial status of farming enterprises may limit the amount of risk they can tolerate. Therefore, analysis of risk must be explicit in the planning of deficit strategies.

In order to support the previous two items **the NG will need greater precision in their calculations and have smaller tolerances for errors in their forecasts**. This need requires that the simplifying assumptions associated with full irrigation will no longer apply. The NG of schedulers will have the following features to support increased precision:

- *Multiple types of physical measurements will be used*. Plant based, soil moisture based, atmospheric, and remote sensing measurements will all be incorporated into the calculation of the soil water balance instead of relying completely on any one source of information for scheduling decisions.
- *Schedulers will allow for quality weighting of various measurements*. Different types of measurement have different magnitudes of error or uncertainty. Further, growers have differing levels of trust associated with newer technologies. The farmers own opinion in addition to the physical evidence should be give credence when combining various measurements.
- *Schedulers will be explicit about spatial and temporal variability*. Soil physical properties, crop characteristics, and depth of applied water all vary spatially. Using deficit irrigation strategies means that schedulers will need to consider spatial variability and its affect on the variability of its recommendations. Being explicit about the variability will help the grower to visualize the range of possible outcomes from their scheduling decisions.
- *Schedulers will be explicit about the risk and uncertainty of their recommendations*. No measurement technology can give a perfect picture of field conditions and the accuracy of weather forecasts is well known. No physical model is perfect. Each of these factors introduce uncertainty that cannot necessarily be separated. Being explicit about the uncertainty will help the grower asses the verity of the recommendations.

The NG of schedulers will be information management systems.

- *Schedulers will use relevant data from online databases*. This will include weather networks, soils databases, and remote sensing data. The scheduler will handle downloading, parsing, and integration of the data into its recommendations.
- *Schedulers will be integrated with the growers own instrumentation*. Personal weather stations have been available and affordable for some time. Increasing availability of cell phone and wireless communications means that users will be able to access the data remotely. However, at present manufacturers often use proprietary or nonstandard formats for data exchange. The NG will leverage existing standards for data exchange to automate the process of extracting instrumentation data.

- *Schedulers will use weather forecasts*. The NG will use weather forecasts to improve forecasts of irrigation needs instead of relying on historical averages.
- *Schedulers will be integrated with irrigation hardware*. Providing accurate forecasts requires knowledge of previous water use. The NG will obtain this information automatically via instrumentation on the irrigation system or through the software used to control the systems.
- *Schedulers will be online applications*. The NG will deliver scheduling recommendations using more than one web based modality. These different forms will include HTML, Web Services, and interfaces appropriate for mobile devices.

The NG of schedulers will be part of a service provided to the grower, rather than a standalone tool.

- *Schedulers will have a substantial 'service' component*. As described in the previous sections, successful schedulers have done most of the time consuming work for the grower. The NG will follow this pattern in that most of the work of preparing the schedules will be done by an organization external to the farm. The service may be public or private and may include some type of fee to the grower.
- *Federal and local organizations will be involved in delivering the service*. Federal agencies will continue to provide support from irrigation scheduling and this support will be an integral part of the irrigation scheduler through either software development or research that supports irrigation scheduling.
- *Schedules will be accessed by irrigation districts and watershed organizations*. This will allow irrigation districts to better plan and manage canal networks.

Conclusion

This paper has been an attempt at stimulating discussion of and (perhaps) outlining the requirements for the next generation of irrigation schedulers. We have described some of the challenges that schedulers face and some of the new opportunities available to them. These challenges where: the complexity of irrigation optimization, the requirements for and risk implications of deficit irrigation, changes in information management technology and its potential impact, and the importance of support from organizations external to the farm enterprise. The challenges were followed by a list of proposed features for the NG. The features were derived from the challenges and are expressed as features the NG could implement to address those challenges. The list of features is long and ambitious. We are not implying that all of these features are required for success. Nor is this list intended to be an exhaustive enumeration of requirements for irrigation scheduling. Rather, the list is intended to broaden the capabilities of irrigation schedulers by stimulating discussion about their features, purpose, and goals.

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