AN ABSTRACT OF THE DISSERTATION OF

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Abstract approved:

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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 dissertation presents three distinct systems for addressing the analytical challenges of deficit irrigation management. The first section of the dissertation presents a simulation framework for agro-ecological simulation. The objective was to develop a method to enable the assembly of simulation models from previously and independently developed component models. Based on a requirements analysis of existing simulation models we developed the ModCom simulation framework. ModCom provides a set of interface specifications that describe components in a simulation. ModCom also provides implementations of the core simulation services. The framework interfaces use well-defined binary standards and allows developers to implement the interfaces using a broad range of computer languages. The Second section describes the Irrigation Efficiency Model (IEM). IEM explicitly analyzes

irrigation efficiency, accounts for spatial variability of soil properties and irrigation uniformity, performs simultaneous scheduling for all fields in the farm, accounts for energy use and its associated costs, and uses both ET and soil moisture measurements to enhance the accuracy of the irrigation schedules. IEM was developed specifically for implementing Deficit Irrigation and therefore includes analyses that go beyond the requirements of conventional irrigation scheduling. The third section describes Irrigation Management Online (IMO), a web application for optimum irrigation management. This system uses IEM to generate and deliver irrigation scheduling recommendations. IMO has been developed specifically to support irrigation management when either water supplies or delivery system capacities are limited. To mitigate the complexities of irrigation constraints the system has been designed so that the irrigation manager is an integral part of the irrigation optimization procedure. The final section outlines some of the 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, this section will discuss how irrigation advisory programs will need to operate differently in terms of what they do and how they do it.

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Optimal Irrigation Management: A Framework, Model, and Application for Optimizing Irrigation when Supplies are Limited

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

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Charles C. Hillyer, Author

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CONTRIBUTION OF AUTHORS

Frits van Evert and Arjan Lamaker both contributed to the development of the ModCom framework. The conclusions chapter was presented at a conference and Peter Robinson contributed to that paper.

TABLE OF CONTENTS

TABLE OF CONTENTS

Page

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

Figure Page

LIST OF TABLES

Introduction

The demand for fresh water is projected to exceed renewable supplies by 2025 (Postel et al., 1996). The world demand for food is increasing because of increased population size and increased demand for resource intensive products (beef, poultry, etc). For irrigated agriculture, at the intersection of these two resource limitations, water shortages will become not only common but even standard operating conditions. This leads to the obvious conclusion that changes must occur, and agriculture, the largest consumer of fresh water, is expected to make big changes in water use. Part of the solution is expected to come from improvements in crop characteristics to reduce water needs and increase stress tolerance (Baulcombe, 2010). However, it is generally recognized that the developing water shortages will also force fundamental changes in the way irrigation is managed (English et al., 2002). Irrigation management will necessarily move from simple stress avoidance (a biological objective) to optimization based on net returns to water (an economic objective). Much more sophisticated irrigation management tools will be needed to support optimal decision making in a water-limited future. And the complexity of such optimal irrigation advisory tools will require a development foundation that facilitates integration of components from different domains.

These challenges have motivated the research program described here. The essential product of this effort has been an irrigation advisory system with the analytical power and sophistication, adaptability and user orientation to meet the needs of irrigation managers in an increasingly water-limited world. The system detailed in this dissertation is a first operational version of what has been called the ‘next generation’ of irrigation management programs.

Managing for Optimal Irrigation

Irrigation water requirements are usually defined to avoid crop stress (Doorenbos, 1979); implicitly assuming that maximum yield is desired. The depth of application is computed so that the average of the low quarter of the field is at or above field capacity (NRCS, 1997), which essentially guarantees that a substantial portion of the field will be over irrigated. The timing of irrigation is recommended to start before soil moisture depletion causes yield reducing plant stress (Hoffman et al., 1990; Martin et al., 1990); necessitating that water be available on a schedule determined by the plant and not the water source.

Optimal irrigation management in a resource limited future will force irrigators to abandon these relatively simple operating rules, and compel them to deal with issues not previously considered in conventional irrigation management, including:

- Deficit Irrigation (DI), a central tenant of optimum irrigation, will be the fundamental management paradigm
- Deficit irrigation management will require addressing new and more complex factors and a much wider range of operating conditions (crop response, ET under low moisture, variable efficiency, salinity management)
- Allowing a margin for error, which is a common practice in conventional irrigation management, will no longer be tenable, requiring higher analytical precision and involve a wider range of temporal and spatial scales

These changes will greatly increase the complexity, computational intensity and data requirements of irrigation management systems, necessitating three management system design requirements that are different from conventional irrigation management systems:

First, the models that estimate water requirements need to be able to account for a broader range of conditions than those associated with conventional irrigation. Models that are more robust must be used to estimate water requirements under Deficit Irrigation. Deficit irrigation (DI) is generally regarded as the optimal method for managing irrigation in agriculture (Fereres and Soriano, 2006). Implementing deficit irrigation usually involves methods that violate the modeling assumptions that are generally true with conventional irrigation. Planned yield stress, delayed irrigation, and reduced adequacy necessitate models that account for the physical and agronomic consequences of these methods (cite??). Further, these strategies are often used together. A model that only accounts for one or a few methods will have limited usefulness. When water resources are limited, the result is essentially unplanned deficit irrigation. The physical consequences are identical to planned deficits and require a similar modeling approach. The violation of these assumptions means that a tool for optimizing irrigation must use a model that is robust enough to simulate the physical consequences of deficit irrigation.

Second, advisory tools used to manage irrigation will need a robust user interface that incorporates the manager into the optimization process. Irrigation decisions are not made ‘in a vacuum.’ Farm managers must consider factors that are not directly related to irrigation, but those factors still affect the irrigation process either by occupying resources that are needed for irrigation (i.e. labor or power) or making certain activities unavailable because of irrigation (i.e. field operations). However, resource and operational constraints cannot all be accounted for by system developer, so user-specific optimization is required. Implementing DI involves balancing a set of objectives that may at times cause competition for resources, increase risk, and increase uncertainty of outcomes. Farms usually have more than one field, and these fields will ‘compete’ for water. Farm managers do not consider fields in isolation because actions on one field may limit actions on another. Because DSS need to be compatible with managers' existing management practices (McCown et al., 2002; McCown, 2002) an irrigation scheduling tool must facilitate managing multiple fields simultaneously. By managing these limitations (resources, risk, uncertainty) an irrigator is essentially implementing the constraints part of an optimization problem. A DSS tool that is optimizing irrigation should use these constraints to define the boundaries of its recommendations. To implement this behavior, the DSS would need to encode all the potential factors that can limit irrigation. This task is difficult at best. Instead, the system that is at the center of this research takes a different approach wherein the manager is an integral part of the optimization process. This integration of the user is achieved through a combination of new management constructs and user interface components.

Third, Increased complexity implies that a multiplicity of teams will share the work, new data sources will be required, and simulation components will evolve over time and independently of each other. Agro-ecological simulations have many common needs. These simulation services can be implemented independently and reused in other simulations. Reuse can also apply to the simulation components themselves. A simulation framework supports both of these forms of reuse as well as enforcing constraints that improve the development of simulation models by forcing the developer to define explicitly the scope of the separate components. Components from different subject domains are likely to be developed by different research groups using different languages and different development environments. Component based development enables separate groups to develop components with a great degree of independence thus alleviating the problems associated with different languages and environments.

Additionally, agricultural management is dependent on external factors that may not be anticipated in advance by a system developer. A practical tool will need to be sensitive to the factors that are external to the simulation domain. This dependence on external factors is not unique to irrigation. Many farm operations affect and are affected by each other. We cannot build a single tool that contains a model of all possible external factors. Instead, we can build a tool that could potentially incorporate any model of an external factor and then include new models as the need arises. A Component based simulation framework can make this potential for integration, where the new components are developed and integrated as the need arises. The simulation framework supports this type of design both at the software level and at the conceptual level.

A Decision Support System for Optimal Irrigation

Virtually all computer-based decision support systems for irrigation management developed during the past forty years have evolved from the ground breaking work of Jensen and others in the late 1960's(Jensen et al., 1970; Jensen, 1969). There have been wide variations in detail and format, but not in the underlying management paradigm. Essentially all such programs have been designed for conventional irrigation, i.e. irrigation to meet crop water demands in order to avoid crop stress that would reduce yields or quality.

The fundamentally new DSS described in this thesis is designed to support the much more challenging paradigm of economic optimization. As such it represents a pioneering departure from the evolutionary line of the past 40 years. Using a development foundation that supports integration of components from different domains, this new DSS can exploit a wide spectrum of data sources and analytical tools. The capacity to readily integrate the collective work of diverse research teams enabled development of an analytical framework that is an order of magnitude more comprehensive, complex and sophisticated than existing systems. Further, the system can be easily adapted to accommodate diverse local circumstances and region-specific science.

As an operational prototype this system is now informing the development of ‘next generation’ irrigation advisory programs for optimal irrigation management in a severely water-limited future. Insights gained from this effort have served to identify and illuminate research needs and practical challenges that need to be addressed in the near term. A task committee, operating under the auspices of the Environmental and Water Resources Institute of ASCE, has recently undertaken a national effort to guide and coordinate development of advanced irrigation decision support systems. A seminal paper presented by the leadership of that committee is included as Appendix 1 of this thesis; that paper was largely derived from the research effort reported in this thesis.

Decision Support Systems (DSS) aim to integrate information, evaluate outcomes, and inform managers about potential strategies and their consequences. In the past DSS’s have been focused on one or a few specific decision domains (e.g. fertilizer applications). The physical processes that directly affect the decision process usually determine the scope of the DSS. To fit in with managers’ current process the DSS needs to include information that is external to the physical processes yet still affects the decision process. Given that development of simulations is likely to continue using physical process to determine scope, DSS will need to include more models/simulations into a combined system.

The research presented here describes a new approach needed for design of an irrigation management Decision Support System. The research moved through three stages. The first was to build the framework that would serve as the foundation for the development of component-based agro-ecological simulations. The second was to demonstrate the different approach to irrigation scheduling to serve as an exemplar for development of new scheduling tools. The third was to build a functioning system and demonstrate its efficacy through field trials.

Outline of the thesis

The following four chapters are four papers that describe the results of this research. The first paper describes ModCom, a simulation framework for agro-ecological simulation. The second paper describes the Irrigation Efficiency Model, a simulation tool for designing irrigation scheduling strategies. The third paper describes Irrigation Management Online, a web based tool for optimal irrigation scheduling. The final paper, presented as Appendix 1, presents insights derived from this research concerning the challenges that the next generation of irrigation schedulers must face to be successful in the future.

The ModCom Modular Simulation System

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Introduction

Mathematical systems models and computer simulations are used by ecological scientists and resource managers to enhance ecosystem management, allocate resources, and understand ecological and biological processes. Simulation models become vehicles for representing in abstract terms a slice of reality consistent with our specific interests in enhancing our understanding of our world. Representation here is the key word: simulation models must provide us with an abstract representation of reality. How we represent the conceptual model we derive from observation of reality therefore should be of considerable interest to the modeler. It is here where programming languages and simulation tools have a central role to play.

In the formulation and description of these models, it is both useful and common to think in terms of models and sub-models. Scientists in ecology will readily recognize the usefulness of considering, for example, a sub-model for crop growth and a sub-model for nitrogen transformation and movement in the soil, in the case of an agricultural model. Yet the computer representations of these models often show little sign of these conceptual decompositions. If an attempt is made to have the structure of a computer program resemble the structure of the conceptual model, for example by using subroutines, the parts of such a computer program are often still linked tightly together and cannot be replaced by equivalent parts from programs developed elsewhere.

Object-oriented techniques and, in particular component-based software development hold promise to obtain a high degree of correspondence between conceptual models and their implementation in computer code. This has led researchers to develop object-based models in a variety of domains. Numerous object-oriented models have been reported in ecological and agricultural simulations (Bolte, 1998; Caldwell and Fernandez, 1998; Van Evert and Campbell, 1994; Folse et al., 1990; Sequeira et al., 1991; Whittaker et al., 1991). All indicated support for model conceptualization, program design, and reuse of the models as advantages of object-oriented approaches for model development.

The objective of this research is to develop a method that enables the assembly of simulation models from previously and independently developed models. The following sections describe the technique (frameworks) and technology (component software) that are used to achieve the objective. Following that is a description of the ModCom simulation framework and its associated parts.

Frameworks

An object-oriented framework is a set of collaborating classes meant to be expanded to form related applications (Gamma et al., 1995). A simulation framework, then, is a set of classes meant to be expanded to create simulation programs. Such a framework may describe the flow of execution, patterns of communication, or data structures used by elements of a simulation. The purpose of constructing a framework is twofold. First, the framework creates a separation of concerns by segregating the application-specific parts of simulations from the application-indemendant code employed by many simulations to accomplish common tasks. Creating this separation greatly enhances code reuse. The second purpose is to create a clear path for building a simulation. By defining what elements of the framework actually contain the model's implementation and how those elements are used, a designer is presented with a clear path from conceptual model to simulation. Further, by defining how model components to interact with other components, a simulation framework greatly enhances the reusability of model components, allows the development of robust metamodeling facilities (e.g. parameter estimators, stochastic analysis capabilities), and speeds the assembly and analysis of complex models. Frequently used classes are provided by the framework, removing the need for individual modelers to "reinvent the wheel."

A framework is manifested as a collection of interfaces (abstract classes), together with concrete classes that implement frequently needed functionality. An interface is an agreement between developers defining the semantics of how to communicate with an object implementing the interface. Programmatically, an interface defines a collection of related methods that implement the interface semantics. If a class implements some interface then it must implement that interface fully and exactly according to the definition of the interface. Thus, when a programmer uses an object implementing the interface, he or she knows what methods the object has, what the method arguments are, and has general knowledge of what the object will do when one of it's methods is invoked. Practically speaking, an interface is an abstract class containing only method definitions without implementations. The interface does not specify how those methods should be implemented. This separation of implementation from definition is an essential part of achieving language independence. The separation also facilitates the management of changes to the code after it has been deployed.

There are drawbacks to using a framework. The designers of a framework aim to support a certain types of applications (Gamma et al., 1995). The development of applications is facilitated by the framework as long as they are of this type; if the applications are sufficiently different from what the framework designers had in mind, the framework ceases to be useful.

An example of a high-level decision support framework was developed by Bolte et al. (1993) and Bolte (1998). This framework provided for the integration of continuous, event-driven, and knowledge-based simulations by providing two major classes and several supporting classes. The first of these, termed the SimEnv, provides for a number of different types of simulation components, including continuous simulators, discrete events, and knowledge-based agents, each of which could be subclassed into more specific types of simulation objects. The simulation environment provides a simulation clock controlling and coordinating time-based operations, maintains an event list of "interesting" events scheduled to occur at some point in future time, provides a number of different notification and message-passing mechanisms allowing communication and interaction between objects at several different levels via messages directed to specific objects, general notification messages, and a blackboard supporting asynchronous communication between objects in the system. Because all objects in the system are derived from a single high-level simulation class, all user-defined simulation components automatically receive robust simulation capabilities, and integration of conventional continuous simulators running at variable time steps, periodic and aperiodic discrete events and expert system-based agents is straightforward.

Other modular simulation frameworks have been developed. Loki, a modular system for X Windows, has been used successfully for ecosystem modeling and forest fire management (Keane et al., 1996). The USGS developed the Modular Modeling System (Leavesley et al., 1996) to address problems of model selection and application for environmental and water resource problems. The High Level Architecture, a general-purpose architecture for simulation reuse and interoperability, was developed by the Defense Modeling and Simulation Office of the Department of Defense (Dahmann et al., 1998). The Modular Modeling Language employs a meta-model approach to module construction and has been used to develop spatial ecosystem models (Maxwell and Costanza, 1997). While not strictly object-oriented, these systems have demonstrated in part the utility of frameworks for modular model development. However, these approaches have had problems with language dependence, lack of robust communication and identification capabilities among modules in the system, and lack of robust time and information flow sequence coordination between modules.

Agro-ecological simulations typically present numerous requirements which are common across systems, including 1) standardized public interfaces defining object access and action initiation, 2) high-level communications capabilities for components of the system to communicate with other components in a non-specific manner, 3) standardized methodologies for collecting and transferring information between components of the system, possibly in a networked or web-based environment, 4) standardized methods for data import, representation, analysis, visualization and export, and 5) mechanisms for synchronizing the sequencing of flow execution among system components. The framework paradigm provides potentially useful capabilities in all of these areas. The standardization of interfaces is a central framework concept, and is readily implemented through the definition of generic interfaces that provide a consistent specification for how objects in a simulation interact with each other and with the framework. An standardized interface specification allows communication between objects without specific knowledge of object's implementation, a critical requirement for the development of high-level, domain-independent modeling frameworks. Synchronization and data collection can similarly be handled in a standardized manner through the specification of high-level interfaces.

ModCom

ModCom is a framework for developing and using modular simulation components. The framework is supplied with a library (ModComLib) that provides components that implement many of the interfaces defined in the framework and provide access to core simulation services. Additionally, development tools supporting rapid creation of components and visual model assembly are being developed.

We wanted ModCom to have the following characteristics: First, the system must be practical and easy to use. The system must be capable of exploiting existing protocols for object communication and data sharing, but this complexity should be hidden from the user as much as possible. A visual tool should be available to help automate the process of model construction and execution.

Several design goals where set for the development of ModCom. First, ModCom should be language neutral. To achieve language and operating system independence, ModCom uses the Component Object Model (COM), an industry standard binary specification of interface definitions. While COM is both a specification and a set of platform-specific libraries, ModCom uses only the COM specification to maintain platform-independance. A second goal was that the entire system should be extendable: a developer should be able to replace any framework component with a different implementation. Finally, modules should be independent of each other. A developer should be able to construct a module without incurring runtime dependencies between other modules.

Core Simulation Management Services

The elements of the ModCom framework are grouped according to the services that they provide. Each service is made available as a set of interfaces that provide access to an implementation of the service. The following sections describe the core simulation services that are used by all simulations. Figure 1 shows a class diagram of the framework with the interfaces grouped according to the services that they provide. Here, we provide a high-level description of the ModCom framework. Specific details about methods are available in the ModCom technical documentation. Interested readers should examine the ModCom technical documentation and users guide for additional details (see Availability of Software).

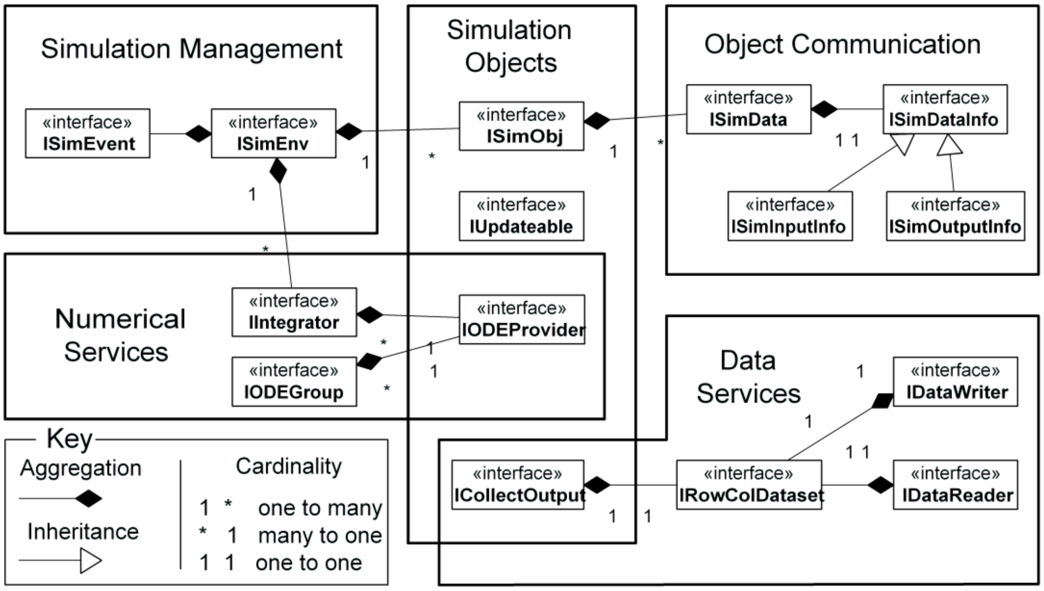

Figure 1 UML class diagram of the core ModCom interfaces. Interfaces have been grouped according to the services they provide. Inheritance means that one class “inherits” functionality from its parent class. Aggregation means that one class contains a reference to another class.

Simulation Objects

A ModCom simulation consists of individual, interacting components implementing one or more ModCom interfaces. Each of the components in a simulation exposes inputs and outputs and communicates with other objects in the system. For example, a crop model might consist of several simulation components: a plant component that implements a series of state equations describing dynamic plant response, a climate-generation component, a soil water balance component, a data writing component periodically collecting and writing simulation results to a file or database, and, if a visual representation of results is needed, a dynamic graphing component that periodically collects results and displays them on a screen. Different components (e.g. a different climate generator) can be quickly swapped into an assembled model as long as they implement at least the ISimObj interface. These interacting components are called simulation objects (or SimObjs). Each SimObj must implement one or more of the following interfaces, but at a minimum, components in a simulation must implement the ISimObj interface described below (NOTE: interface names are prefixed with a capital "I").

The ISimObj Interface

The ISimObj interface specifies basic object identification and data exposure methods and must be implemented by all objects that participate in a simulation. However, many simulation components have more specialized requirements. For example, many model components are represented as a system of differential equation based state variables. Because all objects of this type will require numerical integration services to be solved, additional interfaces are defined that allows general-purpose integrators to solve these object's state equations without the modeler having to implement these methods. But, at a minimum, all objects must implement the ISimObj interface. The object identification is simply a Name parameter exposed as a string. The data exposure methods are more complicated and are discussed in the section on Exposable Data and the ISimData interface.

The IUpdateable Interface

The IUpdateable interface allows a SimObj to be updateable; that is, it will receive periodic messages from a SimEnv (described below) to "update" itself through the SimEnv's time flow synchronization mechanism. Many SimObjs will implement IUpdateable as well as ISimObj.

Objects can interpret what it means to update themselves in their own context. An integrator might update itself by solving the SimObjs associated with it by integrating their state equations for one time step. A graph might update itself by refreshing its data store and redrawing itself. Update messages are provided by the SimEnv based on the updateable SimObj's time step. Updateable SimObjs can control when they start and stop receiving messages, their time step, when they receive their next update, and other aspects of updating.

The IODEProvider Interface

The IODEProvider interface defines support for SimObjs that are represented by one or more ordinary differential equations (ODE). The methods defined by IODEProvider allow integrator objects (described later) to solve these differential equations in a generalized way without requiring the modeler to specify solution procedures for the equations they are implementing.

Simulation Management

The Simulation Environment

ModCom provides support for high-level management of simulations through the ISimEnv interfaces. The interface defines functionality in the following areas:

Registration and management of simulation objects participating in a simulation. Registration is a process where the simulation environment is made aware of simulation objects that want to participate in a simulation. Upon registration the SimEnv determines what messages the SimObj will receive based on what interfaces it implements and schedules the SimObj for the appropriate services.

Time-flow synchronization and control of the updateable SimObjs. A SimEnv accomplishes time-flow synchronization by maintaining an event list that schedules the execution of the IUpdateable.Update method according to each Updateable's TimeStep and priority information.

1. Default integration methods for numerical solution of ordinary differential equations. The SimEnv implementation that is part of ModCom has access to an implementation of IIntegrator (described in the Numerical Services section). The SimEnv will schedule SimObjs for integration services; however, the Integrator actually performs the integration. Additional or alternative integrators can be substituted for the default Integrator.
2. Broker services for inter-object communication. The SimEnv maintains a store of SimData and SimDataInfo (described in the inter-object communication section). Other objects may query the SimEnv for specific variables (SimData) or variables with particular set of attributes.
3. Initializing, stopping, and other execution control functions. The SimEnv is intended to be a simulation controller. It has methods to set the simulation start time and stop time, and to run a simulation.

Simulation Events

In addition to simulation objects, the MODCOM framework supports the concept of a simulation event. An event is simply something that gets executed at a specific point in simulated time. Events have no state; that is, they do not maintain any data. Internally, the SimEnv handles updating simulation objects through an update event scheduler, but modelers can also define their own events and register them with the SimEnv to perform event-driven tasks. Within the framework, events are defined using the ISimEvent interface. The framework provides several general-purpose implementations of this interface. As with all interfaces, modelers can create additional event classes by implementing the ISimEvent interface.

Numerical Integration Services

Numerical integration for ordinary differential equations (ODE’s) is accomplished through an implementation of the IIntegrator interface. Objects designed to provide integration services must implement the ISimObj and IUpdateable interfaces in addition to IIntegrator. The object that provides integration services should perform its calculations during the call to IUpdateable.Update. These two requirements allow the integrator to interact with the SimEnv as a normal updateable SimObj thus simplifying the SimEnv and allowing multiple integrators to exist simultaneously.

An integrator implementation accomplishes integration by maintaining a list of all the ODEProvider objects that require integration services. At each time step the integrator’s IUpdateable.Update method is called. At that point the integrator should collect each ODEProviders state and derivative values and simultaneously integrate each state variable. Multi-step integration methods (e.g. Runge-Kutta) are made possible by iteratively calling the ODEProviders's GetState/SetState and GetDeriv methods.

The ModCom library (ModComLib) has an implementation of IIntegrator that provides several methods of integration. These methods are listed in Table 1. The ISimEnv implementation supplied with the ModCom library uses the IIntegrator implementation to provide integration services automatically. When a SimObj that implements the IODEProvider interface is registered with the SimEnv the object is, by default, scheduled for integration services. Therefore, most modelers will not need to concern themselves with the IIntegrator interface – its use is transparent. However, for those wishing to implement specialized integrators, this interface allows them to do so, and have the resulting component integrate seamlessly with the framework.

Table 1 Integration methods available with the default IIntegrator implementation

Method Name	*Description*
Euler	Simple Euler finite difference method
RK2	Second Order Runge-Kutta method
RK4	Fourth Order Runge-Kutta method
RKF	Fifth order adaptive Runge-Kutta-Feldberg method
RKCK	Fifth order adaptive Runge-Kutta-Feldberg method using Kash-Karp coefficients

Exposable Data and the ISimData Interface

An important capability of any module-based framework is the ability for different components in the framework to be able to communicate and pass information between each other. The framework defines the ISimData interface for allowing data to be exchanged between SimObjs via a series of ISimObj methods. The framework provides a default implementation for ISimData that should satisfy most data exchange needs. Hence individual components should not need to provide an implementation of this interface.

The ISimObj interface defines methods to allow a SimObj to expose any data it wants to make public. This information can be an internal SimObj variable or a derived variable resulting from a computation. The SimData are accessible to other SimObjs via the ISimObj.Output property. As the property name implies SimData exposed via the Output property are intended to be used by other SimObjs, not written to. The ISimObj interface also has an Input property that allows a SimObj to define what information the SimObj itself will use. This combination of Inputs and Outputs defines a rudimentary asynchronous data flow model for combining modules.

The data stored in a SimData is exposed on the interface (and stored internally) as a VARIANT type. The VARIANT data type is a Microsoft standard for containing both fundamental data types such as strings or floating-point variables, and abstract data types in a language neutral manner. As such, a broad range of types can be exchanged between objects using SimData. ISimData defines methods for accessing the VARIANT directly, or as a scalar type (i.e. integer, floating point or string). In addition to providing data, a SimData can provide descriptive information about itself through the ISimInputInfo and ISimOutputInfo interfaces. These two interfaces provide information about the SimData such as data type, physical units, and runtime behavior.

Exposing a variable (one that the module wishes to make available to other components) involves the following steps. First, a SimData is instantiate for each datum that will be exposed. Second, the SimData is made available to other SimObjs (and the SimEnv) via the ISimObj.Output property. Finally, the ISimData.Value property of the SimData instance is maintained by the SimObj throughout the SimObj's lifetime. A detailed example of this procedure is available in the ModCom users guide (see Availability of Software).

Connection Protocols for Inter-object Communication

The ISimEnv interface is responsible for maintaining a store of SimData references; it serves as a "broker" of the data. In addition to storing these variables, the SimEnv automatically builds data reference collections based on the SimObjs exposure of SimData, and allows for querying for specific variables by other objects in the system.

Importing an output from one component to use in another can occur in one of two ways. In a loosely coupled system, where each component has no knowledge of the other a SimObj can query the SimEnv, prior to conducting a simulation. The queried SimData can then be assigned to a SimObj's Input property and can used as a source of information during a simulation. This process of coupling one SimObj's output to another's input can be performed by the objects themselves or by some object acting outside the SimEnv (e.g. a simulation tool).

In a more tightly coupled system, SimObjs can request information (specific SimData) from other components that the SimObj knows about without querying the SimEnv. This method allows greater efficiency of data exchange. The second approach should be used cautiously, as one of the advantages of the framework is the ability to loosely couple objects. In either case, the queries for SimData will return a reference to the SimData exported by another component; the querying object should store this reference (as an input SimData) and refer to it as needed through the ISimData interface methods.

Data Management Services

One of the core services provided by the framework is data management. Virtually all simulations involve the reading, manipulation, sharing, and writing of data. The framework provides a standard method for defining data flow and representation to facilitate data-related simulation tasks. These services are provided through the use of four interfaces: IRowColDataset, ICollectOutput, IDataReader, and IDataWriter.

IRowColDataset

Because "rectangular" datasets, tabular data arranged in rows and columns, are ubiquitous in simulations, support for such datasets is provided by the framework through definition of and implementation of the IRowColDataset. This interface provides methods for accessing, creating, and managing a rectangular dataset based on the VARIANT data type.

IDataReader and IDataWriter

The IDataReader and IDataWriter are intended to provide access to stores of IRowColDataset's. Both interfaces provide a means to specify the source of the data, cause the data to be loaded or stored, and the means to access the data as an instance of IRowColDataset. It is assumed that a class that implements IDataReader or IDataWriter will provide access to a specific type of database. For example, one

DataReader may provide access to tables through the Microsoft ADO API while another might use specially formatted text files. The purpose behind including IDataReader and IDataWriter is to allow developers to leverage existing code bases for reading and writing specialized data files.

ICollectOutput

Implementation of ICollectOutput provides an object participating in a simulation the opportunity to record its output during a simulation. The interface also exposes the recorded data as an IRowColDataset allowing interoperability with the IDataReader and IDataWriter interfaces. The rate at which output collection occurs is specified by the SimObj independently of the update rate of the SimObj. Scheduling of output collection is handled automatically when the SimObj is registered with the SimEnv.

Using ModCom

ModCom can be used to assemble and execute a simulation by connecting MODCOM-compliant components. If the required components are not available, a developer can create them by implementing specific ModCom interfaces with a COM enabled development environment such as VisualBasic, VisualC++, or Delphi. When creating a SimObj, each component must at least implement ISimObj. SimObjs whose inputs and outputs will changes regularly during a simulation should implement IUpdateable. Objects that represent ODE's should implement IODEProvider.

There are some design issues that should be weighed when building a SimObj. The ModCom framework defines SimObjs with the intent that they will be combined with other SimObjs to assemble a simulation. The SimObjs are, logically, parts of (or sub-models of) some larger model. When creating a SimObj the designer should keep in mind that the SimObj will be used as a part of a simulation rather than a simulation by itself.

SimObjs built with ModCom can be distributed in binary form as well as in the traditional form of source code. The SimObjs, once registered on a user's computer, are available in any COM enabled development environment (e.g. Excel, Visual Basic, Delphi, etc.). Building and running a simulation with ModCom involves five basic steps. An example simulation involving a predator/prey system is shown in Figure 2.

```
Sub Macro1()
'
' Example Predator Prey simulation
'
    'Step 1: create the SimObjs and SimEnv
    Dim env As New SimEnv
    Dim predator As New Predator
    Dim prey As New Prey
    Dim preyData As RowColDataset
    Dim predData As RowColDataset
    Dim i, rows As Integer

    'Step 2: register the SimObjs
    env.Register prey
    env.Register predator

    'Step 3: connect the SimObjs
    prey.Input(0) = predator.Output(0)
    predator.Input(0) = prey.Output(0)

    'Step 4: run the simulation
    env.StartTime = StartTime 'variables copied from the
worksheet
    env.StopTime = StopTime
    env.Run

    'Step 5: copy data into the worksheet
    Dim output As ICollectOutput
    Set output = prey
    Set preyData = output.DataObject
    Set output = predator
    Set predData = output.DataObject

    rows = predData.rows
    For i = 0 To rows - 1
       Worksheets(1).Cells(i+1, 1).Value = predData.Get(i, 1)
       Worksheets(1).Cells(i+1, 2).Value = preyData.Get(i, 1)
    Next i

End Sub
```

Figure 2 Predator/Prey example written with Excel VBA.

In this example (written in Excel VBA) the SimObjs, `predator` and `prey`, both implement a single differential equation. When solved together they represent a simple Lotka-Voltara type predator prey system. The input and output values exposed via the SimObj interface represent the predator and prey densities. While this program may be of little practical value, it demonstrates the potential of modular simulation. First, the details of integration management are hidden in the SimEnv. Second, suppose the author wanted to consider the effect of a more complex predator. Using a different SimObj to replace the existing predator would only require that the example code be changed (in fact, only the declaration). The SimEnv, and the existing prey SimObj would not require any modification. Furthermore, a new predator could be written in a different language from the existing prey or the example program.

Because of space limitations we cannot show the implementations of the predator and prey classes. Microsoft COM code tends to be especially verbose however much of it is generated automatically by COM enabled development environments. A complete implementation is available at the ModCom website (see Availability of Software) as well as a users guide that provides a detailed description of how to build a SimObj.

There is an additonal method of using ModCom that involves no programming at all. One of the design goals for ModCom was to enable visual model assembly tools. An additional interface, ISimObjView, was defined for this purpose. The ISimObjView interface allows SimObjs to display themselves and provide display information to visual design tools. One such tool being developed to use the ModCom interfaces is the Visual Modeling Environment (VME). It allowes users to connect SimObjs by manipulating graphical representations of the objects. Using VME users can assemble models from existing components without programming.

Conclusions

ModCom is a robust and versatile framework for developing and using agro-ecological simulations. The framework is language neutral; ModCom Simulation Objects can be developed in any language environment that supports COM. The framework is also fully extendable. Any component can be replaced with a different implementation without affecting the other components. Numerical integration services, time flow synchronization, and data exchange services all simplify the development of simulation modules and facilitate a “plug & play” style of modular simulation.

At present all of the core simulation management services have been implemented. Rigorous testing has been performed and the ModCom library is stable. A test suite was developed concurrently with the library to help with debugging and as an exact expression of the libraries runtime specifications. The test suite covers all of the functionality provided by the ModCom library and is available with the ModCom distribution. Current activities involve two areas of development. First, we are working with several other groups to develop a set of modules that will be of practical use to agro-ecological modelers. The second area of development involves further development of the ModCom framework. In particular we are developing tools that will automate parts of the module construction process. These tools will integrate with several development environments (e.g. Visual C++, Visual Basic, Delphi, etc.) and will be provided as part of the ModCom distribution.

Availability of software

The ModCom source code, and associated development materials are available on the web at http://biosys.bre.orst.edu/modcom.

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The Irrigation Efficiency Model: a simulation tool for producing optimal irrigation strategies

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Introduction

One of the goals of conventional irrigation scheduling is to avoid plant stress. The National Engineering Handbook (NRCS, 1997) recommends that soil moisture be kept at or above the level where plant stress occurs (cite). Similarly, FAO24 defines the irrigation water requirement as "the evapotranspiration rate required … for full production potential" (Doorenbos and Pruitt, 1992). An implicit assumption made in each of these recommendations is that there is enough water and other resources available to reach full potential and avoid stress. Often these resources are not available. Table 2 shows a summary of the USDA Farm And Ranch Irrigation Survey Table 26, "Farms with Diminished Crop Yields Resulting from Irrigation Interruption by Cause", from the last four survey years (USDA, 1995, 1999, 2004, 2009). Shortage of surface or ground water accounted for 63% of the farms that reported diminished crop yield from interrupted irrigation in the 2008 survey. Water shortages are not an uncommon occurrence in US farms.

Table 2 USDA Farm And Ranch Irrigation Survey, Table 26 Summaries

	Farms Surveyed		*Farms With Diminished Yield*		*Percentages*	
Year	Farms	Acres	Farms	Acres	Farms	Acres
2008	206,834	198,160,896	33,052	8,997,812	15.98%	4.54%
2003	210,106	195,969,172	39,887	10,192,594	18.98%	5.20%
1998	182,101	175,944,902	23,724	9,969,458	13.03%	5.67%
1994	198,195	184,876,643	32,722	9,687,248	16.51%	5.24%

IEM has been designed for irrigation management in a water short or resource limited context. Where conventional SIS is focused on maximizing yield (a biological objective) IEM/IMO attempts to help the user optimize net returns from water use (an economic objective). The latter task involves different assumptions and a different tool set. Irrigation optimization is the process of allocating water according to one or more specific goals rather than only maximizing production (English et al., 2002). Optimization may have many goals including maximizing net returns, minimizing costs, maximizing yield, optimal distribution of limited supplies, managing ground water pollution, or compensating for limited irrigating capacity (Martin et al., 1990). Implementing irrigation optimization presents several challenges, three of which are addressed below.

First, optimization implies some level of deficit irrigation. The level is not arbitrary and must be carefully managed to avoid unnecessary yield loss. Therefore, in order to plan irrigations based on expected yield reduction yield estimates must be simulated alongside soil moisture estimates. Second, efficiency is linked to irrigation intensity. One of the techniques for implementing optimization involves changing set durations, application rates, system flow rates, as well as delaying irrigation events. These changes will mean that the nominal design efficiency will no longer be adequate for estimating losses. In order to account for these changes efficiency must be simulated rather than assumed. Third, limitations in water allocation and delivery capacity usually apply to all or many fields simultaneously. Any attempt to optimize irrigation when supplies are limited must be sensitive to farm level constraints. Finally, optimization applies not to individual fields but to the whole farm. Most farms have more than one field. Costs are Revenues from each field apply to the whole farm. No field can be considered or optimized in isolation unless there are no constraints on irrigation. Thus, an irrigation scheduler must generate schedules for all fields conjunctively if resource limitations are to be considered at a farm level. (Martin and van Brocklin, 1989) demonstrated some of the complexities of multi-field scheduling using dynamic programming to schedule irrigations for a mix of crops. Lamacq et al. (1996) used a farm simulation to demonstrate how, for center pivots, improved labor practices, and deficit irrigation where important adjustments for dealing with reduced water supplies.

Oregon State University and the NRCS have cooperatively developed a tool for implementing irrigation optimization. This tool is composed of two separate systems: the Irrigation Efficiency Model (IEM) and Irrigation Management Online (IMO). IEM is a simulation tool that models the disposition of water during irrigation, forecasts crop water requirements, and generates irrigation management recommendations. IEM uses a simulation model that is robust enough from a physical perspective to simulate conditions associated with reduced irrigation and robust from a management perspective to generate irrigation recommendations that are practical given a set of management constraints. IMO is a web application that provides user interface components and algorithms that allow managers to use IEM & IMO to implement optimal irrigation scheduling. The purpose of this paper is to describe, in detail, IEM. Some of the outputs produced by IMO will be used here to demonstrate the features of IEM however; a full description of IMO will be presented in a second paper.

Of the challenges presented, being sensitive to resource availability constraints is one issue not addressed by IEM in a conventional way. IEM is aware of some of these constraints and tracks when they are violated but does not enforce the constraints when generating irrigation schedules. Typical optimization systems seek to produce a solution while, at the same time, keep the solution within the specified constraints.

IEM does not do this. The constraints that affect water supply and delivery and power availability are varied, complex, and in some cases unique to local conditions. Attempts to codify these constraints will always be incomplete. Instead, the IMO system is built such that the user can enforce the constraints as they choose. In this way, the user becomes an integral part of the optimization process.

Model Description

IEM uses a water balance model as the basis of its soil moisture estimates. The representation is different from most water balance models used in irrigation scheduling in that IEM does not use a daily time step. The components of the water balance are expressed as ordinary differential equations rather than finite difference equations. A numerical integration method (explained in the next section) is used to solve these equations during the simulation. The numerical method uses a variable size time step where the step size is proportional to the error associated with the estimates.

By expressing the model as an Ordinary Differential Equation and using variable time step integration, IEM is able to simulate processes that occur over a broader temporal range than is possible with a daily time step without being constrained to a small time step. Schedulers that use a daily time step must express water balance components as cumulative amounts occurring over a 24 hour period. Processes that occur at time scales smaller than 24 hours (e.g. infiltration and runoff) must be simulated with models that have exact solutions with respect to time.

Water Balance

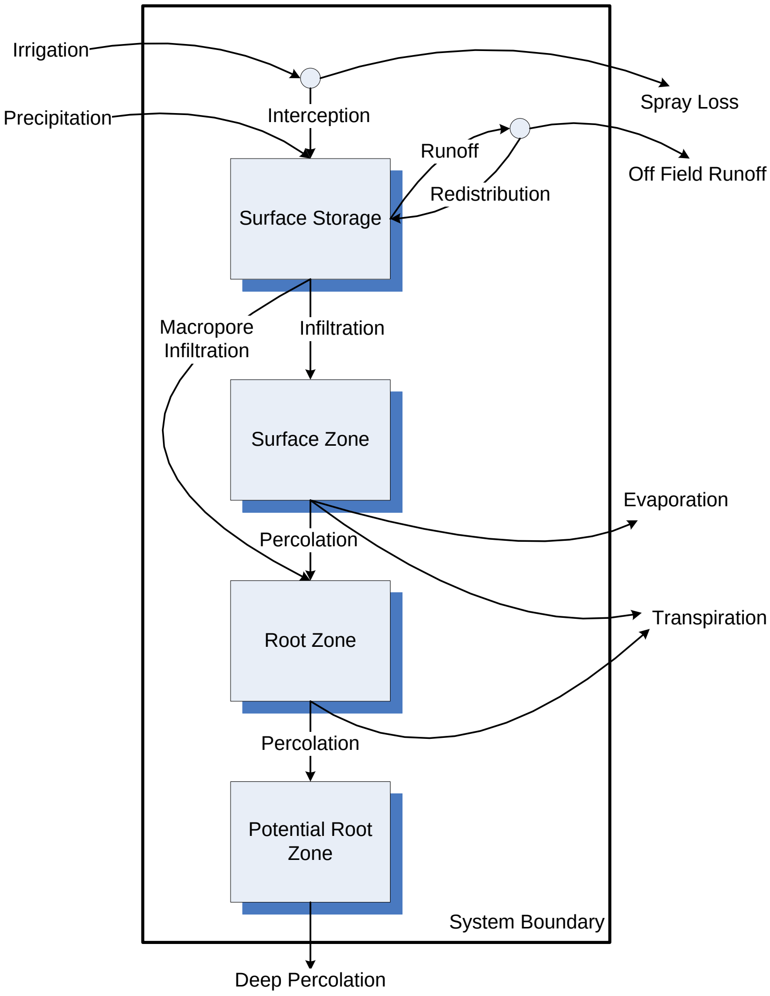


Figure 3 System Diagram of the IEM water balance

Figure 3 shows a system diagram depicting the IEM water balance. Eqns. [1]- [4] are the ODEs for each of the state variables and Table 3 shows names and physical units for each of the terms used in the ODEs. The blocks in Figure 3 represent the state variables and the arcs represent the water flows to and from the state variables. The water balance is composed of three soil layers and a surface storage compartment.

The top layer is the evaporative layer, which has a fixed width. The second layer is the root zone which increases in width during the simulation. The third layer is the potential root zone which decreases in width during the simulation.

$$\frac{dW_{SS}}{dt} = P + R_{On} - R_{Off} - Inf_{Surface} - Inf_{Macro} + Irr \qquad [1]$$

$$\frac{d\theta_{SZ}}{dt} = (Inf_{Surface} - Perc_{SZ} - ET_{SZ})/z_{SZ} \cdot 10 \qquad [2]$$

$$\frac{d\theta_{RZ}}{dt} = (Inf_{Macro} + Perc_{SZ} - Perc_{RZ} - ET_{RZ})/z_{RZ} \cdot 10 \qquad [3]$$

$$\frac{d\theta_{PZ}}{dt} = (Perc_{RZ} - Perc_{PZ})/z_{PZ} \cdot 10 \qquad [4]$$

Table 3 Description of terms used in water balance equations 1 - 4

Symbol	*Name*	*Units*
W_{SS}	Surface storage	mm
θ_{SZ}	Surface zone volumetric moisture content	mm/mm
θ_{RZ}	Root zone volumetric moisture content	mm/mm
θ_{PZ}	Potential root zone volumetric moisture content	mm/mm
P	Precipitation	mm
R_{On}	Incoming surface redistribution (‘run on’)	mm/day
R_{Off}	Outgoing surface redistribution (‘run off’)	mm/day
$Inf_{Surface}$	Infiltration	mm/day
Inf_{Macro}	Macropore infiltration	mm/day
Irr	Irrigation water applied	mm/day
$Perc_{SZ}$	Percolation out of surface zone	mm/day
$Perc_{RZ}$	Percolation out of root zone	mm/day
$Perc_{PZ}$	Percolation out of potential root zone	mm/day
ET_{SZ}	Evapotranspiration from surface zone	mm/day
ET_{RZ}	Evapotranspiration from root zone	mm/day
z_{SZ}	Width of surface zone	cm
z_{RZ}	Width of root zone	cm
z_{PZ}	Width of potential root zone	cm

Crop ET

Crop evapotranspiration appears in the rate equations as $\mathrm{ET}_{\mathrm{SZ}}$ and $\mathrm{ET}_{\mathrm{RZ}}$ for the surface and root zones respectively. These rate values are calculated using a modified version of the FAO 56 dual crop coefficient model (Allen et al., 1998).

Total Evaporable Water (mm) (FAO 56, p.144, eq.73)

$$\mathrm{tew} = 10(\Theta_{\mathrm{FC}} - \frac{1}{2}\Theta_{\mathrm{PWP}})\, z_{\mathrm{SZ}} \qquad [5]$$

Soil Evaporation Reduction Coefficient (FAO 56, p.146, eq.74)

$$k_r = \begin{cases} 1, & \mathrm{D} < \mathrm{rew} \\ \dfrac{\mathrm{tew} - \mathrm{D}}{\mathrm{tew} - \mathrm{rew}}, & \mathrm{D} \le \mathrm{rew} \end{cases}, \qquad [6]$$

where

$$\mathrm{D} = \begin{cases} (\theta_{\mathrm{FC}} - \theta_{\mathrm{SZ}}) z_{\mathrm{SZ}} 10, & \theta_{\mathrm{SZ}} < \theta_{\mathrm{FC}} \\ 0, & \theta_{\mathrm{SZ}} \ge \theta_{\mathrm{FC}} \end{cases} \qquad [7]$$

and rew is the readily evaporable water in FAO 56, Table 19.

Fraction of Evaporable Water (FAO 56, p147, eq.75), assuming entire surface is wetted (ignoring fw)

$$\mathrm{few} = 1 - \mathrm{fc} \qquad [8]$$

Where fc, the average fraction of soil surface covered by veg, is calculated as per eqns 72 & 76 in FAO56.

Soil Evaporation Coefficient (FAO 56, p.142, eq.71)

$$\mathrm{k_e = Min(k_r \cdot (MaxKCrop - k_{CB}), few \cdot MaxKCrop)} \qquad [9]$$

Where FAO 56, p143, eq.72 is used to calculate MaxKCrop.

The Total Available Water (TAW) in the root zone (FAO 56, p.162, eq.82)

$$\mathrm{TAW} = (\theta_{\mathrm{FC}} - \theta_{\mathrm{PWP}})\mathrm{z_{RZ}}10 \qquad [10]$$

Was replace with a partitioning of TAW in to the surface, and root zone layers. The equation for TAW

$$\mathrm{TAW_{SZ}} = (\theta_{\mathrm{FC}} - \frac{1}{2}\theta_{\mathrm{PWP}})\mathrm{z_{SZ}}10 \qquad [11]$$

$$\mathrm{TAW_{RZ}} = (\theta_{\mathrm{FC}} - \theta_{\mathrm{PWP}})\mathrm{z_{RZ}}10 \qquad [12]$$

Root Zone Depletion, mm (adapted from FAO 56, p.170). Instead of the difference equation (FAO 56, eq.85) we use the root zone water (Θ_RZ) to calculate the current depletion amount in both the surface zone and the current root zone. In both cases the depletion is constrained to be less than the Total Available Water in its respective layer.

$$D_{SZ} = \mathrm{Min}((\theta_{FC} - \theta_{SZ}) z_{SZ} 10, \mathrm{TAW}_{SZ}) \qquad [13]$$

$$D_{RZ} = \mathrm{Min}((\theta_{FC} - \theta_{RZ}) z_{RZ} 10, \mathrm{TAW}_{RZ}) \qquad [14]$$

The Soil Water Depletion Fraction is the fraction of AWHC that can be extracted without crop stress. In earilier versions of IEM this quantity was calcuated by interpolating values from FAO 33, Table 20. Instead the following is used (:

$$p = \begin{cases} p_c, & ET_{max} \le 2 \\ p_h, & ET_{max} \ge 10 \\ p_c - \dfrac{ET_{max} - 2}{8}(p_c - p_h), & \text{otherwise} \end{cases} \qquad [15]$$

Where

$$ET_{max} = ET_{ref}(k_{CB} + k_e) \qquad [16]$$

IEM uses either tall crop (alfalfa), or short crop (grass) reference ET based on the source of the crop coefficient data. Two sources of crop coefficient data are included: ARIMET, and crop coefficients used by the CIMIS (Snyder, personal communication). ET_{ref} is assigned an appropriate (tall or short crop) value by the weather object prior to starting the ET calculations. The crop stress coefficient (FAO 56, p.167, eq.84) is caluclated using the boundary equation (FAO 56, p.162, eq.83) defined as

$$\mathrm{k_s} = \begin{cases} 1, & \mathrm{D_t} < \mathrm{p} \cdot \mathrm{TAW} \\ \dfrac{\mathrm{TAW} - \mathrm{D_t}}{(1-\mathrm{p})\mathrm{TAW}}, & \mathrm{D_t} \geq \mathrm{p} \cdot \mathrm{TAW} \end{cases} \qquad [17]$$

where,

$$\mathrm{D_t} = \mathrm{D_{RZ}} + \mathrm{D_{SZ}} \qquad [18]$$

although we ignore the depletion in the surface zone bcause it us usally trivally small. Crop ET adjusted for water stress (FAO 56, p.161, eq.80)

$$k_c = \mathrm{Min}(k_{cb}\, k_s + k_e\,, MaxKCrop)$$

$$ET_c = k_c\, ET_r$$

Partition total et between surface zone (surfaceZoneDepth), and current root zone (rootZoneDepth) and limit so that ET is 0 when theta < 0.5PWP for surface zone and ET is 0 when theta < PWP for current root zone

$$W_{SZ} = \begin{cases} (\theta_{SZ} - \frac{\theta_{PWP}}{2}) z_{SZ} 10 & \theta_{SZ} > \frac{\theta_{PWP}}{2} \\ 0 & \text{otherwise} \end{cases} \quad [19]$$

$$W_{RZ} = \begin{cases} (\theta_{RZ} - \theta_{PWP}) z_{RZ} 10 & \theta_{RZ} > \theta_{PWP} \\ 0 & \text{otherwise} \end{cases} \quad [20]$$

$$W_t = W_{SZ} + W_{RZ} \quad [21]$$

$$ET_{SZ} = \begin{cases} \frac{ET_{SZ} \cdot k_e}{few} & \theta_{SZ} > \theta_{PWP} \\ 0 & \theta_{SZ} \le \theta_{PWP} \end{cases} \quad [22]$$

$$ET_{RZ} = \begin{cases} ET_C & \theta_{RZ} > \theta_{PWP} \\ 0 & \theta_{RZ} \le \theta_{PWP} \end{cases} \quad [23]$$

When simulation time is before planting date or after harvest date the ET rates are all assumed zero.

Crop

The crop component contains methods for interpolating the basal crop coefficient K_{cb} and the crop related equations defined in FAO 56. The crop component also contains the yield model calculations.

Basal Crop Coefficient

IEM can use either the four segment Kcb curve as defined in FAO 56 & FAO 24 (when the CIMIS network is used) or a 20 segment Kcb curve as defined by AGRIMET. The two weather networks that are used by IEM/IMO both have separate sets of crop coefficients and each crop definition in the database contains information indicating which functional form of the curve to use.

Percolation

IEM calculates percolations using the method described by Isbell (2005) which is based on a modified version of the model proposed by Nielsen et al. (1973).

Infiltration

IEM has two methods for calculating infiltration rates. Both are based on the Phillips model (cite). The first calculates the infiltration rate (mm/day) using the derivative of the Phillips equation. The second calculates in instantaneous infiltration depth (mm) using the integrated form of the Phillips equation. The sorptivity term in the Phillips equation is approximated using Dingman eq. 6-18, p.235. The basic form of the Phillips equation assumes that the application rate is constant with respect to time. When pivot or linear move systems are used the application rate is assumed to be parabolic and the time to ponding and infiltration depth are solved using a 3rd order power series approximation.

The first method is used whenever there is water present in the surface storage compartment ($W_{ss} > 0$) and when there is available capacity in the current root zone (i.e. when $\theta_{RZ} < \theta_{SZ}$).

The second method is used only when an irrigation event occurs.

$$J = \frac{S_p}{2\sqrt{d}} + K_{sat} \qquad [24]$$

d = duration of event (days), K_{sat} is the saturated hydraulic conductivity, and S_p is the Phillips sorptivity. S_p is approximated using Dingman eq. 6-18, p.235.

For Pivots a parabolic application rate is defined as

$$I(t) = 6\frac{h}{d^2}t - 6\frac{h}{d^3}t^2 \qquad [25]$$

This gives an application rate curve with area equal to the depth applied (h) and width equal to the time it takes the pivot to pass over the field sector (d).

A 3rd order power series is used to approximate the Phillips curve and is used to solve for the intersections of the infiltration rate curve and the application rate curve. These intersections define the time of ponding and the time when the infiltration rate exceeds the application rate after ponding. From these points we solve for the depths of infiltration and ponding separately. The infiltrated depth is then partitioned into each of the soil layers. The ponded depth is added to the surface storage (W_{SS} in Table 3) and infiltrates over time according to the first infiltration method.

Root Zone Depth

Root zone depth increases at a daily time step and the depth is estimated using a model from Borg & Grimes (1986). The model is defined as:

$$\mathrm{dtm} = \mathrm{FullCoverDate} - \mathrm{PlantingDate}, \qquad [26]$$

$$\mathrm{dap} = \begin{cases} \mathrm{PlantingDate} - \mathrm{t}, & \mathrm{PlantingDate} \ge \mathrm{t} \ge \mathrm{HarvestDate} \\ 0, \text{ otherwise} & \end{cases}, \qquad [27]$$

$$\mathrm{z}_{\mathrm{RZ}} = (\mathrm{RZ}_{\mathrm{Max}} - \mathrm{RZ}_0)\left[\frac{1}{2} + \frac{1}{2}\sin\left(3.03 \cdot \left(\frac{\mathrm{dap}}{\mathrm{dtm}}\right) - 1.47\right)\right] + \mathrm{RZ}_0, \qquad [28]$$

The root zone depth is constrained to be one cm less than soil depth value generated when the field sector is created and one cm greater than the surface zone depth. These one cm boundaries prevent floating point divistion errors casued by zero width soil layers.

As the root zone increases in size fractional amounts of water are moved from the potential root zone layer to the current root zone layer. Doing this preserves the water balance as the root zone increases. We chose finite difference approach is used because the model is expressed as a function of time rather than a rate. A derivative of the model could be used but this would require adding another state variable which would incrase computational load.

Spray Loss

Spray loss is calculated according to the SCS method as described in (NRCS, 1997).

Runoff and Redistribution

Surface redistribution is based on an empirical algorithm which routes water to each FieldSector. The depth of water that each sector receives depends on the total depth of runoff across the field and a random weighting vector that is generated at the beginning of the simulation.

Spatial Variability

The importance of spatial variability in irrigation has been recognized for some time. Bernardo (1988) showed that spatial non-uniformity is a significant source of risk. Similarly, Sadler et al(2005) concluded that DI requires precision irrigation that, in turn, requires improved spatial and & temporal resolution. IEM simulates spatial variability through a Monte Carlo approach. To demonstrate how IEM does this consider the field shown in Figure 4. This field is composed of two soil types having different physical characteristics. Figure 5 shows a histogram of measured holding capacities for the field. Representing this field with 'average' properties would effectively misrepresent the entire field. Half of the field would be under irrigated and the other half over irrigated. IEM avoids this problem by performing replications of the water balance described previously. Each of these replications is called a Field Sector and is conceptually similar to simulating a water balance of the soil around a single neutron probe access tube. The similarity lies in that at a field scale the volume measured by a NP can be construed as a point measurement. The Field Sector is also construed as a point in the field, however its exact spatial location is not considered. Instead the field is partitioned by soil type (or depth if it is significantly different), and the Field Sectors associated with the partitions. When a simulation is created Field Sectors are instantiated using a template representing the soil physical properties. Two of these properties are randomly generated: Available Water Holding Capacity, and Soil Depth. A normal distribution is used by default and the mean and variance are part of the templates variables. Other distribution types are available in IEM but they have not been tested. The number of Field Sectors created from each template is proportional to the percentage of the field area occupied by each soil type.

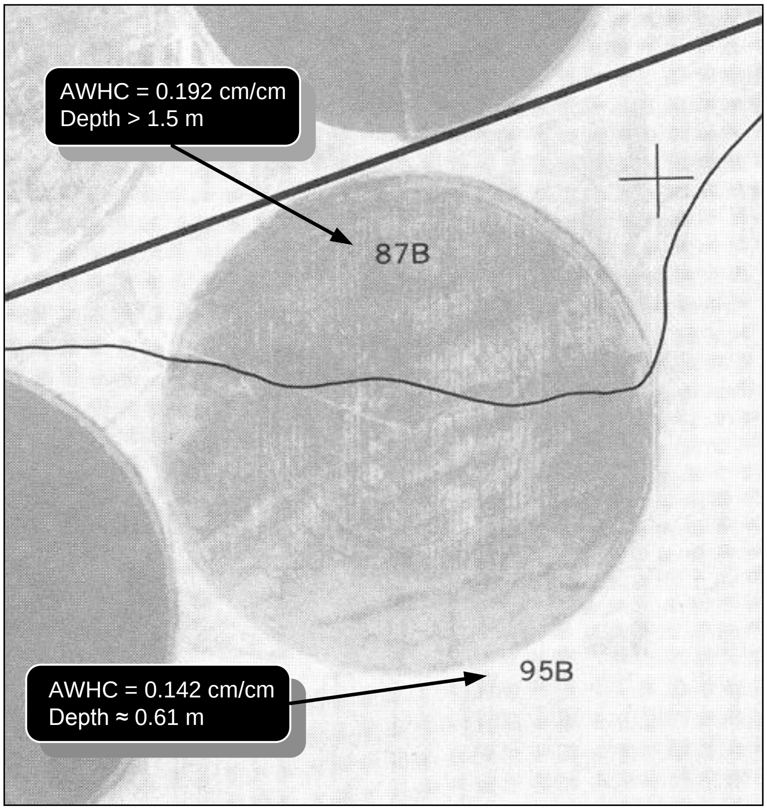


Figure 4 A field with two soil types

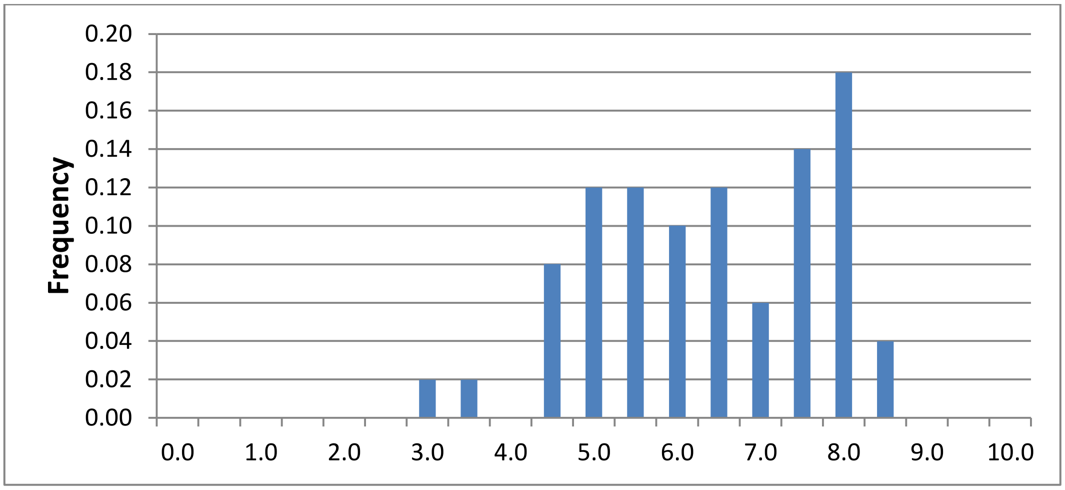


Figure 5 Histogram of measured field capacities

By using the Monte Carlo approach, IEM is able to simulate spatial variability without being spatially explicit in the geometric sense. The Field Sectors are points and thus have no area in a two dimensional space. With a geometric representation, the scale of the processes represented will determine the size of the geometric elements that make of the field. If the model were spatially explicit, the computational load would be proportional to the area of the field. Instead, IEM's load is proportional to the degree of spatial variability. An additional advantage is that IEM has a degree of spatial scale independence. By avoiding a geometric spatial representation, IEM also avoids scale constraints associated with the size of the geometric elements. So long as the Field Sector can be construed as a point in the field then the scale independence will hold. A disadvantage of this approach is than adjacency information cannot be represented. This shortcoming is manifested in the surface redistribution model in that no specific routing of flow between the sectors can be represented.

IEM simulates application non-uniformity by treating the applied depth in the i^{th} sector, d_i, as a random variable defined as

$$d_i \sim N(D, \sigma_d) \qquad [29]$$

Where D is the expected depth of application for a perfectly uniform system and σ_d is the variance of applied depth.

Irrigation events are simulated by generating a value of di for each sector, each time an event occurs. The order and timing of when an individual sector receives water depends on the total event time and the irrigation system type (the details of the system specific properties are in the next section). If the events are longer than the weather measurement interval, a new value for σ_d is calculated before generating additional depth values.

The variance, σ_d, is estimated using the method described in the original IEM implementation (English et al., 1992). First a uniformity coefficient (UC) is estimated using

$$UC = A_0 + A_1 w + A_2 w^2,$$

where w is wind speed in m/s. Then σ_d is calculated using

$$\sigma_D = 1.235\,D(1 - UC).$$

The coefficients used in the UC equation were specified in the original IEM as shown in Table 4. The continuous move system values were derived from data published in Jensen (1981), Ganger (1980), and Rapp et al (1979). The wheel line systems were taken from Pair (1967), and the solid set values from McBride (1973). The Drip/Micro coefficient was estimated based on consultations with UC Davis farm advisors.

Table 4 Uniformity equation coefficients

System Type	A_0	A_1	A_2
Continuous Move	0.9	0	0
Wheel Line	0.87	-0.00298	0
Solid Set	0.90	-0.0264	-0.0031
Drip/Micro	0.95	0	0

In drip irrigation only a portion of the soil volume is wetted. This is also true in micro sprinkler systems where the spray only covers a portion of the surface. In some cropping systems (orchards in particular) and micro sprinkler systems the root zone will extend beyond the wetted volume. In some cases the antecedent moisture content in the non-wetted portion can be large enough to contribute to the final ET estimates. IEM accounts for this by introducing a parameter that represents the percentage of the root zone that is wetted during irrigation events. If this parameter is less than 100% only a fraction of the Field Sectors will receive water during an irrigation event. Selection of an appropriate value is left to the discretion of the user.

Energy Use

In the western US irrigation and power use are closely linked (cite?). This is especially true in the Pacific Northwest where hydropower is a significant source of energy. IEM includes these factors in its analysis by incorporating components that estimate energy use and costs associated with pumping. The central component in this analysis is the PumpingPlant. Each irrigation system can be associated with a single plant which designates that plant as the system's water source. Pumping plants can also be associated with each other to indicate that one plant supplies water to another. A single plant can supply more than one irrigation system or pumping plant, but each system can have only one supplier. The pumping plants are composed of a set of Pump and Motor objects. Each Pump has an associated pump curve (modeled as a 3^{rd} order polynomial) used for defining the flow-head relationship. Pumps can be connected in series or in parallel and each motor can drive one or more pump. During a simulation the pumping plant monitors the irrigation systems and estimates the total system flow (m3), cumulative poser use (kW-h), peak power use (kW), and total cost of use for the pumping plant. Also included in the specification are the power rating of the motors, the total system supply capacity (m3/sec), and maximum head (m) and the plant tracks when these limitations are exceeded during a simulation.

While the calculations for estimating energy use are well understood, the typical procedure for doing these calculations involves describing a flow network. This is done in order to estimate head losses. One of the design goals was to make the component as simple as possible. The burden is on the user to provide the information required to describe a flow network (pipe materials, elevations, fittings, etc.). Removing this burden makes the power component simpler and reduces the complexity for the user. To that end some assumptions where made that makes head loss calculations unnecessary. These assumptions are 1) the entire flow network and each irrigation system is pressure regulated, 2) the manager never operates the system at a flow rate that is below the pressure regulation point. By making these two assumptions, and using some numerical methods, we can assume that the total system flow rate is the sum of all the operating irrigation systems and a pump curve can be used to estimate the head produced. The Pressure vs. Flow curve and Efficiency vs. Flow are each represented by a third order polynomial. For pumps in series, the procedure is direct because the head produced is the sum of all pumps operating. For parallel pumps, the situation is more complex because we must calculate the Q of each individual pump.

The total cost of pumping is based on two factors: peak power use, and the cumulative power use. The peak is simply the maximum kW value observed multiplied by a cost per kW. The cumulative power use calculations can include variable rate pricing schemes. These variable rate schemes are common incentives offered by power utilities to encourage use during off-peak times. These pricing schemes vary by utility district and may have multiple price levels, may vary by time of day or day of week, and the levels may change monthly or quarterly. IEM uses a hierarchical data structure to accommodate virtually any pricing scheme.

Yield Estimation

IEM uses the parameter $\mathrm{Available\ WaterAtMaxYield}$ to define depth of application at which yield reduction from over irrigation occurs. When the cumulative infiltration is greater than this value the Solomon yield reduction equation is applied.

Yield reduction caused by water stress is calculated according to the FAO 33 model.

$$YR_{FAO33} = \begin{cases} 1 - k_r\left(1 - \dfrac{CET_C}{CET_{MaxYield}}\right), & CET_C \le CET_{MaxYield} \\ 1, & CET_C > CET_{MaxYield} \end{cases}$$

The Cumulative Yield @ Max ET and Water Applied @ Max Yield are both specified on a per-field basis rather than being associated with the crop definition. This distinction allows field specific calibration of the yield parameters.

Yield reduction caused by over irrigation is calculated using the model from Solomon (cite)

$$w = \frac{\text{Actual Available Water}}{\text{Available Water At Max Yield}}$$

$$x = c_0 + c_1 w + c_2 w^2 + c_3 w^3 + c_4 w^4$$

$$YR_{Solomon} = \begin{cases} x & x > 0 \\ 0 & x \le 0 \end{cases}$$

The actual Yield, Y_a, is calculated as

$$Y_a = \begin{cases} Y_M \cdot YR_{FAO33} & AW_A < AW_{@MaxYield} \\ Y_M \cdot YR_{Solomon} & AW_A \ge AW_{@MaxYield} \end{cases}$$

Given the parabolic form of the Solomon model negative Y_a are possible. When this occurs, the yield is assumed zero.

Soil Moisture Measurements

IEM can use soil moisture measurement to correct it’s water balance calculations during the simulation. Typically a water balance is calculated using weather measurements to estimate how much water is being consumed by the crop.

Irrigation scheduling using direct soil moisture measurements is a common practice as an alternative to ET based scheduling. Both of these approaches have some error associated with them. Both of these methods have some error associated with them but the source of the error differs as does its manifestation in the scheduling recommendations. Direct measurement has the distinct disadvantage in that forecasting is not possible. The ET based water balance method can be used for forecasting but the error become progressively worse over time especially when deficit irrigation is used. IEM contains a simple algorithm that allows the integration of direct soil moisture measurements into the water balance calculation.

During a simulation when a soil moisture measurement event occurs the system calculates the average volumetric water content, $\bar{\Theta}_v$, for the whole field for each soil layer and the difference,

$$\Delta_\Theta = \left(\Theta_m - \bar{\Theta}_v\right) \cdot f \ .$$

This difference is added to each field sector so that the entire distribution is shifted without changing the shape of the distribution. Individual sectors are kept within the Field Capacity & Permanent Wilting Point boundaries of their respective soil types regardless the magnitude of Δ_Θ. Additionally a weighting factor, $f \in \left[0,1\right]$, is used to allow the user to bias the correction towards either the measurement value (by using f=1) or the current ET value (f=0). This correction procedure is repeated for each of the three soil layers. The system expects measurements to be expressed as volumetric water content at multiple depths. During the simulation, the measurements are integrated with respect to depth and only the portion corresponding to each soil layer is used to perform the correction. Any number of corrections can be performed during the simulation and the measurements can be associated with a particular soil type to avoid correcting unmeasured parts of the field.

Weather

IEM requires weather measurements to drive it s water balance calculations and spray loss estimates. Table xx shows the parameters that are required. IEM was developed with the general assumption that measurements will be taken on a daily basis but any measurement frequency can be used. The measurement values must be rates (rather than cumulative totals) and are assumed to be averaged over the sampling period. By requiring weather data to be expressed as a rate other model equations could be developed independently from the sampling frequency. When measurements are missing or irregularly spaced in time the accuracy will suffer accordingly but the simulation can continue unperturbed.

Table 5 Required Weather Parameters

Parameter	*Units*
Tall Crop ET	mm/day
Short Crop ET	mm/day
Precipitation	mm
Air Temperature	°C
Relative Humidity	Percent
Average Wind Speed	m/s
Solar Radiation	Watts/m^2

IEM does not estimate reference ET. Instead, it is assumed that the weather network (or other data source) will provide an ET estimate. Not including ET calculations was a design decision made specifically to avoid creating a dependency on a particular calculation method or local calibration. Not calculating ET effectively makes IEM non-region specific at the expense of increasing the data burden. IEM does have the capability to calculate ET using the ASCE Standard (cite), however this method is only used when the weather data provider only supplies either a tall or short crop estimate and both are needed.

Simulation Description

The previous section described the various models that make up IEM. This section describes the simulation components which perform the calculations described previously. Figure 6 shows a UML class diagram of the principal components used in the IEM simulation. Each of these classes is essentially the same as a ModCom SimObj (as described in Hillyer 2003). The classes are encapsulated relative to each other and any of these classes could be replaced without affecting any of the other classes. All of the simulation machinery necessary for running and managing the simulation is implemented separately from these classes. This separation of simulation services from simulation object is one of the principal goals of the ModCom framework.

The water balance state variables (contained in the FieldSector) are modeled using first order differential equations. These ODEs are solved numerically using an implementation of the Runge-Kutta-Fehldberg (RKF5) variable time step integration method (Doorenbos and Pruitt, 1992). The variable time step feature is what allows IEM to simulate processes that operate at different temporal scales. When a process at a smaller scale begins changing a state variable the RKF5 algorithm decreases the integration step size to accommodate the more rapid changes of the state variables. When the process stops affecting the state variables the time step is increased thus allowing the simulation to run at a higher speed.

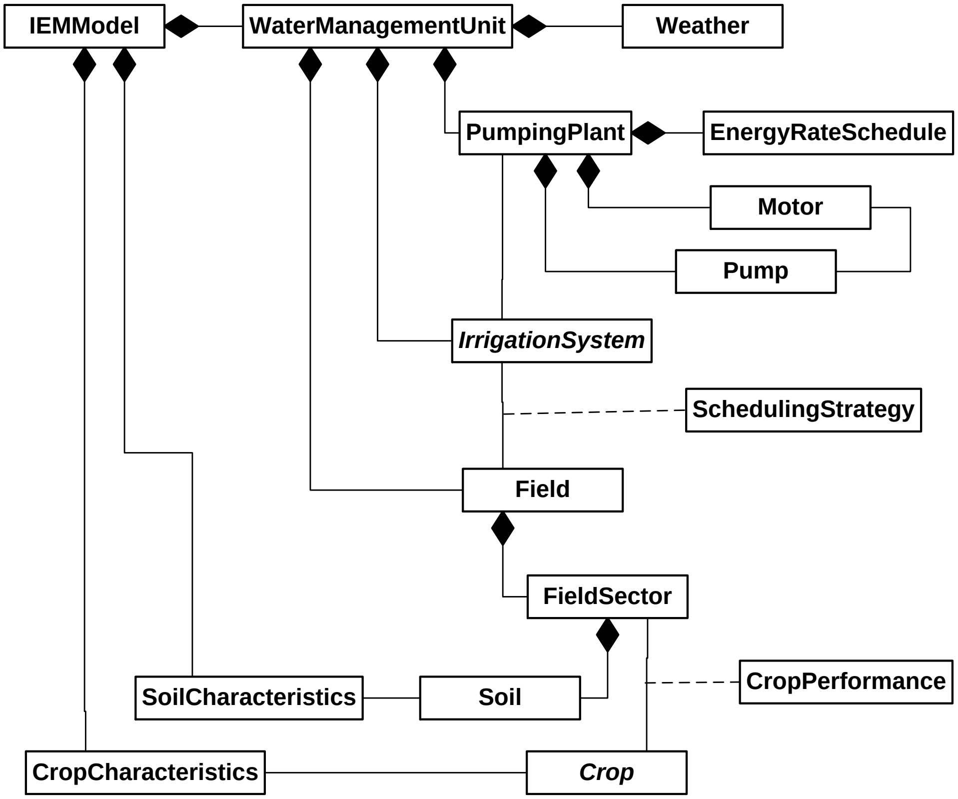


Figure 6. Overview of IEM Components

Figure 7 shows a UML class diagram of the irrigation system types available in IEM. The distinction between continuous and set move systems is made because of the differences in how these systems are used. In IEM irrigation events are specified by when they occur and their duration. For continuous move systems, the duration property applies to how long the system takes to cover the field completely. For set move systems the duration applies to the duration of the individual sets. The set move systems have additional scheduling parameters that define the time of day that a set can start. During a simulation the irrigation system will determine when each set starts based on the previous set’s end time and the next available start time. This level of detail serves two purposes. First, the labor constraints associated with set move systems can be prohibitive in terms of when a set can start (i.e. labor is only available during daylight hours), and this limitation affects the total amount of time required to cover the field. Second, a specific goal of IEM is to track the potential conflicts between irrigation systems on separate fields. Accurately accounting for when a system is operating is a key part of monitoring these conflicts. Ignoring set times would limit IEM’s ability to detect when set move systems have overlapping operation times. The level of detail is also relevant to continuous move systems but for a different reason. The application rate curve is estimated based on the event duration and this rate curve allows IEM to account for infiltration differences resulting from faster or slower system speeds.

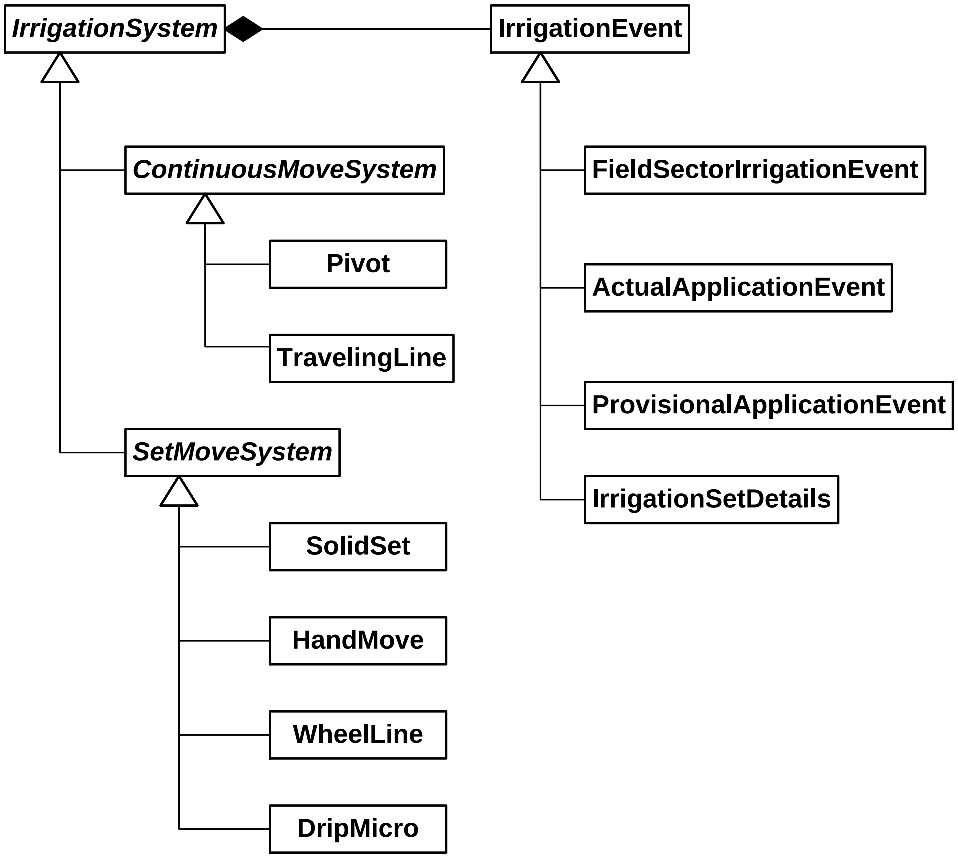


Figure 7. Irrigation Systems & related events

Scheduling Algorithm

The IEM scheduling algorithm is implemented in the SchedulingStrategy class shown in Figure 1. This class defines the relationship between the irrigation system and the field and encapsulates all of the complexity of the scheduling calculations. During a simulation the SchedulingStrategy objects are queried (on a daily basis) about the status of the field. When the soil moisture depletion is below a specified level, the

Management Allowed Depletion (MAD), the SchedulingStrategy generates a series of events that will simulate an irrigation event. The duration and/or number of irrigation events is based on how much of the soil profile should be refilled. This level is called the Target Refill Level (TIL). The duration of the events is either fixed (based on user input) or calculated based on the current depletion and a user provided estimate of system efficiency. Calculating the event durations allows IEM to incorporate a user's estimate of system efficiency without assuming system efficiency in the water balance calculations. When fixed duration events are used the SchedulingStrategy will either generate a single event or continuously generate events until the target level is reached. Estimating the current depletion is done through two alternate methods. It is in these depletion calculations that the FieldSectors and simulation of spatial variability are critical.

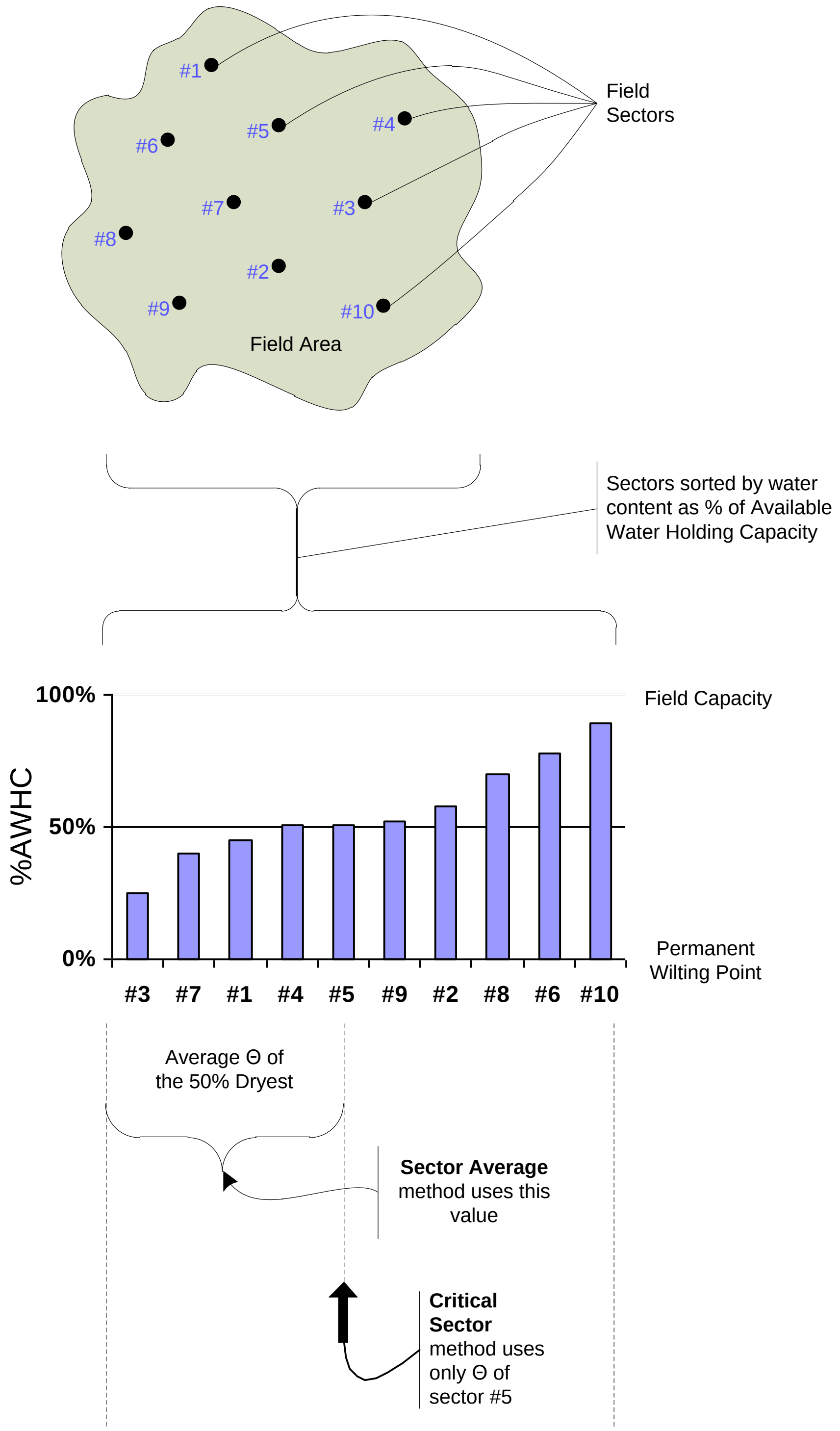


Figure 8 Graphical representation of the depletion calculation

Figure 8 gives a graphical representation of the calculation procedure. The two methods of calculating depletion are termed Critical Sector, and Sector Average. In the Sector Average method, the FieldSectors are ranked according to their current percent depletion and the average depletion of the driest sectors is calculated. The fraction of the sectors considered the driest is determined by an input called Critical Sector Value. This input value is conceptually similar to irrigation adequacy (the % of the field that is fully irrigated. When the distribution of depletion values is approximately normal the Critical Sector Value is approximately ⅔ (Adequacy - 1).

The second method, Critical Sector, is meant to simulate the practice of scheduling based on a small part of the field that is assumed to be representative of overall irrigation needs. In this method the FieldSectors are ranked by Available Water Holding Capacity in millimeters. A single FieldSector is then selected based on the ranking and the Critical Sector Value. This FieldSector is then used throughout the simulation as the estimator for depletion for the whole field.

The primary input parameters to the SchedulingStrategy can be varied during the irrigation season according to a schedule defined by the user. This feature is how IEM implements critical growth stage scheduling. Also, the timing of when the SchedulingStrategy is applied can be specified independently from the field's cropping dates. These start/stop parameters allow simulation of partial season irrigation.

There are two logical parameters that control how many irrigation events are generated. The first, called IrrigateToTarget, determines if the SchedulingStrategy should continuously generate irrigation events until the TIL is reached, or simply generate one event and then wait until the MAD level reached again. The second parameter is VariableDurationEvent and it determines if IEM should estimate set durations (for set-move systems) or pivot speed based on the TIL. This parameter is particularly useful with set-move systems because it can demonstrate the inefficiencies associated with fixed set durations when the set duration does not match up precisely with the current depletion.

Results

The primary outputs of IEM are 1) time series describing the physical parameters of the fields, 2) an array of irrigation events generated during the simulation, 3) an array of warnings that indicate when critical thresholds have been exceeded. There are 36 different output parameters for each simulated field, the most significant of which are the current soil moisture estimate, and cumulative values for the water balance components. Output samples are shown in Figure 9 and Figure 10. These figures show soil moisture estimates (blue line), SchedulingStrategy parameters (Target Irrigation Level and MAD), soil parameters, irrigation events (red), rainfall (green) and soil moisture measurements (black squares). Both figures were generated by the Irrigation Management Online web application described in the following chapter. The first graph shows the estimates with the soil moisture correction algorithm engaged, and the second shows the estimates without correction. Both of these graphs are from a recent trial of the IMO system near Hermiston, OR and, unless otherwise noted, all of the output samples use field setup data from that trail. Complete details of the field trail appear in the following chapter. Here, the system's ability to generate irrigation schedules is presented.

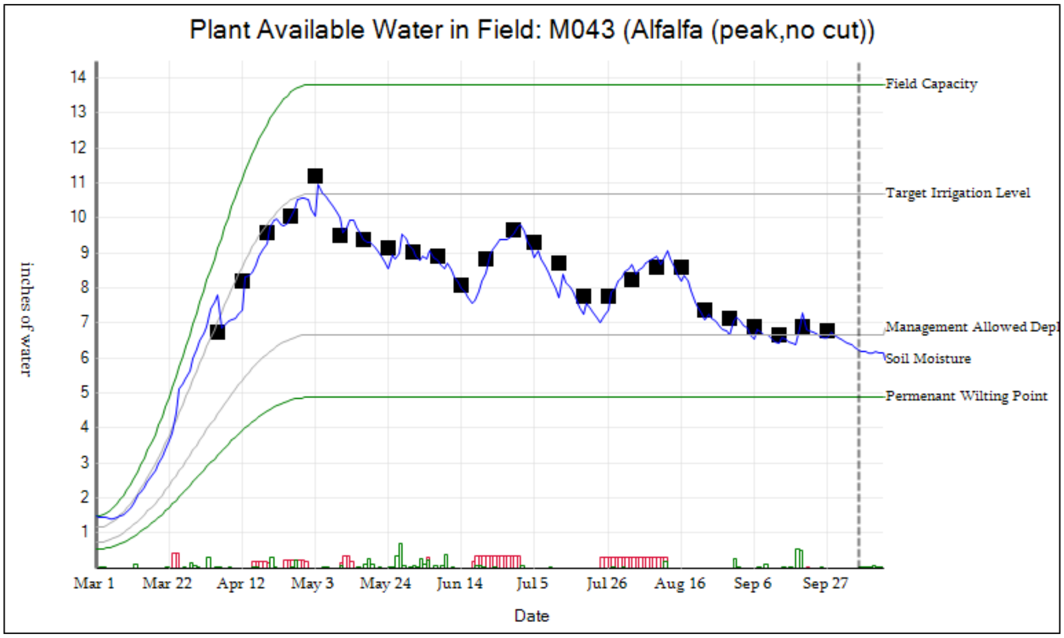


Figure 9 Soil Moisture estimate and irrigation schedule (with correction algorithm)

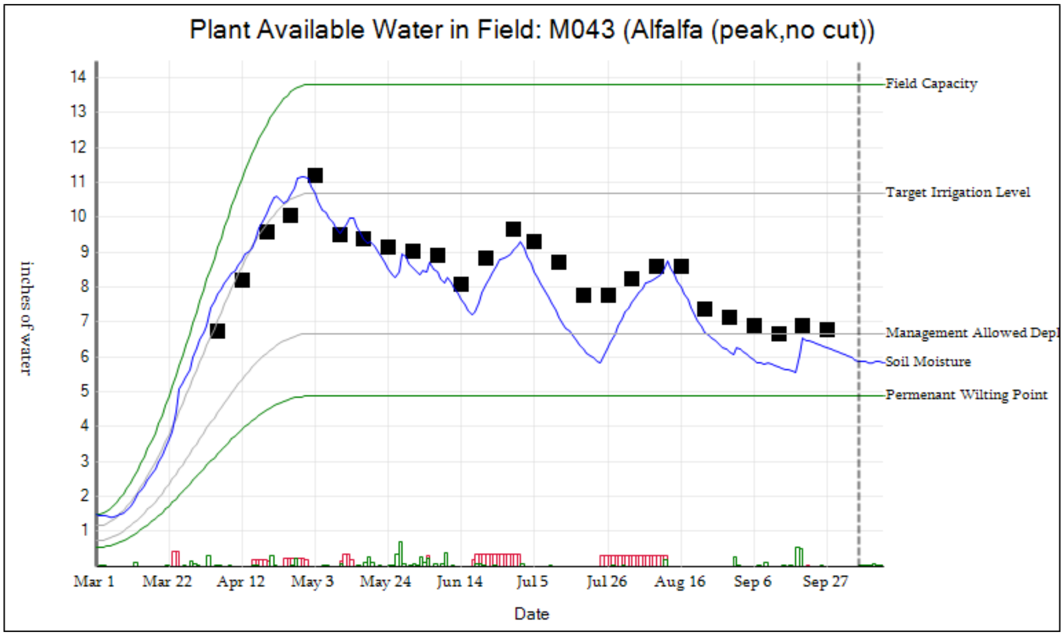


Figure 10 Soil moisture estimate and irrigation schedule (without correction algorithm)

Spatial Variability

Simulation of spatial variability is one of the key aspects of the IEM model. The accuracy of the model depends on the number of Field Sectors (the Monte Carlo replications) used to simulate the field. The default number of FieldSectors is 50. This number was chosen because it provided an adequate balance between runtimes and stability of results. To check how the number of field sectors affects accuracy a sensitivity analysis was performed using the two fields described in the previous example. Figure 11 and Figure 12 show the results of running the IEM model with different numbers of FieldSectors with the two versions (single averaged soil and three soils) of field M048 from the previous example. The solid line shows the average value from 25 runs with different random number seeds and the dotted line are 95% confidence intervals.

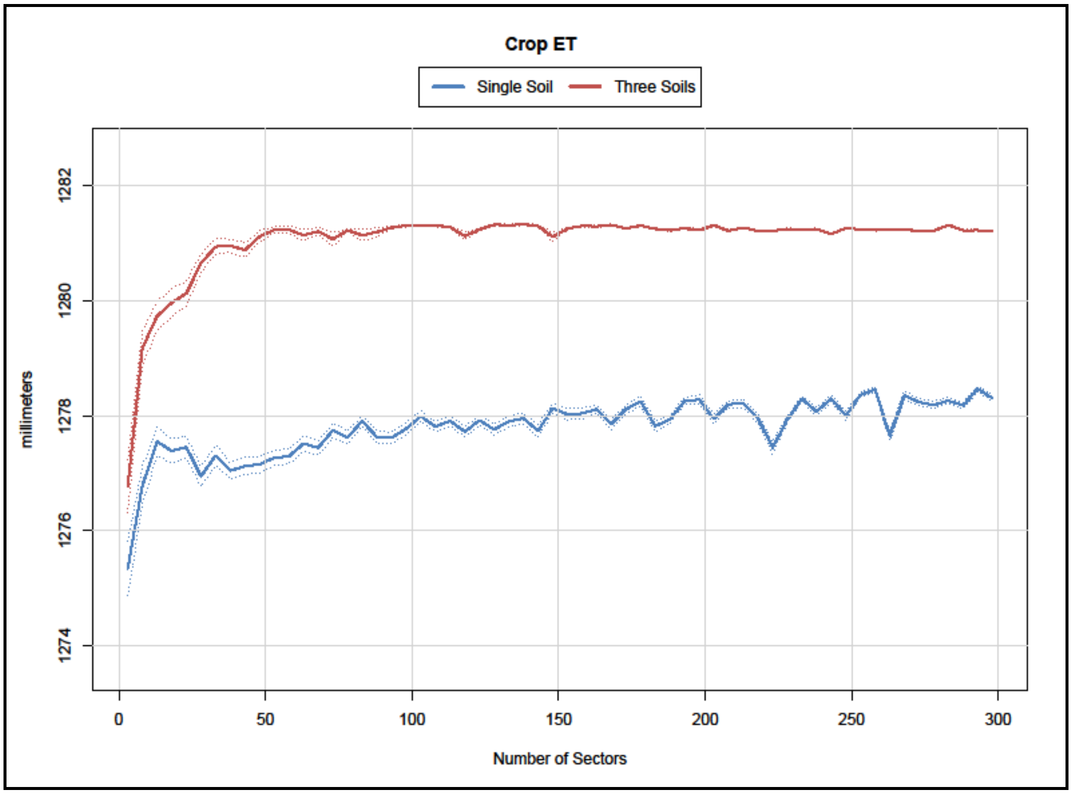


Figure 11 Sensitivity of Crop ET to # of Sectors

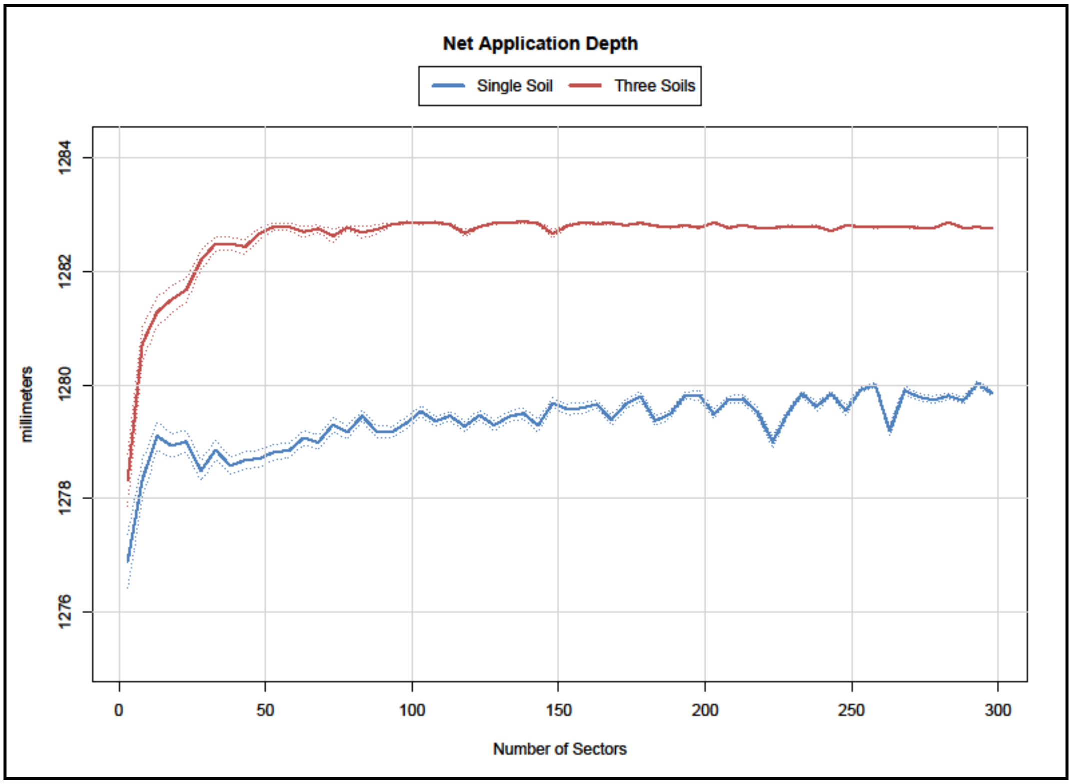
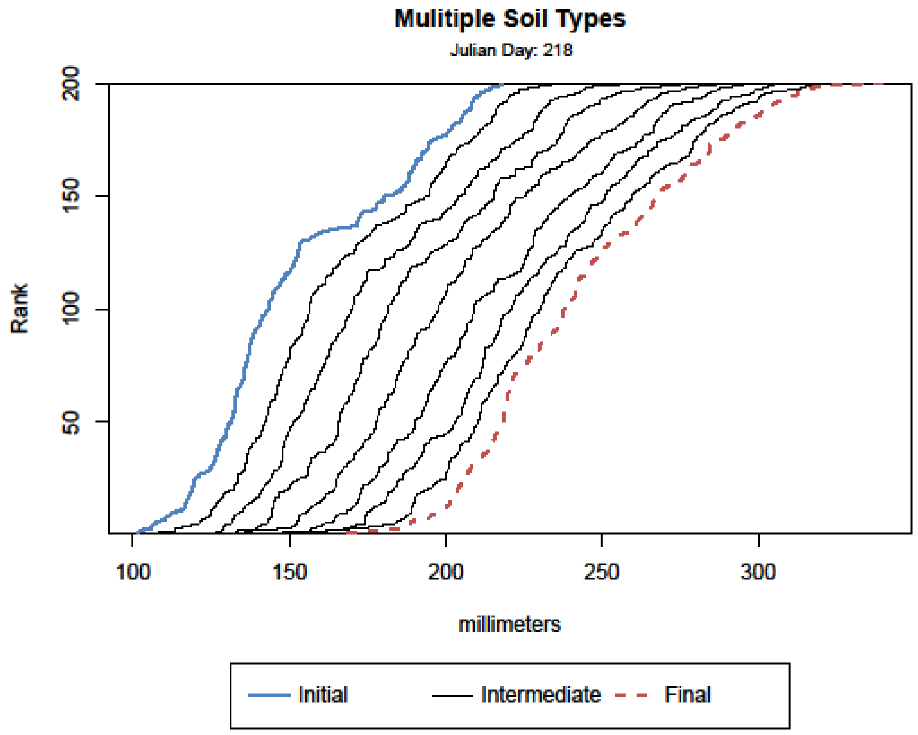


Figure 12 Sensitivity of Net Application Depth to # of Sectors

Multiple Soil Types

To examine the effectiveness of simulating multiple soil types vs. a single soil a sensitivity analysis was performed with one of the fields used in previously mentioned trail. This field (M048) has three soil types and contained a planting of alfalfa in its third year of production. A summary of the soil properties is shown in Table 6. A second hypothetical field was constructed in IEM by averaging the soil parameters weighted by the area occupied by each soil type. Graphs of the estimated soil moisture and generated irrigation schedule of both fields are shown in Figure 13 and Figure 14. The simulation summary for both of these fields is shown in Table 6. As would be expected, the cumulative ET and water application depths are identical for both fields. However, the timing of the events is significantly different as is apparent in the figures. The timing differences can be explained with Figure 15 and Figure 16. There, the soil moisture content (in mm) is shown immediately prior to and during the first irrigation event. The sectors sorted by increasing moisture content so that the traces approximate a cumulative probability density function. The heavy line is the soil moisture content when the irrigation event begins, the



dashed line is when the irrigation even ends, and the solid lines correspond to each rotation of the pivot. The rank of each sector is used as the vertical value. These plots approximate a cumulative probability distribution of soil moisture in the field. The field with the averaged soil properties appears as a Normal distribution. However, the field with three soil types has a bi-modal distribution and this difference in shape accounts for the differences in timing. From a seasonal planning perspective the difference in distribution shape does not have a significant effect on the field's performance. The short-term effects are significant when considered in the context of managing multiple fields. The starting date of the events differs by several days and, when pumping capacity is limited, timing of events is critical.

Table 6 Soil properties summary for field M048

Soil Type Name	*Percent of Area*	*AWHC (mm/mm)*	*Field Capacity (mm/mm)*	*Saturation (mm/mm)*	*Hydraulic Conductivity (in/day)*
Burke	8%	0.2	0.28	0.38	13
Shano	64%	0.21	0.28	0.5	13
Ritzille	28%	0.16	0.22	0.4	6.43
Weighted Average		0.1952	0.2632	0.4624	11.16

Table 7 Simulation summary

Parameters (inches)	*M048*	*Mean_M048*
Total Applied Gross	55.8	56.3
Total Applied Net	49.0	49.1
Cumulative ET	42.1	49.0
Cumulative Precip,	3.3	4.2
Spray Loss	1.3	1.5
Deep Percolation	5.5	5.3
Run Off	0	0.0
Yield Reduction %	0	0

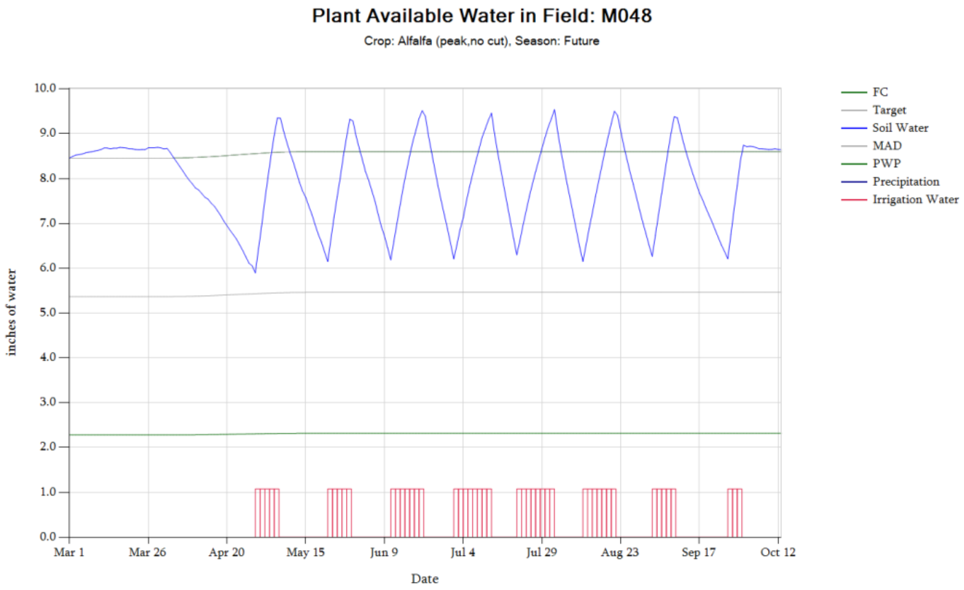


Figure 13 Soil Moisture Plot for field M048 with three soil types

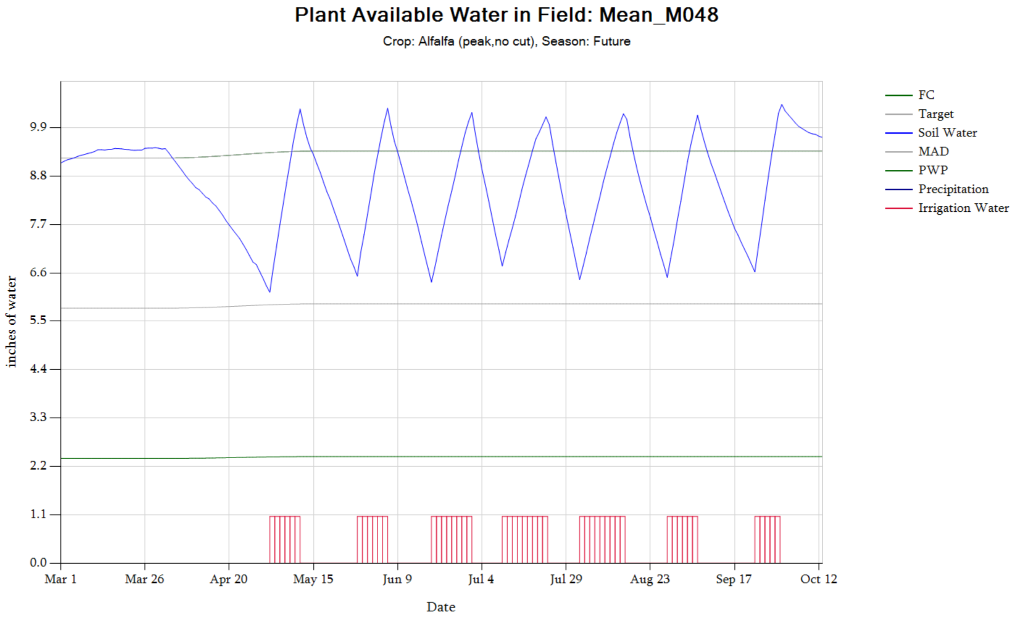


Figure 14 Soil Moisture Plot for field M048 with a single average soil type

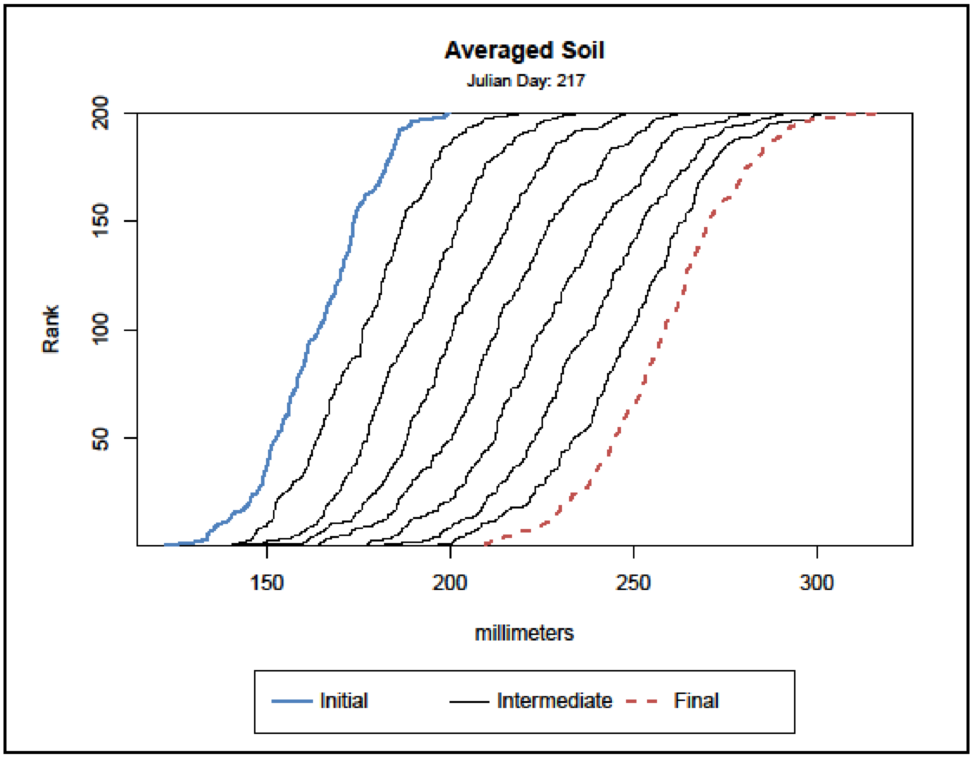


Figure 15 FieldSectors soil moisture content during an irrigation event, for the ‘Averaged’ field. Each black trace (and the final) represents one pass of the pivot.

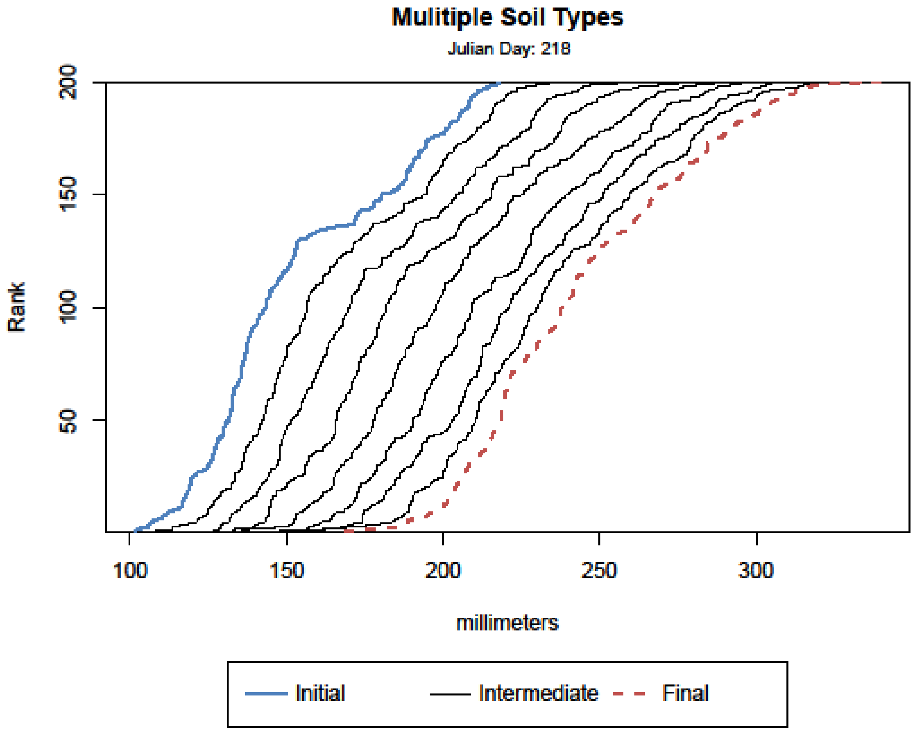


Figure 16 Field 'M048' FieldSectors soil moisture during and irrigation event.

Intensity vs. Efficiency

IEM's response to changing irrigation intensity is demonstrated in Figure 17. These data were generated by simulating the M048 field described previously using a full irrigation strategy and varying the pivot speed from 8 to 48 hours. The simulation was run 25 times for each pivot speed value and 95% confidence intervals for each of the water balance components were computed. The simulated crop ET remains constant for each pivot speed because, under full irrigation only a small part (1/8th or less) is allowed to reach the level were stress occurs; 50% depletion as prescribed by the FAO56 model. The losses (the sum of spray loss, run off, and deep percolation) are small relative to the total ET (approximately 0.4 to 1 % of the total) however, they are not constant.

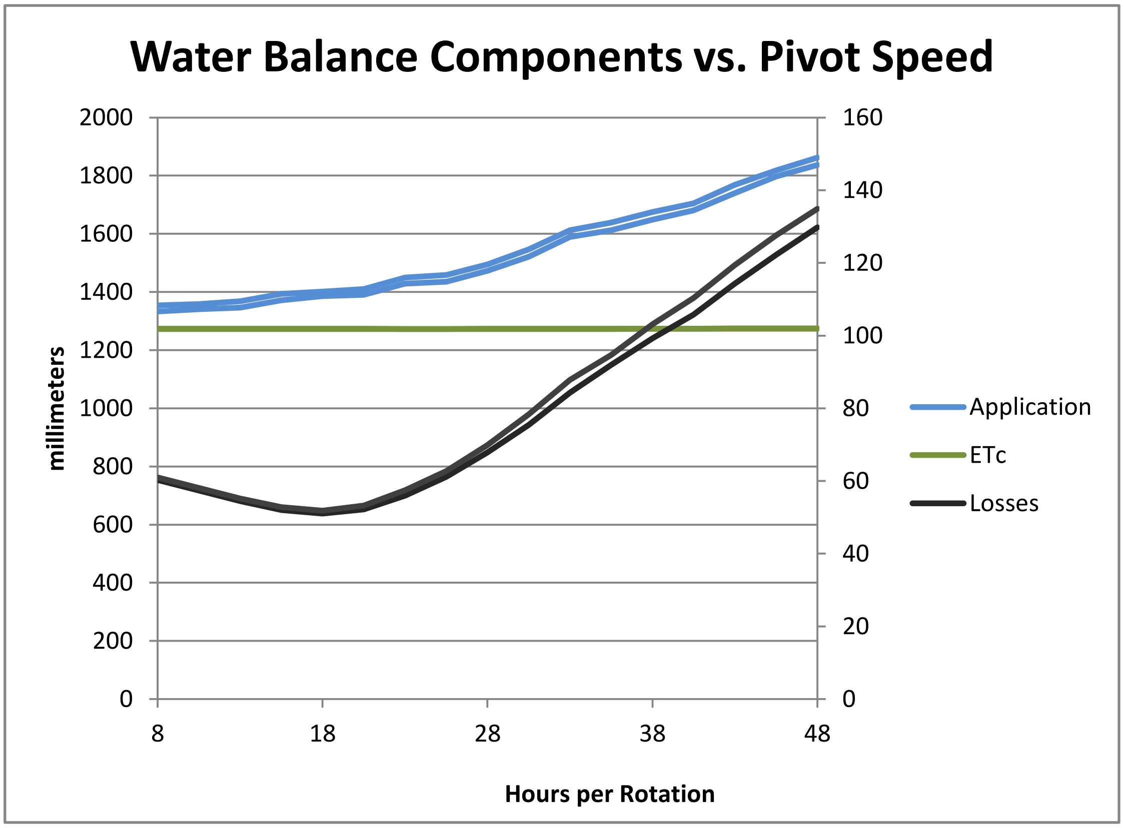


Figure 17 95% Confidence intervals for water balance components as a function of pivot speed. Losses are shown using the right hand side scale; Application and ETc use the left scale. Both scales have units of millimeters.

Scheduling Strategies

Figure 18 through Figure 23 demonstrate the range of irrigation schedules that can be generated via different scheduling strategies. Each of these schedules was generated using the same field setup; 90 Ac of winter grain on silt loam soil and irrigated by a 1200 gpm pivot system. Table 8 and Table 9 summarize the field performance and yield estimates for each of the scheduling strategies. The strategies were configures as follows

- Figure 18 shows the Interval strategy where the field is irrigated every 4 days regardless of soil moisture status. This type of scheduling is still used by some irrigators so it was included so that non-scientific scheduling can be compared to the various other strategies.
- Figure 19 demonstrates the Full irrigation strategy where irrigation is started when the field is 50% depleted (MAD=50%) and is irrigated continuously until the driest 25% of the field has reached zero depletion (Target = 100%).
- Figure 20 demonstrates a deficit strategy with MAD=60%, Target = 80%.
- Figure 21 demonstrates a deficit strategy with critical growth stage scheduling. During the first part of the season the MAD and Target are the same as the previous scenario. Immediately prior to the estimated full cover date the Target is raised to 100% and MAD to 50%. The scheduling levels return to the deficit strategy after approximately two weeks. This is meant to simulate avoiding stress during flowering/heading stage of growth.
- Figure 22 is a deficit strategy where the pivot rotation time is calculated based on the magnitude of depletion and user estimated system efficiency. The rotation times are limited to be between 48 and 12 hours. This feature is particularly useful with soil set and drip/micro systems were varying set times is more practical. The generated schedule is reported to the user as a start date/time and a set duration expressed in hours.
- Figure 23 demonstrates an alternative method for implementing a deficit strategy. Here the system does not irrigate to the target level. The star time of the events is computed in the same manner as the other schedules however the system stops after one irrigation event. This strategy can

potentially allow the most flexibility when scheduling multiple fields because the pumping capacity is not occupied for multiple pivot rations. On the other hand, this is a higher risk strategy because the next irrigation event must occur sooner.

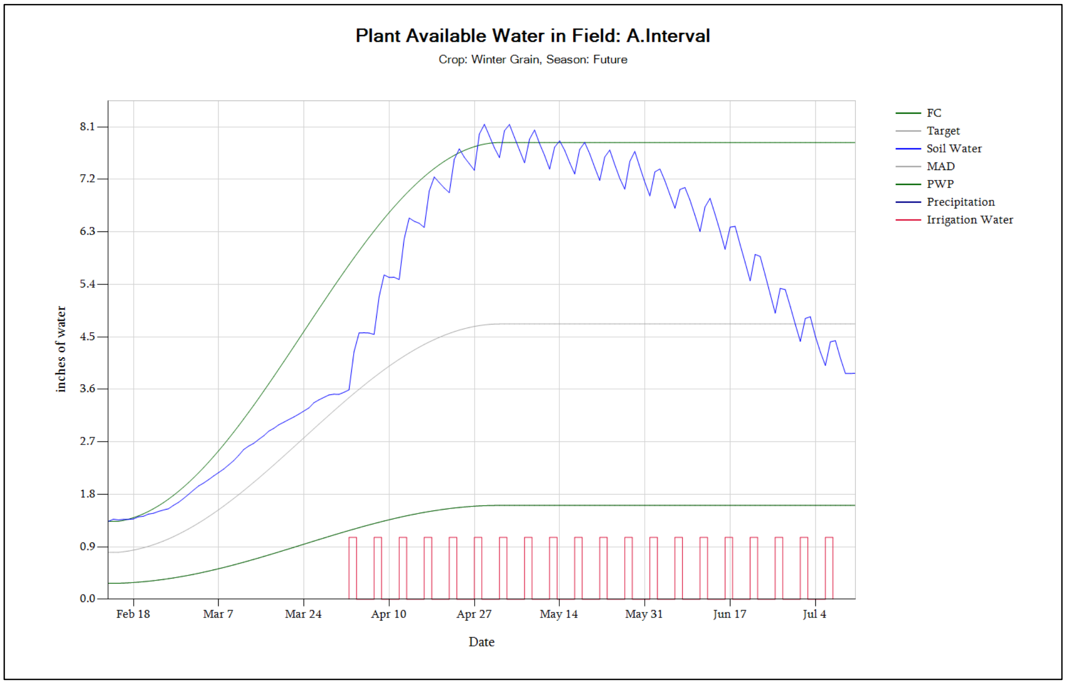


Figure 18 Interval Scheduling Strategy

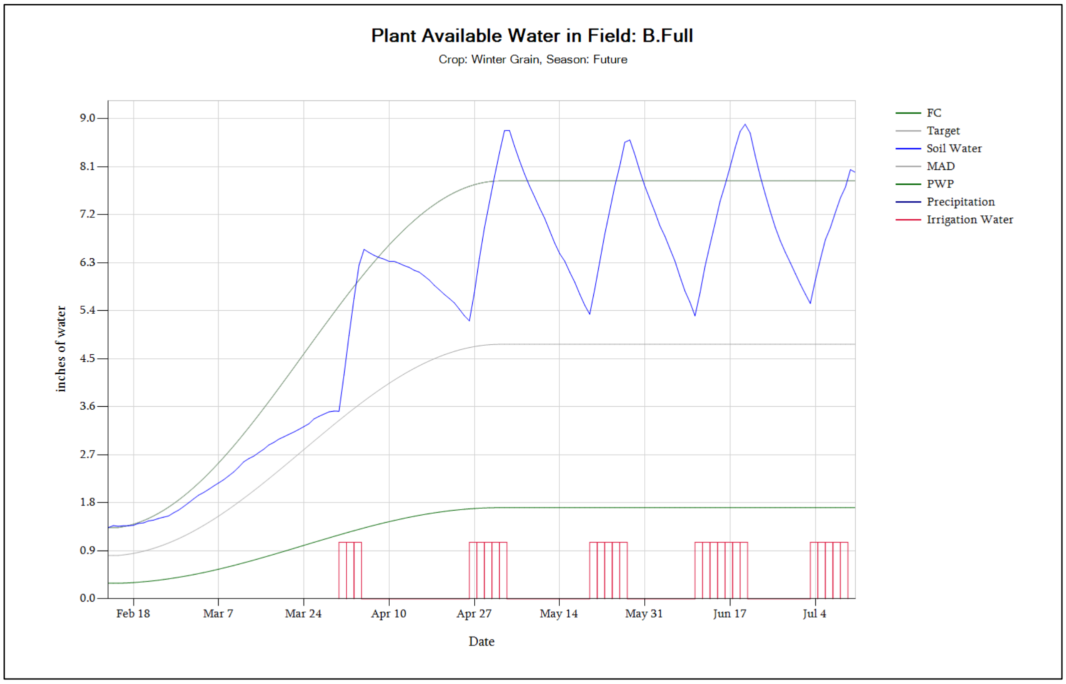


Figure 19 Full Irrigation Strategy

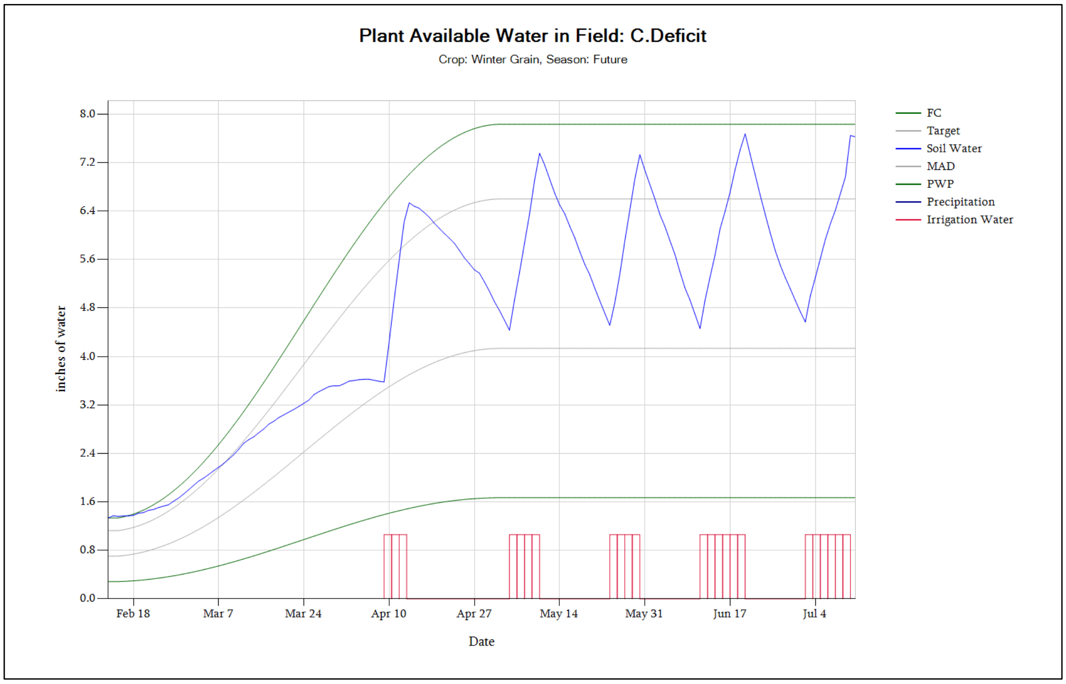


Figure 20 Deficit Irrigation Strategy

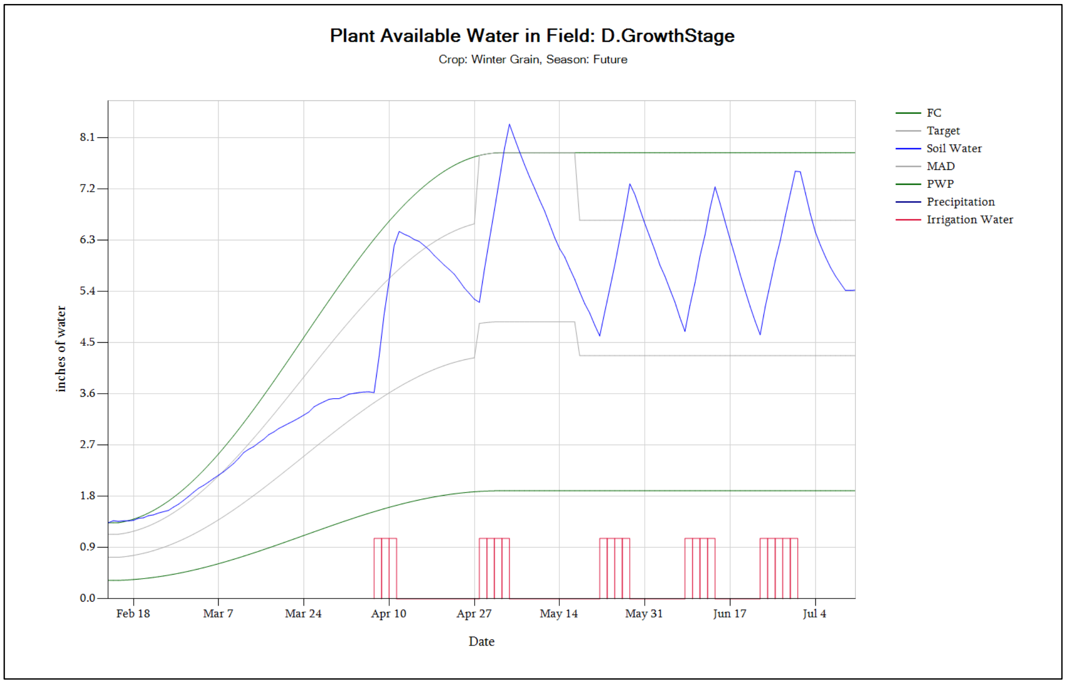


Figure 21 Critical Growth Stage Strategy

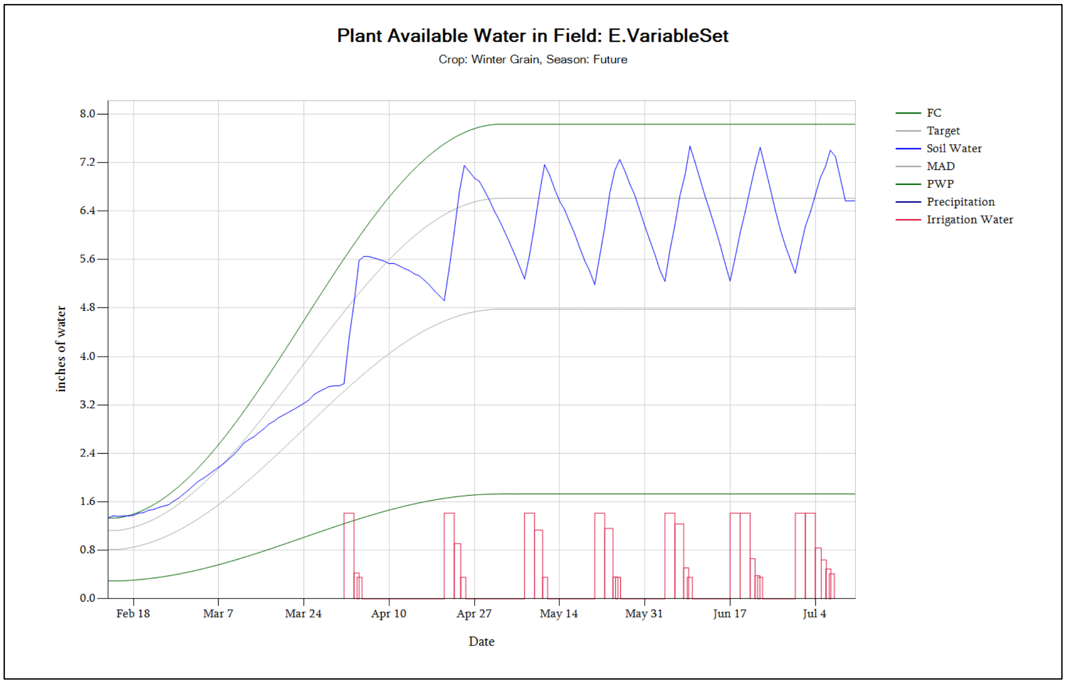


Figure 22 Variable Pivot Speed Strategy

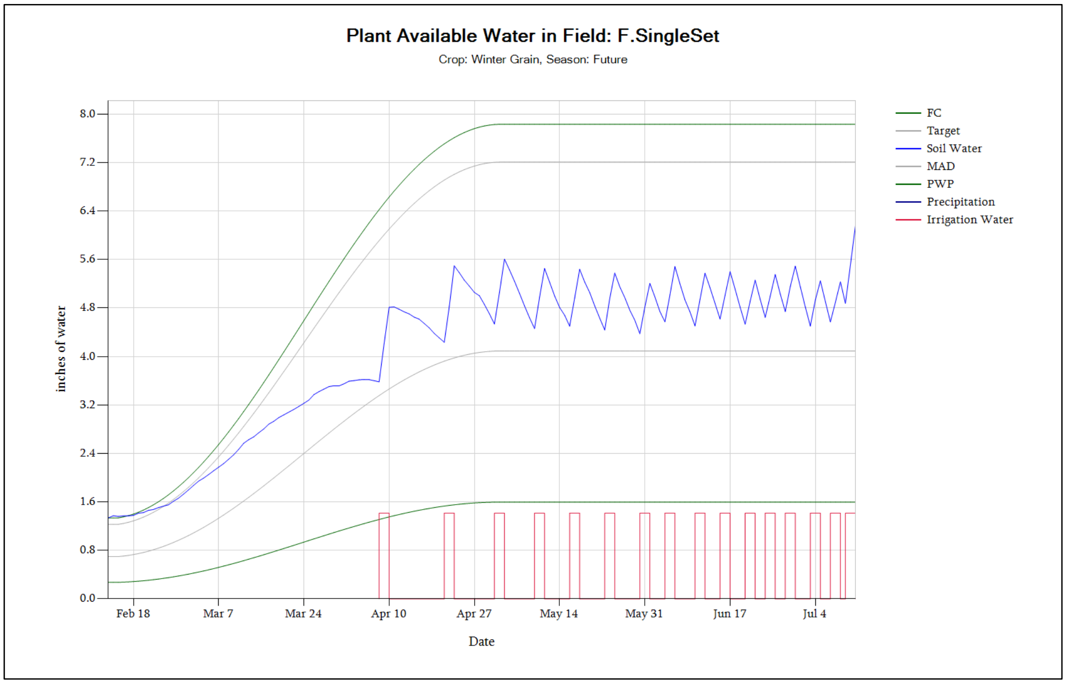


Figure 23 'Single Set' Deficit Strategy

Field Name	*FAO33 Yield Estimate*	*Yield Reduction %*	*Simulated Crop ET (mm)*	*Potential Crop ET (mm)*
A.Interval	150	2%	699	729
B.Full	150	0%	693	719
C.Deficit	149.7	2%	686	724
D.GrowthStage	149.9	2%	676	696
E.VariableSet	150	1%	711	737
F.SingleSet	149.6	5%	686	744

Table 8 Yield reduction estimates for five different scheduling strategies

Table 9 Field irrigation performance estimates for five different irrigation strategies (all values are in millimeters)

Field Name	*Gross Appl.*	*Net Appl.*	*ETc*	*Precip.*	*Spray Loss*	*Deep Perc.*	*Run Off*
A.Interval	737	602	701	198	15	23	5
B.Full	871	594	693	198	18	56	8
C.Deficit	818	587	686	198	18	8	5
D.GrowthStage	737	577	678	198	15	10	5
E.VariableSet	810	610	709	198	18	8	15
F.SingleSet	775	587	688	198	15	3	25

Soil Moisture Corrections

The soil moisture correction algorithm is the most significant component with regard to maintaining the accuracy of the model's results. Figure 9 and Figure 10 demonstrate the difference in results when applied over a full season of irrigation. Figure 24 and Figure 25 demonstrate how the correction algorithm modifies the distribution of soil moisture during a simulation. Both of these plots were produced using neutron probe measurements collected during the 2010 season from the field trials mentioned previously. The first figure shows the correction algorithm applied to a field (M043) with a single soil type (Burke silt loam). The heavy trace is the estimated soil moisture distribution based on the water balance model. The blue vertical marker indicates the moisture content estimated via a neutron probe measurement. The two lighter traces show the distribution after applying the correction with 50% and 100% weighting of the measurement. The full weight correction has shifted the distribution so that the mean matches the measurement but has not changed the variance.

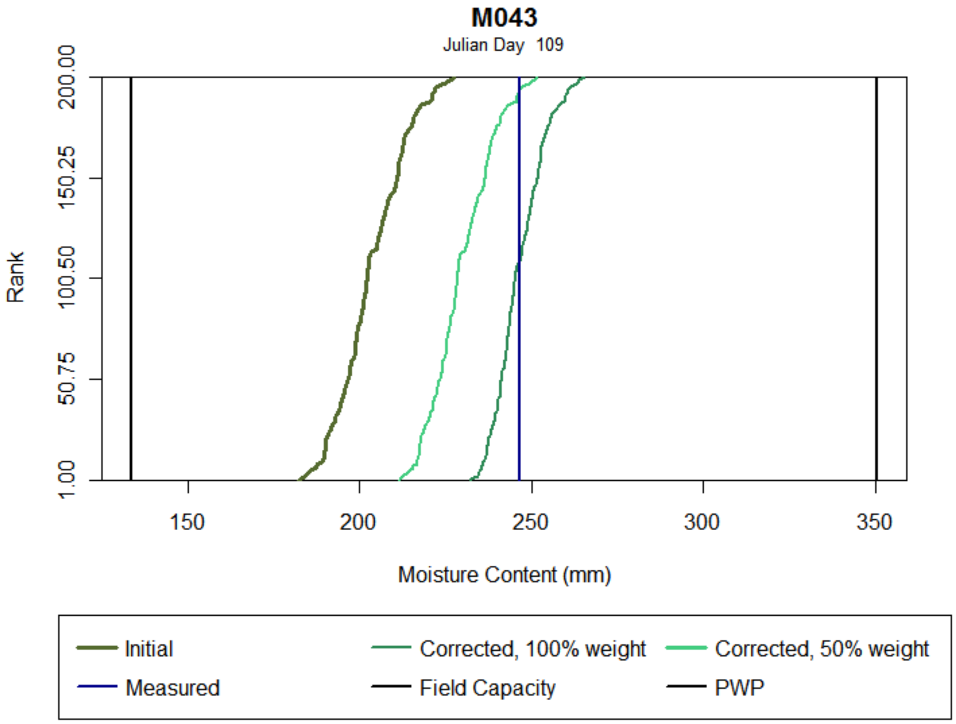


Figure 24 Soil moisture correction effect at full and 50% weighted measurement value in a single soil type field

Figure 25 shows a measurement being applied in a field with two soil types (Shano vf sandy loam and Burke silt loam, equal areas of both). The measurement was taken in the Shano series soil. Prior to the measurement, the Shano Field Sectors have a higher depletion relative to the Burke, giving the overall distribution a bi-modal shape. The correction algorithm is only applied to the sectors representing the soil where the measurements are taken. The correction only modifies the Shano sectors and changes the overall variance of the distribution.

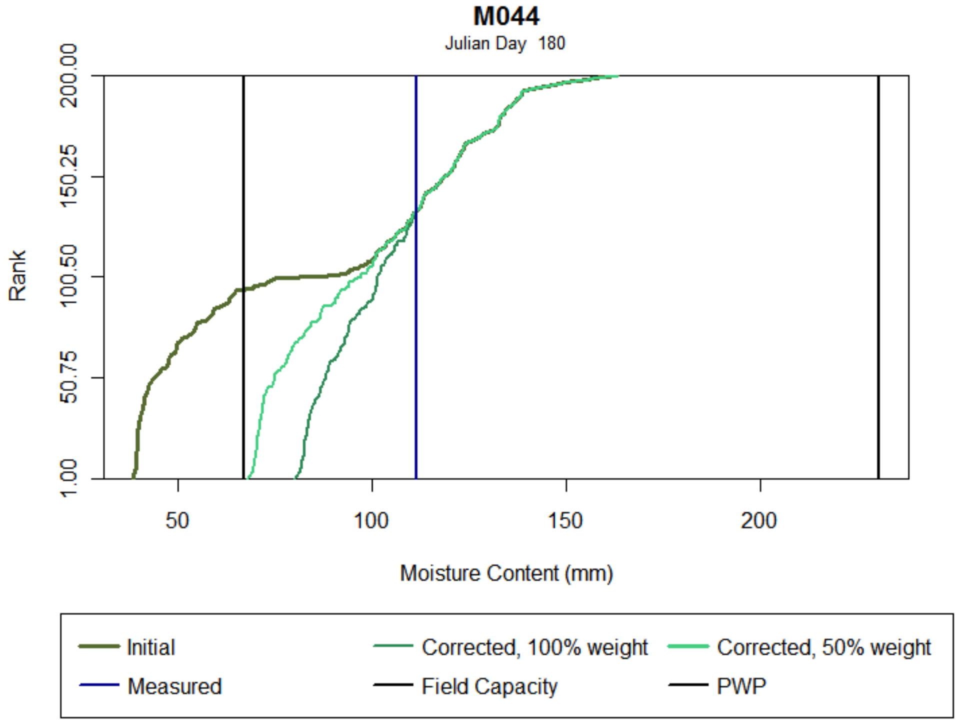


Figure 25 Soil moisture correction effect in a field with two soil types

Discussion

IEM has undergone field trials for 5 years as part of the testing of the Irrigation Management Online system. During that time, IEM has been used on 40+ fields, some of which the IEM/IMO system has been used continuously for four years.

During the field trials, we found that model calibration is always a significant challenge.   By incorporating soil moisture measurements into the simulation, any calibration issues become obvious immediately. The user benefits from this because they are less likely to accept erroneous scheduling recommendations. The disadvantage is that the miss-calibration can be discouraging to users if the source of the error is not immediately obvious. It is important to note that in many cases the magnitude of the miss-calibration errors would not grossly over or under irrigate. Large magnitude errors generally occurred only when there was some error during setup (e.g. the user entered an incorrect system flow rate). The soil moisture correction procedure did alleviate some of this frustration but does so at the expense of disguising calibration problems.

One notable omission from IEM is surface irrigation. During the initial design, surface irrigation was excluded because of the modeling complexity and computational requirements needed for surface irrigation. The USDA ARS is currently implementing a modular version of the WinSurfr software package (cite Bautista in Phoenix). When the package becomes available, it will be integrated into IEM.

The development of IEM was frustrated as several points by the lack of generally accepted or practical models for certain physical processes. In particular, IEM lacks physically robust physical models of subsurface distribution in drip and micro sprinkler systems and surface redistribution in general. Several accurate models of subsurface distribution were available however, they required performing computationally intensive 2D or 3D simulations. The current model was developed in cooperation with University of California farm advisors. IEM's implementation is a statistical compromise and, thus farm, has been acceptable in orchards. The surface redistribution model is lacking is for similar reasons.

The most significant model shortcoming we faced was the lack of robust yield estimation. The FAO33 model is a useful approximation but it lacks the range of inputs that are relevant for deficit irrigation, critical growth stage scheduling in particular. There is also some concern that the yield response coefficients may not be relevant for some newer crop varieties. Additionally, FAO33 is a yield reduction model rather than a yield model per se. One of inputs required is an estimate of the maximum yield. This requirement creates an analytical limitation in that the system cannot be used for yield maximization, only yield loss reduction.

Conclusion

IEM is a robust model of the disposition of applied water. Further, the system has the requisite analytical components necessary to implement deficit irrigation scheduling. Explicit analysis of uncertainty, simulation of efficiency, integrated yield estimation, full season simulation, and varied scheduling options are all included in the system. This was the central goal of IEM's development.

The initial development of IEM occurred during 2005. During the ensuing five years several field trials of the IEM/IMO system have been conducted. Throughout these trials development and extension of IEM continued. New modules for drip/micro irrigation, a different crop representation, and energy use calculations were added to the original system. The ModCom framework and modular design in general was essential to adding to the existing system without requiring significant modification to existing modules.

Integrating soil moisture measurements into the simulation has proven useful for implementing DI. Direct soil moisture measurement is a generally accepted method for irrigation scheduling. Including these measurements allows the user to detect problems with both methods and motivates further evaluation of the system calibration and greater understanding of conditions in the field. By using the soil moisture correction algorithm, IEM is able to combine both methods rather than simply using them in parallel.

One issue that has not been fully addressed is an assessment of the precision of the spatial variability simulation. In each of the field trails evaluation of model performance has been based on the average estimate of soil moisture. The variability generated internally (i.e. the distribution computed by the Field Sectors) has not been explicitly compared to field measurements. The reason for this has been the expense and difficulty in obtaining measurements of the spatial variability of soil moisture.

The development of IEM will never be complete in the sense that no new features are needed. The underlying design philosophy is that new modules are expected to be added. However, to be successful in the long term, use and development of the system components must be possible by persons other than the system's creators. To that end, development of an open source version of IEM is underway.

Access to the IEM model is available through the IMO web application at oiso.bioe.orst.edu.

Irrigation Management Online: a web based application for optimal irrigation management

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Introduction

How do we optimally manage irrigation when resources are limited? There have been numerous attempts to find strategies for optimal allocation of water. However, these previous attempts produce solutions that are static in that the allocations are based entirely on the algorithms encoded in the optimization system. These solutions are presented as 'most optimal' and altering the solutions to accommodate different management requirements involves altering the encoded algorithms. Given a solution from an optimization-search system the user can either implement the solution, or not. If the solution is unacceptable, the user's only recourse is to adjust input parameters and compute a new solution. For this process to be successful, the optimization system must be able to generate solutions that are not only optimal but also practical and acceptable to the farm manager as well.

In the past an optimum outcome was generally defined as the minimum amount of water needed to meet crop water demand or the profit maximizing level of water use. In a resource limited future optimality will be defined differently for different circumstances and practicality constraints will be more complex and more stringent. Additionally, given the reduced margin for error under deficit irrigation, the farm manager's risk tolerance becomes an important consideration. An optimization algorithm cannot capture the full range of factors the farm manager will be concerned with, nor realistically quantify the manager's attitudes about profit and risk. An optimal strategy may also be too ephemeral to be determined precisely by a computer; i.e. what is optimal today may change during the season in response in response to variations in weather, crop development and other contingencies (English, 2003).

In view of these considerations, a decision support system for optimizing irrigation water use will need to be readily adaptable for changing circumstances and differing user-defined objectives, and the user (the farm manager) will need to be an integral part of the system.

The General Optimization Problem in Irrigation Management

Scientific Irrigation Scheduling (SIS) via computers began in the late 1960's (Jensen, 1969; Jensen et al., 1970). The objective of SIS has been (generally speaking) yield maximization or crop stress minimization without applying excessive amounts of water. While SIS tools are often described as producing optimal irrigation schedules the tools can only be regarded as optimization tools in a limited sense. Optimization problems are usually defined in terms of an objective function and some constraints. The scheduling tools were, and generally still are, unconstrained; i.e. water supplies and delivery system capacities are presumed to be non-limited. Current SIS programs are still predominantly based on the 1970's model. Tools such as KanSched (KSU, 2005) and WaterRight (CIT, n.d.) have been successfully used for several years. In a recent review of current irrigation scheduling programs (Henggeler et al., 2010) ten of the eleven systems reviewed used the same basic algorithm described by Jensen in 1969.

Maidment and Hutchinson (1983) categorize irrigation water management models into two groups: 1) demand simulation models and 2) economic optimization models. Tools which use the approach defined by Jensen (mentioned previously) fall into the first category. The economic optimization models (the second category) are usually based on a water production function that defines a deterministic relationship between yield and water applied. For examples of the second kind see Oweis and Hachum (2009) or Kou et al. (2001). More sophisticated approaches to irrigation optimization have addressed economic optimization while including demand simulation and constraints. The objective has been defined in terms of maximization of net farm income, and water supplies and/or delivery system capacities are treated as constrained variables. Early efforts were largely based on mathematical programming to maximize net economic returns, e.g. convex linear programming and dynamic programming (Martin and van Brocklin, 1989). Other approaches addressed the issues of uncertainty and risk. These included chance constrained linear programming, (Maji and Heady, 1978); stochastic dominance methods (Cochran and Mjelde, 1989); (Harris and Mapp, 1986), and Bayesian Decision Theory (Anderson et al., 1977; English and Orlob, 1979). To fully and realistically represent the diverse and complex physical processes, operational constraints and management objectives associated with optimal irrigation management some research teams have relied on computationally intensive simulation modeling, sometimes coupled with an efficient search procedure to reduce the number of alternatives to be considered. Genetic algorithms have been proposed as a search algorithm for this purpose (Canpolat, 1997; Ortega Álvarez et al., 2004).

The work on economic optimization may be of limited usefulness to irrigation managers. Economic research in the 1970's indicated that profit maximization alone may not be an appropriate objective. Lin et al. (1974) found that profit maximization was not a good predictor of farm management behavior. Instead Lin et al. framed the optimization problems in terms of maximization of *utility*, and observed that farm managers' Lexicographic utility functions could commonly be expressed in terms of four factors: 1) family living standard, 2) a firm growth objective, 3) a net income goal, and 4) a security, survival, or risk aversion goal. Lin et al. derived utility functions based on risk acceptance/aversion which were later used by English and Orlob (1978) to develop irrigation management strategies. These strategies were constructed to be consistent with the utility functions of the individual farm managers who participated in the work of Lin et al. English and Orlob found pronounced differences in the strategies that would be selected by various farm managers with differeing tolerance for risk. This is further supported by Bosch and Eidman (1987) who found that the economic value of scheduling information varies depending on the managers risk preferences, and that, in cases of high risk affinity, irrigation scheduling information may have little or no value. Based on these research efforts it is clear that irrigation managers' decisions will be affected not only by the expectation of profit but also by uncertainty and other factors.

The key point regarding risk is that while it is generally possible to identify irrigation strategies that maximize profit, those strategies may not be consistent with the value systems of the individuals involved. Any effort to advise individual irrigators on optimal irrigation strategies must therefore incorporate the manager's utility function. In short, the objective function will be difficult or impossible to quantify objectively.

The other elements of an optimization problem, the constraints, also present a very significant challenge. While some constraints may be obvious and easily quantified, the experience gained from pilot testing the IMO system has been that some constraints are ephemeral and cannot be anticipated. Examples might include observations of incipient disease that would preclude irrigation of an individual field, or labor problems that temporarily limit the capacity of a farm to implement irrigation sin a timely manner. Other constraints may be too vague to be readily articulated by the managers involved. For two examples: 1) an irrigation recommendation may conflict with past experience (e.g. the visual condition of the crop makes the manager nervous); 2) a manager may have a background hunch that the relative prices of two crops are soon going to change, implying a need to allocate the water between those crops differently.

It is a central tenet of this dissertation, then, that the analyst cannot reliably quantify or codify the objective function or the constraints that are relevant to a farm manager. It is for that reason the system described here has been designed to incorporate the manager directly into the optimization search procedure in order that their attitudes, preferences and biases are fully expressed in the search of an optimum strategy.

Objectives

The basic research question we are trying to answer is: given the complexity of optimizing irrigation, is it possible to build an irrigation decision support system that exposes the necessary analyses without overwhelming the user with the complexity of the analyses being performed. Further, what sorts of user interface tools are useful for interacting with and controlling a deficit irrigation scheduling system while still begin practical enough for daily management of multiple fields. In the process of building and testing this system, we also hope to detect what the likely obstacles are when implementing optimal irrigation scheduling in the future.

This paper is the second in a series describing a system for optimal irrigation management. The previous paper described the Irrigation Efficiency Model (IEM), which is a simulation tool for analyzing irrigation. The primary goal of IEM is to simulate the physical consequences of less than full irrigation and to generate irrigation schedules that implement a variety of deficit irrigation strategies. The questions addressed in this paper go beyond the primarily analytical goals of IEM regarding the types of analyses necessary to implement deficit irrigation.

This paper will present Irrigation Management Online (IMO), a web based system designed as a tool for implementing optimal irrigation management when resources are limited. In the first section the system design and concepts unique to IMO are presented. This is followed by a section describing the systems features and technical details. The second section contains a description of the results of five years of field trials. In the third section we describe some of the feedback that was obtained from the trial participants. Also described are the recommendations made by a panel of professional peers and farm managers who reviewed IMO on three separate occasions. A brief conclusions section follows with recommendations for future research.

The design of IMO has two potentially competing goals: make the system robust enough to optimize irrigation and still be practical enough to appeal to a broad range of users. The user must be able to interact with the simulation rather than being a passive recipient of the results. Given the rapid evolution of web based technologies, a modular design was a necessity. An additional goal was that the system should be localize-able with respect to all of the parameter values needed to drives IEM's calculations. By doing this the system will not be constrained to any particular geographic region by making assumptions about parameter values based on the local climate and cultural practices.

Optimal irrigation implies some level of Deficit Irrigation (DI). Implementing DI scheduling necessitates several changes to conventional scheduling algorithms. These changes include a need for greater accuracy and a more complex physical model. The variety of methods for implementing DI also requires a more robust scheduling algorithm. IEM accounts for a majority of the physical aspects of DI and schedule generation. Optimal irrigation scheduling generally involves a strategy of managed yield reduction while balancing the use of limited resources and practical limitations of irrigation. From an optimization perspective, the magnitude of yield reduction (rather than the total yield) is the objective function. The physical, practical and management limitations of irrigation define the constraints on the objective function.

Irrigation affects and is affected by nearly all farm operations. Limitations on resource availability increase the complexity of the effects on irrigation management. To include these constraints in an optimization algorithm would involve codifying the constraints is a manner appropriate for an optimization framework. Encoding all possible constraints is not an achievable goal because we cannot possibly know what all the constraints are in advance. Including most of the constraints would still involve constructing quantitative representations of the different farm processes. Instead of building a simulation of the whole (or nearly whole) farm enterprise IMO takes a different approach. The central thesis of IMO is that the best way to implement or express these constraints is to build a system that includes the only entity that is aware of all these constraints: the grower.

Irrigation Management Online (IMO)

IMO is composed of a set of tools that allow the user to generate an irrigation schedule, modify the schedule, and re-evaluate based on those modifications. This basic iterative procedure, generate-evaluate-modify, is how user directed optimization works in IMO. The tools needed to implement this optimization cycle are substantially different from conventional optimization tools. The schedule generation tool, IEM, must accept as input a modified version of the previous outputs. Conventional optimization tools produce an output that the user can accept or reject, but not necessarily modify. Irrigation scheduling has an additional complication in that optimization occurs at two different temporal scales and two different spatial or organizational scales. When the manager is planning for a coming irrigation season, decisions about what crops to plan are influenced by the ability to meet the crop water demands of a particular arrangement of crops. Planning at this temporal level involves decisions about practical yield reduction levels, deficit levels, and likelihood of resource conflicts. The temporal scale for these decisions is approximately monthly. The spatial scale involves decisions on a per-field scale and a multi-field scale. During the irrigation season, the scales change and the temporal scale shifts to few days or weeks. Decisions become focused on maintaining soil moisture levels while working around resource limitations (labor, canal operations, etc) and balancing needs of different fields. During the season, management requires a different type of tool that focuses on the short term decision-making that typifies operational irrigation scheduling in a resource limited context. These two temporal & spatial scales define the partitioning of the tools in IMO. Additionally, IMO introduces two analytical concepts that aid in conceptualizing and organizing the optimization process. These concepts are the Irrigation Scheduling Strategy, which encapsulates the algorithmic aspects of irrigation scheduling, and the Water Management Unit, which provides an organizational structure for evaluating resource constraints at higher organizational scales.

Managing Long Term Constraints

Optimal irrigation management under resource limited conditions involves balancing current crop water needs and anticipated future needs with the restrictions that limit the availability of water. Uncertainty about current conditions and expected future conditions put limits on a manager’s ability to choose optimal management strategies. Much of that uncertainty is physical in nature. Variability in soil holding capacity and application depth, as well as model errors are each addressed by IEM using Monte Carlo simulation. By combining ET based soil moisture estimates with physical measurements IEM also mitigates model errors.

IEM does not address climate uncertainty but IMO does so by simulating three alternative future weather scenarios. These alternative scenarios correspond to high, low, and average ET demand. The scenarios are produced by averaging historical weather measurements from the weather station selected by the user. All of the weather data available for the selected station is downloaded to compute means and variances for each day of the year for each weather parameter. The Low ET scenario is computed as the μ – ¼σ and the High ET as μ + ¼σ. Once the setup is complete the user can edit these values if desired. A sample of the historical data used from the AGRIMET weather station in Echo, OR is shown in Figure 26.

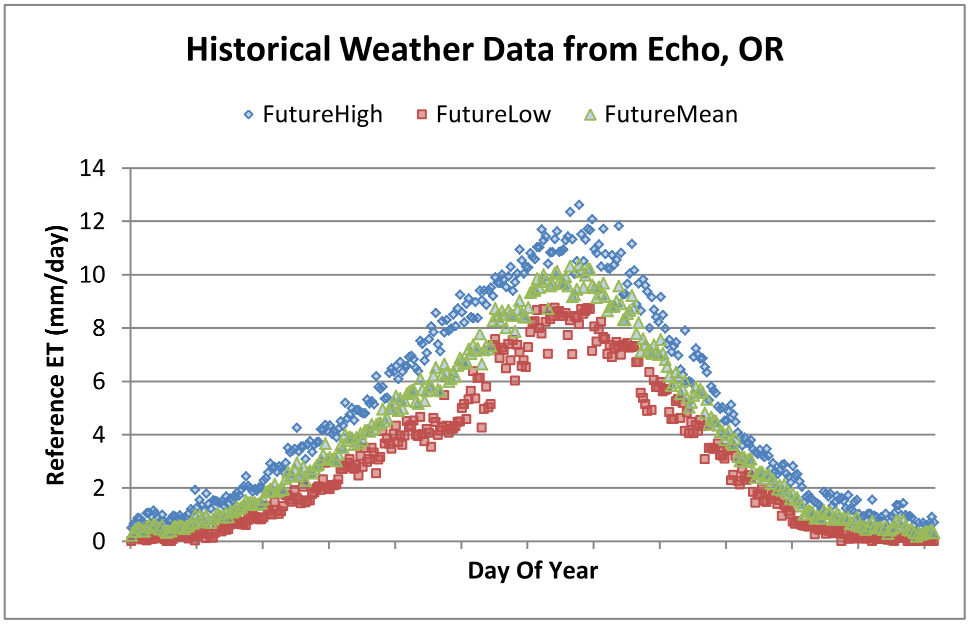
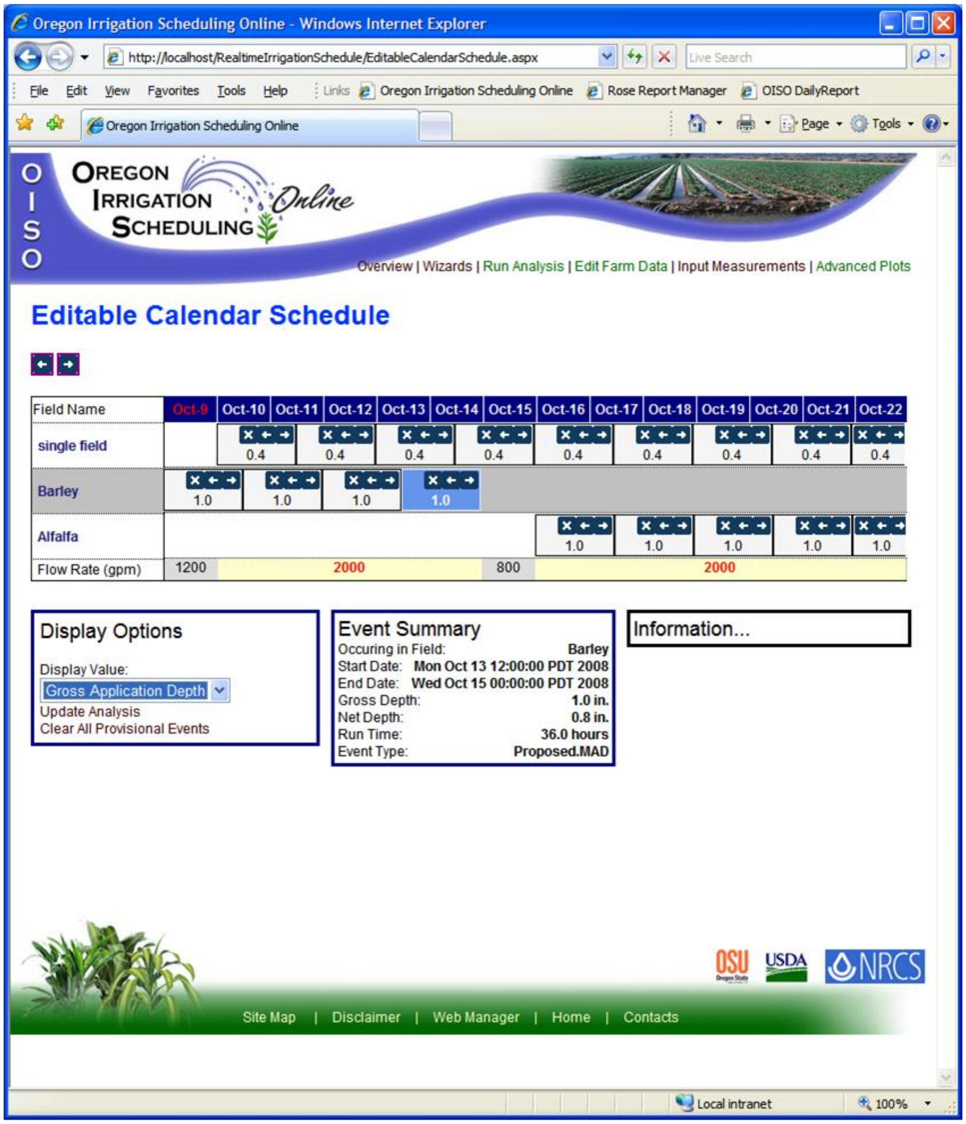


Figure 26 Weather Data Sample

When IEM simulates an irrigation season the model expects a full seasons worth of data to be available. During the irrigation season IMO will execute the IEM model four times whenever updated schedules are required. The first calculations are performed using actual data from the current season. IEM runs from the beginning of the season up to the last day that actual weather data is available. The endpoint of this simulation is presented as the estimate of 'current' soil moisture status. The endpoint is also used at the starting point for three future weather scenarios. When the simulations are complete the user is presented with three alternative irrigation schedules (and complete analyses) corresponding to the three weather scenarios. These three scenarios are how IMO helps managers mitigate uncertainty about the future water demand. The average scenario is the one most commonly presented by planning tools. The high & low scenarios roughly correspond to worst and best case outcomes respectively. These scenarios help the manager to make long term decisions by roughly bracketing the range of likely outcomes.

An example use of this feature during the season would be to assess the utility of continuing to irrigate when a severe mid-season shortage occurs. The manager could use the low ET scenario to determine the best possible outcome and decide if the best that could happen will meet some minimum yield requirements.

Managing Short Term Constraints



Editable Calendar Schedule

Field Name	Oct-9	Oct-10	Oct-11	Oct-12	Oct-13	Oct-14	Oct-15	Oct-16	Oct-17	Oct-18	Oct-19	Oct-20	Oct-21	Oct-22
single field		0.4	0.4		0.4	0.4		0.4	0.4		0.4	0.4		0.4
Barley	1.0	1.0		1.0	1.0									
Alfalfa								1.0	1.0		1.0	1.0		1.0
Flow Rate (gpm)	1200	2000					800	2000						

Display Options

Display Value: Gross Application Depth

Update Analysis

Clear All Provisional Events

Event Summary

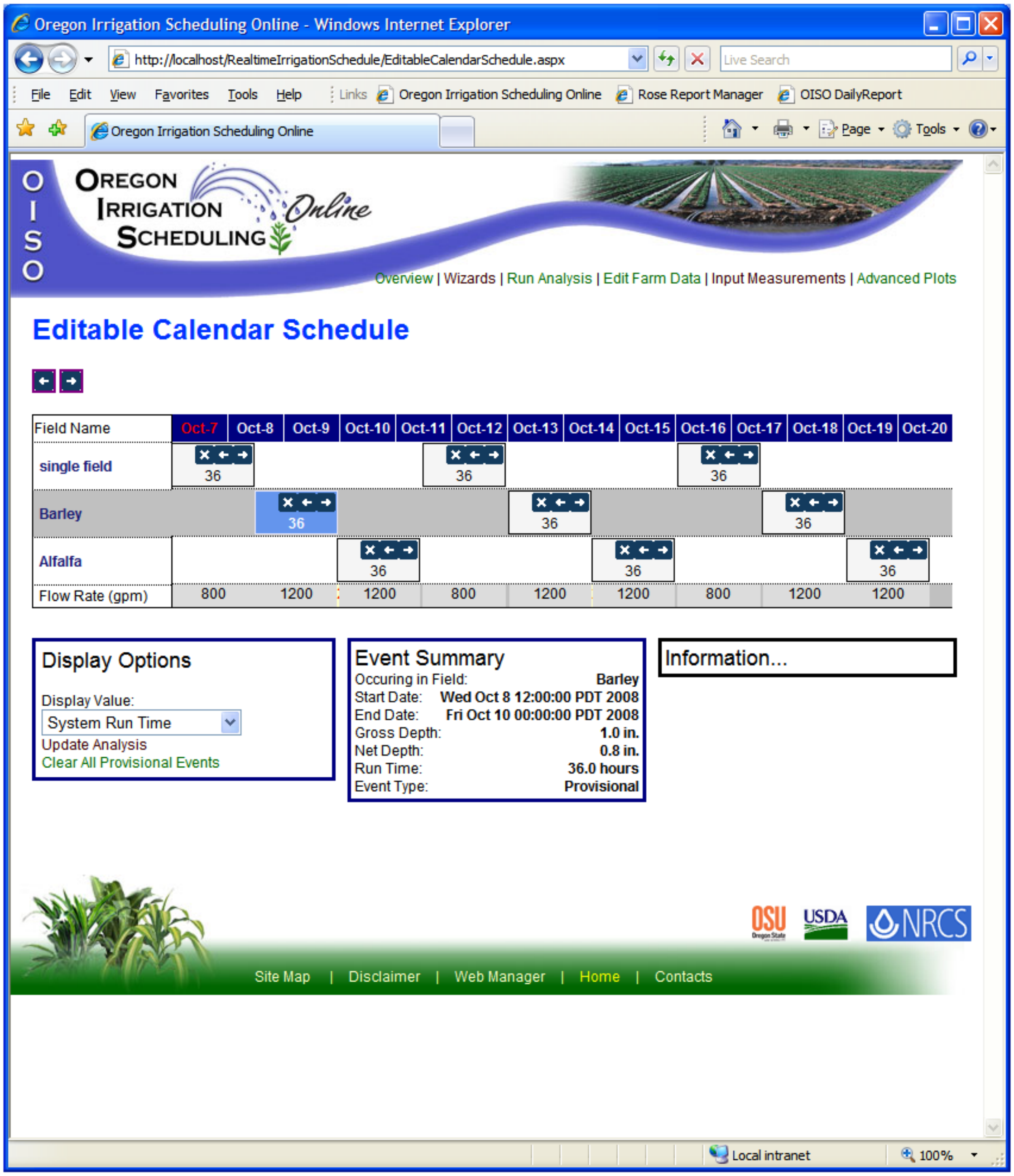
Occuring in Field:	Barley
Start Date:	Mon Oct 13 12:00:00 PDT 2008
End Date:	Wed Oct 15 00:00:00 PDT 2008
Gross Depth:	1.0 in.
Net Depth:	0.8 in.
Run Time:	36.0 hours
Event Type:	Proposed.MAD

Information...

Figure 27, Screen shot of the editable irrigation schedule

Short term constraints apply to the day to day operational decisions that managers must make. The shorter time frame necessitates a process that is different from long term planning. IMO uses an interactive 10 day schedule to facilitate operational irrigation management. Figure 27 shows a screen shot of the calendar being edited. Graphically, the schedule is a modified form of a Gantt chart. Each row corresponds to a single field and the blocks within each row are individual irrigation events. The bottom row shows the pumping demand (in gallons per minute) and indicates when supply capacity limitations are projected to occur. The editing process involves a point-and-click procedure where the user can add, delete, and modify the timing of the events. As the events are edited the bottom row is updated. The text within the event blocks can be hours of operation (as in the screen shot) or as depth of application. Figure 28 shows the same fields as in Figure 27 after the editing process is completed and supply conflicts have been eliminated. At the end of this process the schedule can be printed and given to field workers.

After editing the generated schedule, the user can direct IMO to re-run the IEM model using the edited schedule rather than the forecast one. After the re-run is complete the user can evaluate if the changes to the schedule produce an acceptable change to the estimated soil moisture status. If the user decides that the changes are not acceptable the schedule can be edited further and the IEM model executed again. In effect, the output of the previous model run becomes the input for the next model run. This iterative procedure is how IMO differs from conventional optimization tools. The user is not limited to adjusting the input parameters in order to obtain an acceptable result. Instead, the user acts as the constraint function and the objective function of the optimization algorithm



Editable Calendar Schedule

Field Name	Oct-7	Oct-8	Oct-9	Oct-10	Oct-11	Oct-12	Oct-13	Oct-14	Oct-15	Oct-16	Oct-17	Oct-18	Oct-19	Oct-20
single field	✕ ← → 36				✕ ← → 36					✕ ← → 36				
Barley		✕ ← → 36					✕ ← → 36				✕ ← → 36			
Alfalfa				✕ ← → 36				✕ ← → 36					✕ ← → 36	
Flow Rate (gpm)	800	1200		1200	800		1200	1200		800	1200		1200	

Display Options

Display Value: System Run Time

Update Analysis

Clear All Provisional Events

Event Summary

Occuring in Field:	Barley
Start Date:	Wed Oct 8 12:00:00 PDT 2008
End Date:	Fri Oct 10 00:00:00 PDT 2008
Gross Depth:	1.0 in.
Net Depth:	0.8 in.
Run Time:	36.0 hours
Event Type:	Provisional

Information...

Figure 28, Calendar Schedule after editing

It is important to note that IEM/IMO does not try to enforce the supply constraints or the seasonal constraints when generating irrigation schedules. IMO will simulate any irrigation schedule the user defines. The user must decide what schedules are feasible and which conflicts to avoid.

Concepts Unique to IMO

Managers typically operate at a whole farm level but conventional scheduling software typically does not. Conventional scheduling is simplified by assuming availability of water. Irrigation schedules are generated for each field independent of any other fields, and anticipating or understanding allocations of limited water between fields is left up to the user. The algorithm for optimal scheduling will necessarily be more complex and will consider more than one field at a time. IMO introduces two concepts that are intended to mitigate the complexity of whole farm management and more complex scheduling algorithms. These concepts are the Water Management Unit, a logical grouping of fields, and the Scheduling Strategy, an encapsulation of the scheduling algorithm. The user is introduced to these concepts during the setup process and continues to use them while managing irrigation.

Water Management Unit

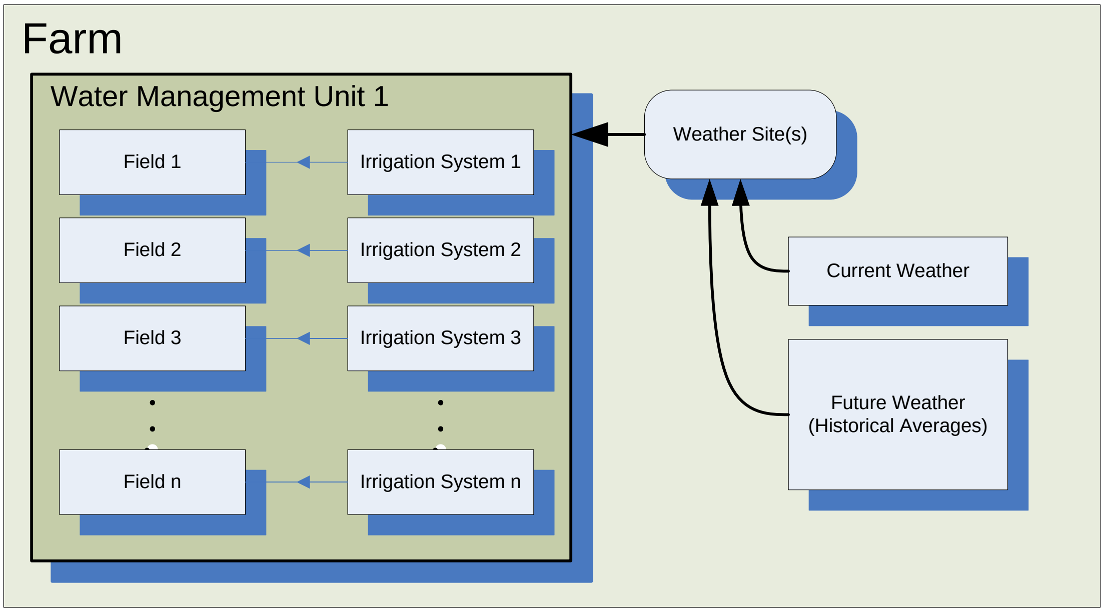


Figure 29 Conceptual view of the Water Management Unit

Figure 29 shows a conceptual view of a Water Management Unit (WMU). In general, a WMU is a group of fields, irrigation systems, and pumping plants that all share the same weather and the same resource constraints.

In general, the purpose of the WMU concept is to enable conjunctive management. From a user directed optimization perspective the WUM is the conceptual level at which conjunctive management occurs. The IMO interface allows the user to evaluate irrigation strategies on a per constraint basis. This is the basic premise of conjunctive management: irrigation constraints usually apply to most (but not always all) fields. Evaluating these constraints on a per field basis is possible but inconvenient. From a practical standpoint, the WMU parallel conceptual grouping that already occurs in larger farming operations. The WMU encapsulates the fields, irrigation systems, and management constraints. In larger farm operations, similar groupings occur for a variety of reasons such as geographic separation, tax assessments, or historical reasons. The WMU can mirror existing groupings and thus maintains conceptual divisions that already exist.

Small farms will typically have only one WMU. When a farm has only one WMU then the WMU is conceptually equivalent to a farm. When the user creates a new farm in IMO, a single WMU is created by default and the user is only required to specify supply capacity and seasonal water allocation constraints. Throughout the rest of the site WMU selection is automatic and no additional WMU modifications are required. Thus, when the WMU is not needed it is relatively transparent.

One potential disadvantage of the current implementation is that a WMU cannot contain other WMUs. Furthermore, constraints apply equally to all fields in the WMU. Some constraints are hierarchical rather than serial. For example, pumping systems often have a hierarchical structure where one pumping plant supplies several smaller plants that in turn supply groups of fields. To evaluate constraints for the larger plant it must be duplicated in each WMU.

Scheduling Strategy

The algorithm that IEM uses to generate irrigation schedules requires several input parameters. The Scheduling Strategy is an encapsulation of all of these parameters. The Scheduling Strategy defines the relationship between the Field class and the IrrigationSystem classes in the IEM simulation. Details of how the scheduling algorithm works are detailed in the previous paper on IEM (how to cite this?).

The user is introduced to the Scheduling Strategy concept during the setup process. Creating a new field in IMO is a three step process: first define the physical field, second define an irrigation system, and third create a scheduling strategy for them.

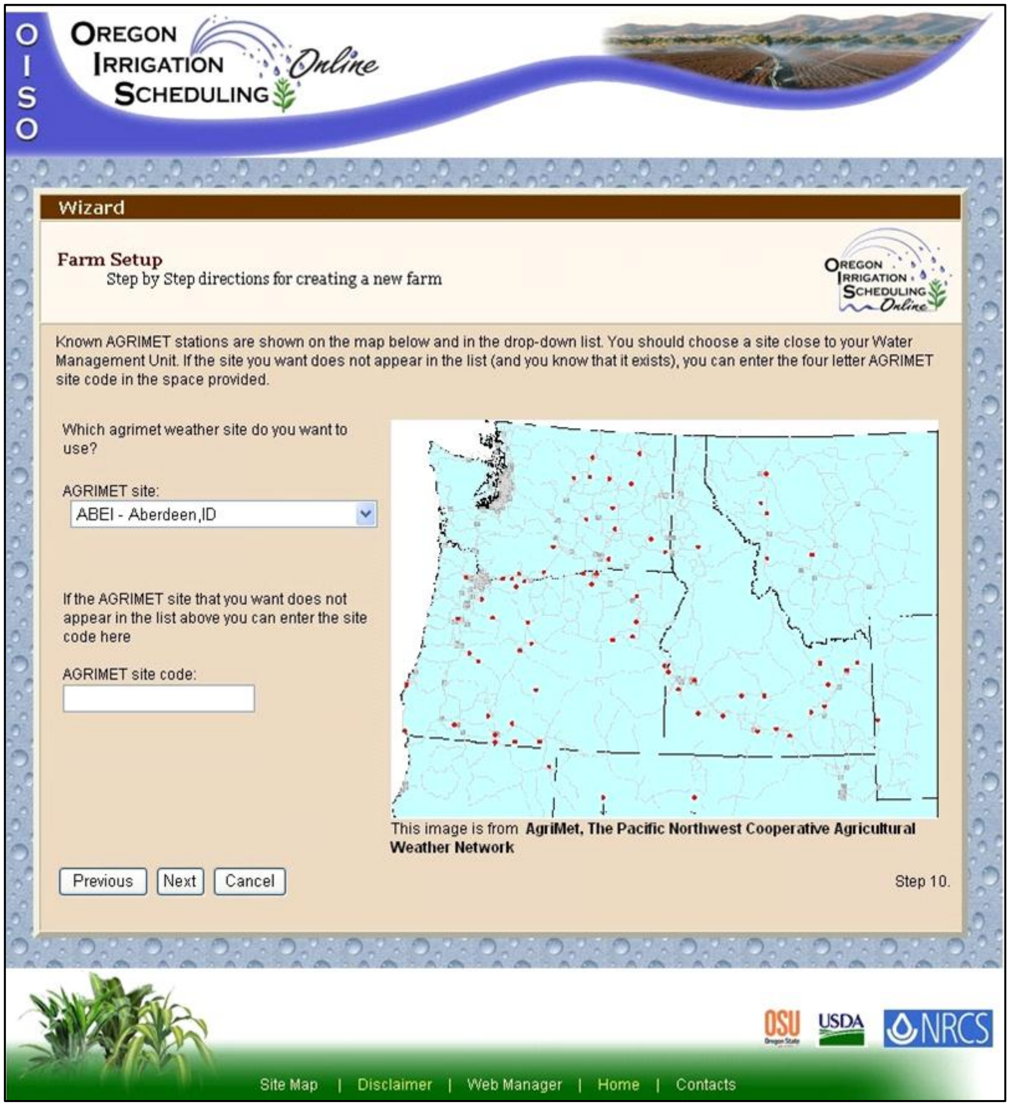
Two default scheduling strategies are available. The first is called “Conventional” and it implements a full ET replacement strategy based on the low quarter average (87.5% adequacy) of soil moisture depletion. The second default is “Reduced Water Use” which implements a basic deficit irrigation strategy where Management Allowed Depletion is increased to 60%, and Target Irrigation Level is decreased to 90%. A “Customized” option is also available that allows the user to specify each of the parameters that define the Scheduling Strategy. The “Conventional” strategy is selected by default.

Design of a Scheduling Strategy is part of the optimization process. Part of the process of managing long term constraints involves iteratively modifying the scheduling strategy and evaluating seasonal water demands until the conflicts within a Water Management Unit seem manageable. During the irrigation season IEM continues to use the strategy to generate daily scheduling recommendations. The strategy can be modified during the season if the recommendations are consistently implausible.

System Features

The ASP.NET pages that make up IMO are partitioned into four groups that correspond to four basic use patterns: setup, calibration, data entry, and outputs.

IEM requires a substantial set of technical information much of which the average user will not have readily available. Requiring users to collect this information prior to setup was deemed an unrealistic expectation. Instead, a set of wizards were developed that simplified the setup process and minimized the information burden on the user. There are 12 wizards in IMO that facilitate nearly all the setup processes but only four of these wizards are required prior to generating analyses. These four are the Farm, Field, Irrigation System, and Irrigation Scheduling Strategy. In the Farm wizard the user chooses a weather data source and provides some basic Water Management Unit information. In the Field wizard, the user describes the area, crop, and soils information. In the Irrigation System wizard, the user described the physical characteristics of the irrigation system. In the final wizard, the user selects an Irrigation Scheduling Strategy. Figure 30 shows a screen shot of the Farm wizard where the user is selecting a weather station.



Farm Setup
Step by Step directions for creating a new farm

Known AGRIMET stations are shown on the map below and in the drop-down list. You should choose a site close to your Water Management Unit. If the site you want does not appear in the list (and you know that it exists), you can enter the four letter AGRIMET site code in the space provided.

Which agrimet weather site do you want to use?

AGRIMET site: ABEI - Aberdeen,ID

If the AGRIMET site that you want does not appear in the list above you can enter the site code here

AGRIMET site code:

This image is from **AgriMet, The Pacific Northwest Cooperative Agricultural Weather Network**

Figure 30. Screen shot of the Farm wizard

After setup is complete IMO can send emails that contain updated analyses and scheduling recommendations. Each day a server side application (implemented as an SQL CLR stored procedure) downloads the previous day's weather data, runs the IEM simulation for each farm, updates the stored analyses, and sends emails as directed. These emails contain links that take the user back to the data entry pages so that they can provide updated water user information.

During the setup process the user must select a weather station that will serve as the source of weather data for all analyses. IMO is designed so that the user will not need to deal with managing weather data again after making this selection. All weather data is downloaded automatically and is transparent to the user. The downloaded data is available for display and the user can edit the downloaded data if they choose. Currently IMO can connect to the USBR AgriMet network and the California DWR CIMIS network.

Technical Summary

IMO is implemented as an ASP.NET web application composed of 50+ pages. The code behind is written in C#. SQL Server 2005 is used as the database software and SQLCLR integration is used to implement stored procedures for automatic weather downloads, simulation updates, and email distribution. The email content is generated using Microsoft Reporting Server 2005. Figure 31 shows a deployment diagram of the entire IMO system.

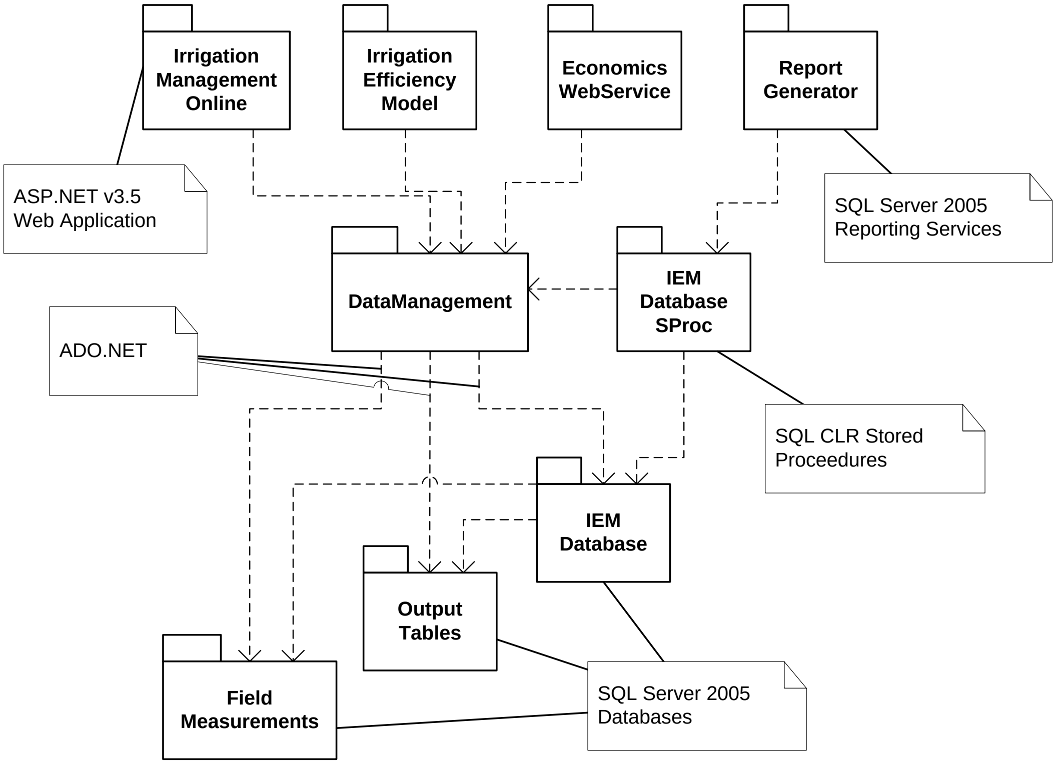


Figure 31, Deployment diagram of the IMO system

Results

Testing and validation of IMO has proceeded in two phases. The first phase (Phase 1) involved extensive field trials of IMO as a conventional or 'full irrigation' management tool. Phase 2 was a trial of IMO as a deficit irrigation management tool in a resource-limited context.

Phase 1

Phase 1 began in 2005 and continued for 5 years. During each year field trails where conducted on several cooperating farms and some of these farms participated for multiple years. Development of IMO was ongoing during the 5 year period and the trails were used to a) determine what features where needed and not included in the original design and b) test and evaluate new features, and c) validate the accuracy of IEM/IMO as a deficit irrigation scheduling tool. During the irrigation season bug fixes where made as they were reported. In between seasons, improvements and additions were made to IMO based on comments collected during the irrigation season. Table 10 shows a summary of the Phase 1 trials.

Table 10, Phase 1 field summary

Year	*Region*	*Farms*	*Total Area (hectares)*	*Fields*
2005	Central OR	2	65.6	2
2006	Klamath OR	1	30.8	2
	Central OR	5	714.4	16
2007	Klamath OR	9	355.3	17
	Central OR	4	420.6	9
2008	Washington	8	289.0	26
	Klamath OR	6	422.9	14
	Idaho	2	124.6	3
	Central OR	2	87.8	2
2009	Washington	9	569.2	30
	Central OR	4	562.8	12
	CA	5	560.1	13
2010	Washington	3	134.0	12
	Central OR	2	330.8	7
	CA	5	560.1	13

During the first year grad students performed setup and calibration for all of the participating farms. Students performed in-season data entry for all but one of the cooperating farms. The second year was a continuation of the same growers as the first year. The second year involved less calibration but the in-season data entry was still handled by students. During the third year setup was performed by students. During the fourth year initial setup for most of the new farms was done by the growers and the farm configuration was checked by students or farm advisors after setup was complete. In-season data entry was mixed between growers and students however, students performed calibration.

Phase 2

The second phase of development was a trial of IMO as a deficit irrigation management tool in a resource limited context. The goals of this trial were threefold: first, evaluate the performance of the IEM model under deficit conditions, second, evaluate the practicality of the schedules generated by IEM, and third, evaluate the useability of IMO as a planning and management tool.

The trial was conducted on a farm in Hermiston, OR during the 2010 irrigation season. A group of seven fields was setup in IMO at the beginning of the irrigation season. Table 11 shows a summary of the physical characteristics of the fields and the crops used. The fields are part of a larger operation but are managed as a single unit. The irrigation systems and pumping plants were specifically designed for deficit irrigation and, as such, they do not have the capacity to completely match evaporative demand. In-season management currently involves a daily evaluation of irrigation need decisions are made by an experienced irrigation manager. Even with the supply limitations, these fields have been managed profitably for more than ten years.

Table 11, Phase 2 Field Summary

Field Name	*Crop*	*Area*
M043	Alfalfa (4)	65.5
M044	Winter Grain	65.5
M045	Alfalfa (4)	116.0
M046	Canola	123.9
M047	Alfalfa (2)	79.4
M048	Alfalfa (2)	177.9

In the beginning of the 2010 season a graduate student setup the seven fields in IMO. Experiments had been done on these fields previously so much of the field data necessary had already been collected. Each of the irrigation systems were instrumented with pressure sensors. Irrigation dates and amounts were verified using these sensors. On one system the pressure sensor failed and some of the irrigation dates were estimated. An independent consultant contracted by the grower made weekly neutron probe measurements. The contractor provided the readings via his website and had been providing this service to the grower for several years. The readings were downloaded from the contractor's website, converted into form appropriate for IMO, and entered manually using the web interface.

To evaluate the practicality of IEM's generated schedules a simulated pre-season analysis was performed. The analysis was conducted at the end of the season after a satisfactory calibration was obtained. An initial set of full season schedules was generated using average future weather conditions based on the Hermiston

AGRIMET station and assuming full ET replacement. Figure 32 shows the expected pumping demand from the initial estimate. The initial analysis indicated (which the grower already knew) that the pumping demand cannot be met for a significant portion of the season. The scheduling strategy for each field was adjusted by incrementally reducing the target irrigation level and MAD until the pumping demand was more manageable. For some of the alfalfa a fields a variable target level and MAD was used so that, for a portion of the season, stress levels were high enough to free up capacity for other crops that were at their peak ET demand. Additionally, adequacy was reduced for some of the alfalfa fields. The general strategy used (which is approximately the same as the irrigation manager's current strategy) was to sacrifice some yield from the alfalfa in order to avoid excess stress on other crops during critical growth stages. Figure 33 shows the revised pumping demand after strategy modification. Table 12 shows the changes to the scheduling strategy parameters and the model estimates for yield reduction before and after the modification.

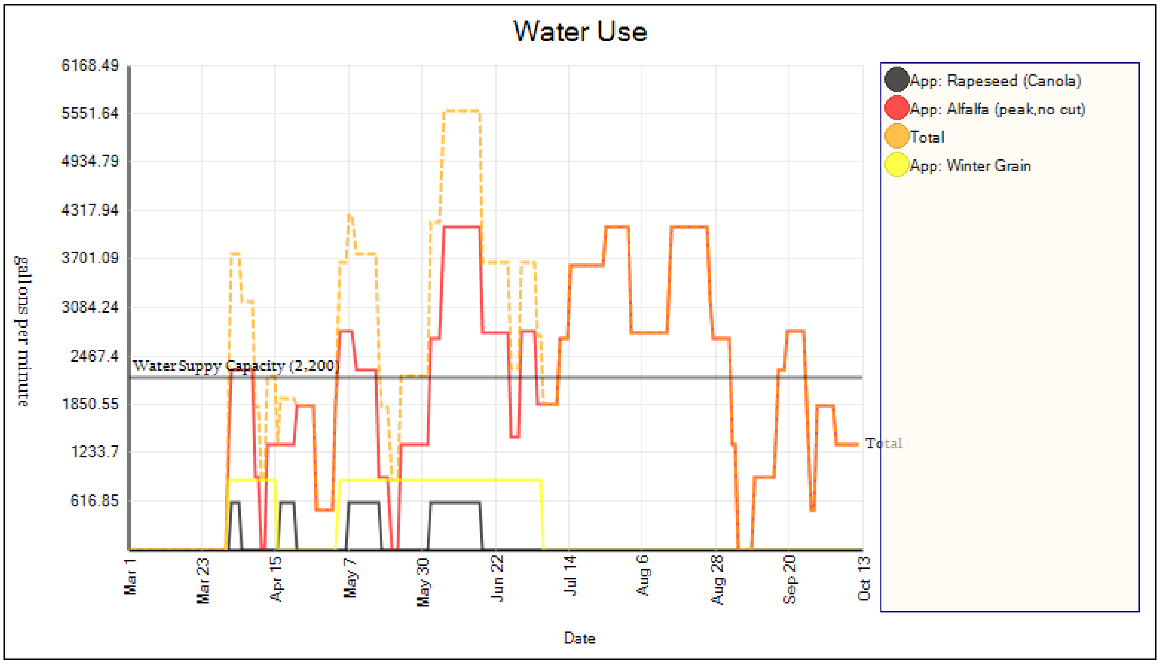


Figure 32, Initial pumping demand estimate

Table 12, Scheduling Strategy Changes

Field	*MAD%*	*Target%*	*"Critical %"*	*Date*	*MAD%*	*Target%*
	Early Season				Late Season	
M043	80	60	50	5-Jun	85	40
M044	70	70	33	10-Jun	75	50
M045	85	60	25	5-Jun	85	40
M046	80	75	33			
M047	80	60	25	5-Jun	80	40
M048	80	60	25	5-Jun	80	40

The pumping demand plot gives the user an estimate of how often conflicts are expected. The changes to the scheduling strategy reduce the expected frequency of conflicts but does not eliminate them entirely. To evaluate how practical the generated schedules were we compared what the irrigation manager did vs. what IMO suggested. This comparison was done at a field level on a day by day basis using an animation. The animations were constructed using the soil moisture plots from each day of the irrigation season. The plots are the frames in the animation and are displayed sequentially by date. These animations are available for download at http://oiso.bioe.orst.edu/IMOPhase2Results.zip.

Figure 34 shows pumping demand that actually occurred. The spikes above supply capacity line are from a few events that where estimated because of the failed instrumentation. Some of the events were partial coverings of the field. Those events where modified in IMO so that the run time used by IEM produced the same depth of application.

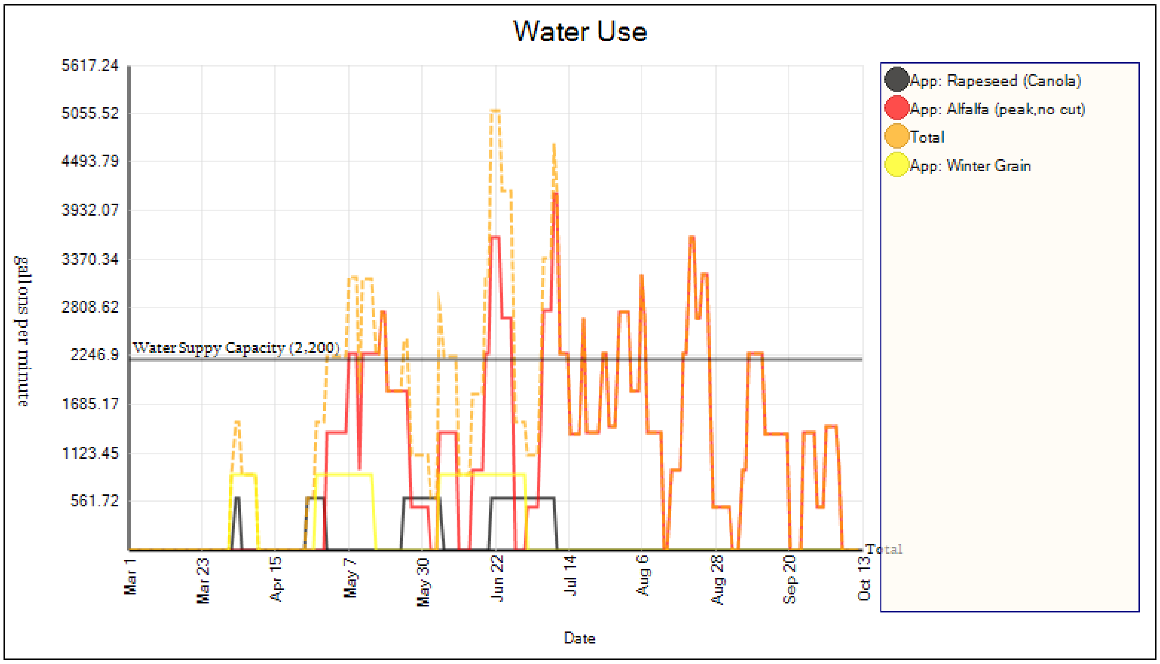


Figure 33 Revised pumping demand estimate

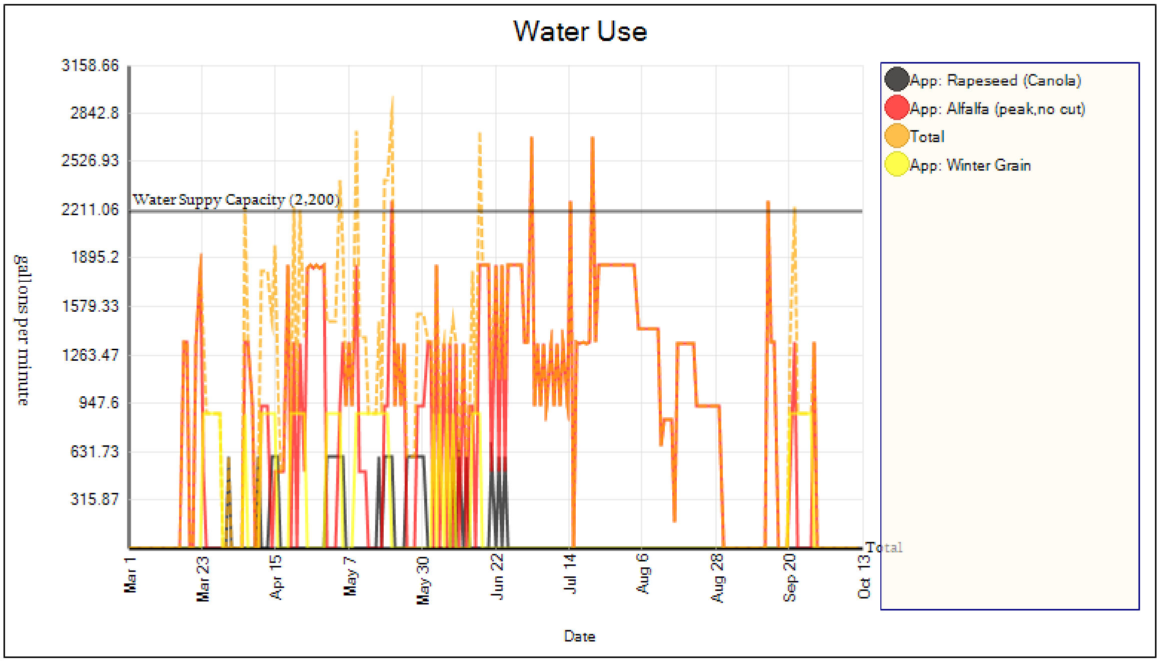


Figure 34 Actual 2010 water use based on pivot instrumentation

Figure 35 through Figure 46 show the soil moisture estimate for each field with and without the soil moisture correction algorithm. In some of the fields (M048 particularly) the correction algorithm appears to be having very little effect. These fields have multiple soil types and the neutron probe access tube was installed in a soil type that made up a smaller fraction of the field. The correction algorithm only corrects the portion of the field with the soil type that the measurement is associated. Consequently, the average soil moisture estimate is not changed significantly by the measurements.

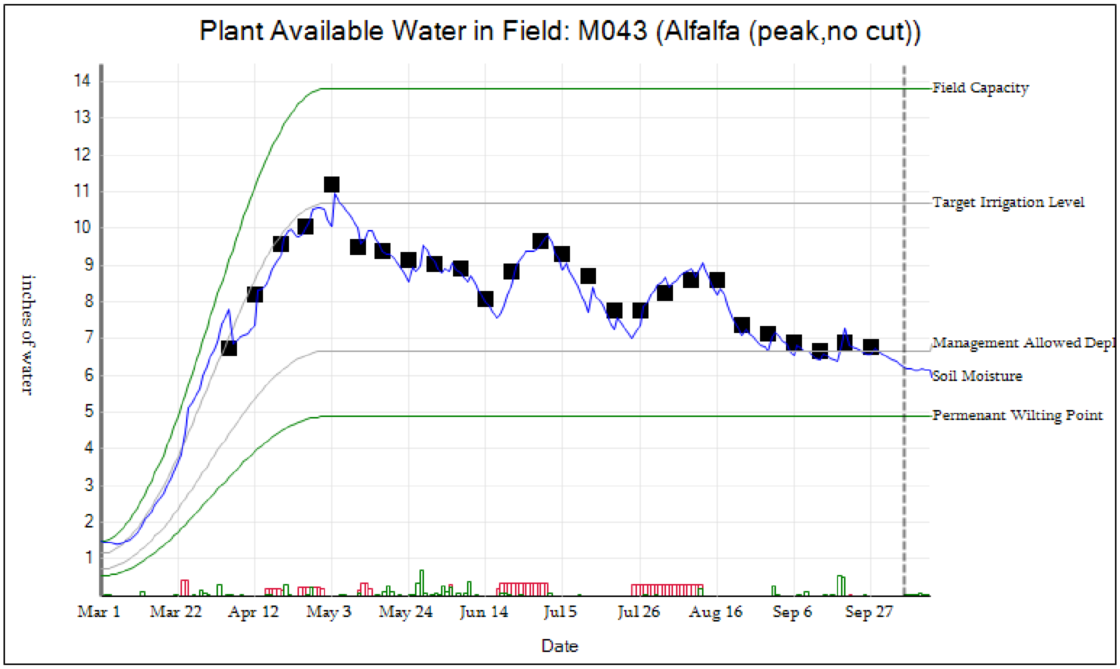


Figure 35 Field M043 with correction algorithm

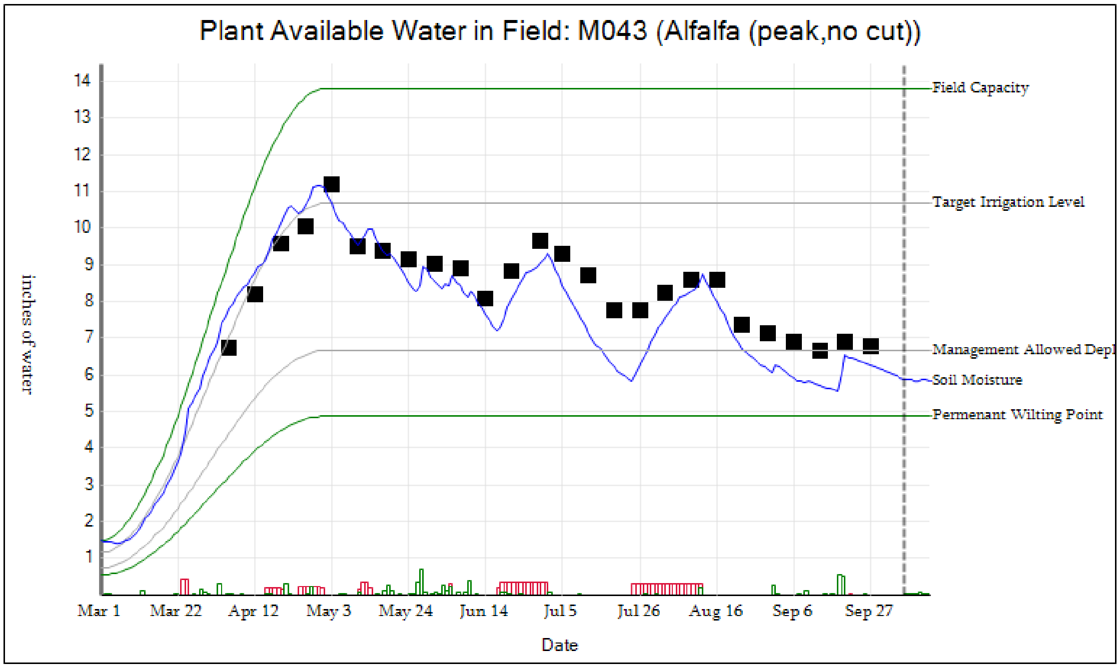


Figure 36 Field M043, uncorrected

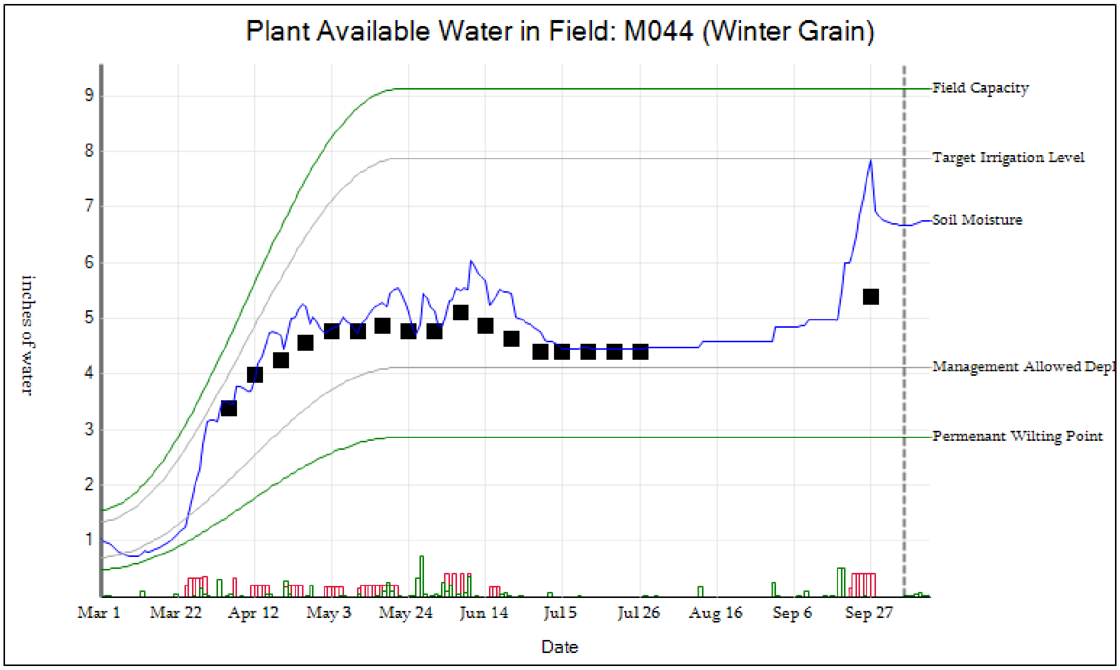


Figure 37 Field M044 with correction algorithm

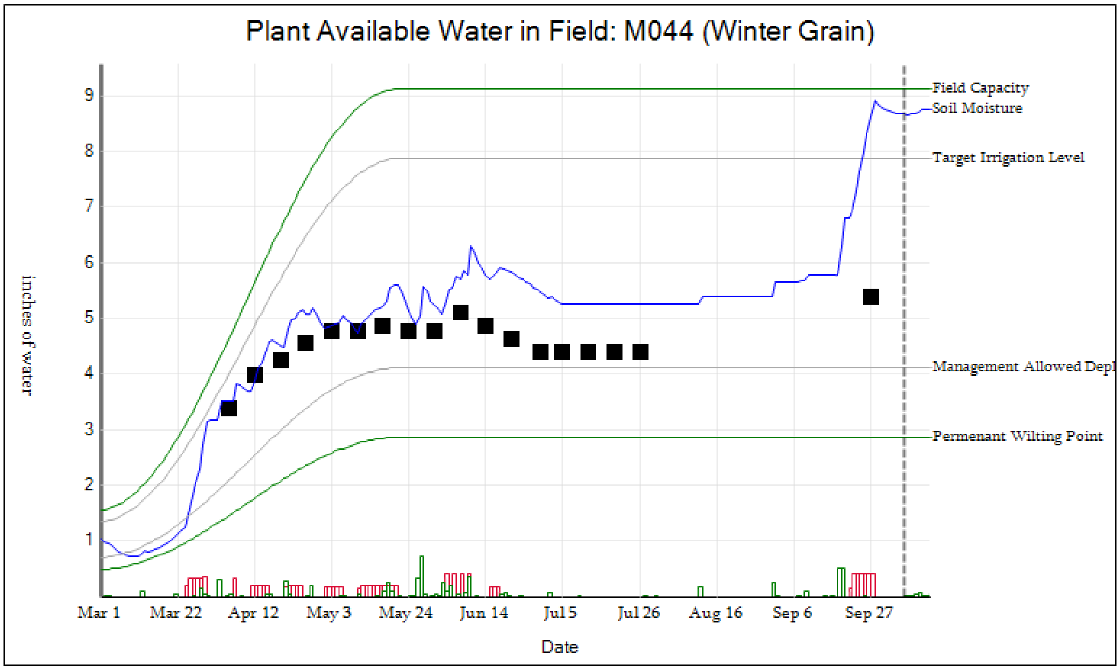


Figure 38 Field M044, uncorrected

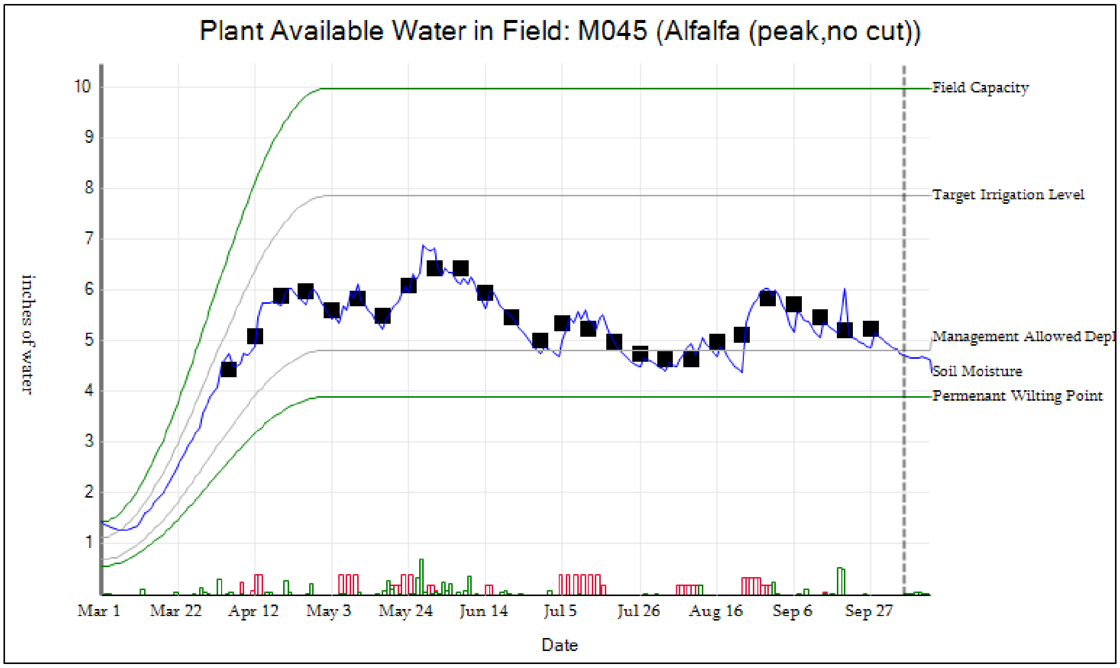


Figure 39 Field M045 with correction algorithm

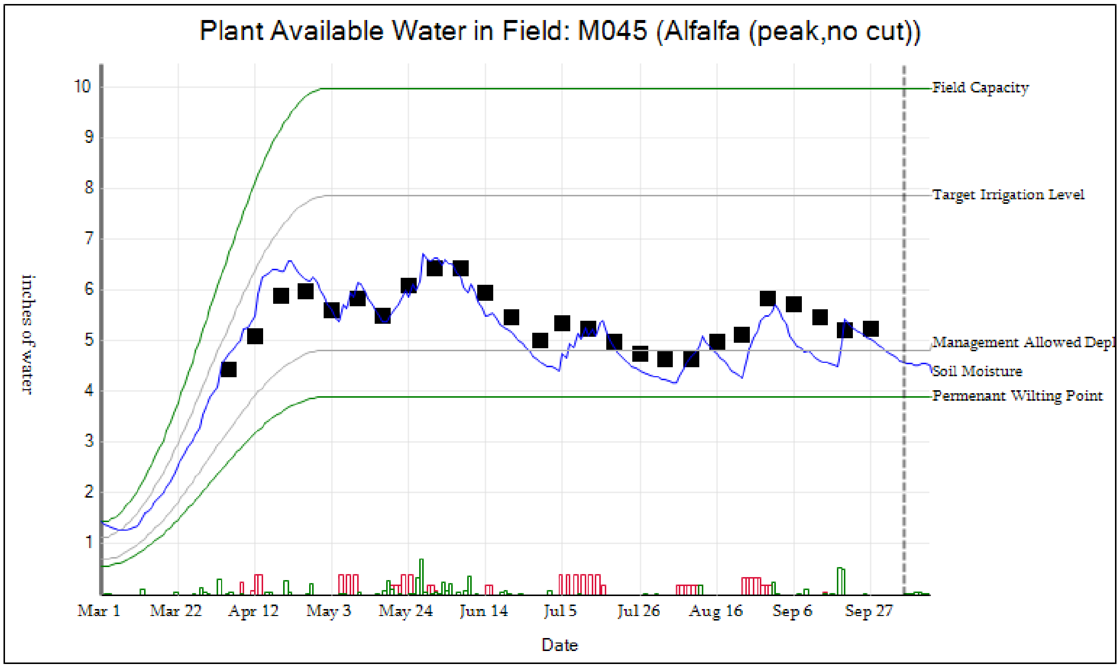


Figure 40 Field M045, uncorrected

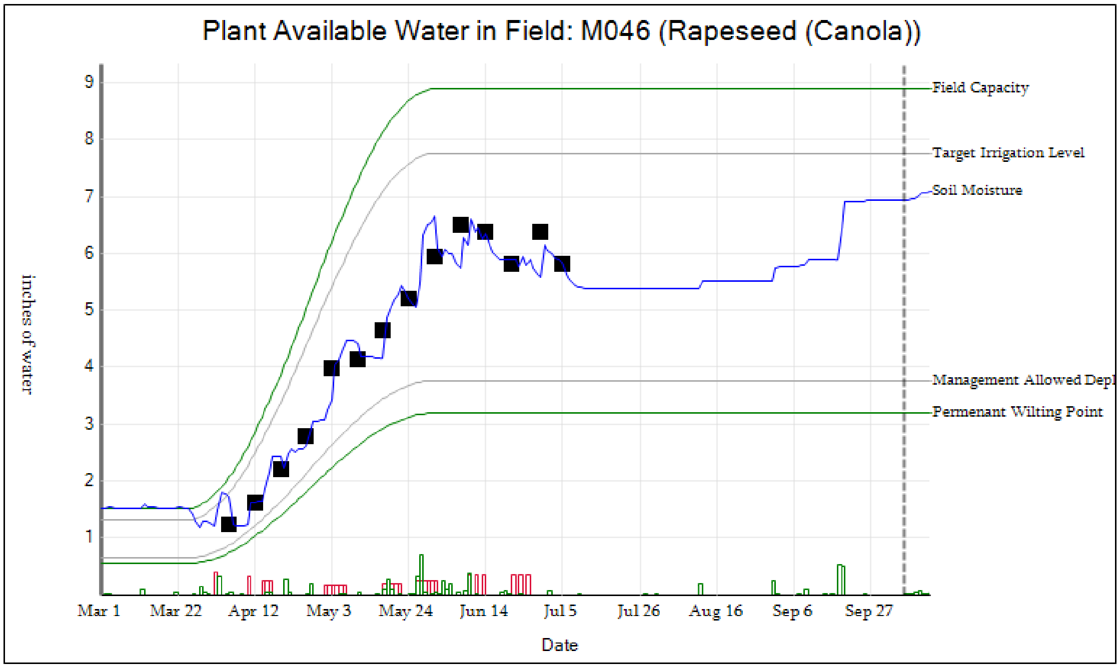


Figure 41 Field M046 with correction algorithm

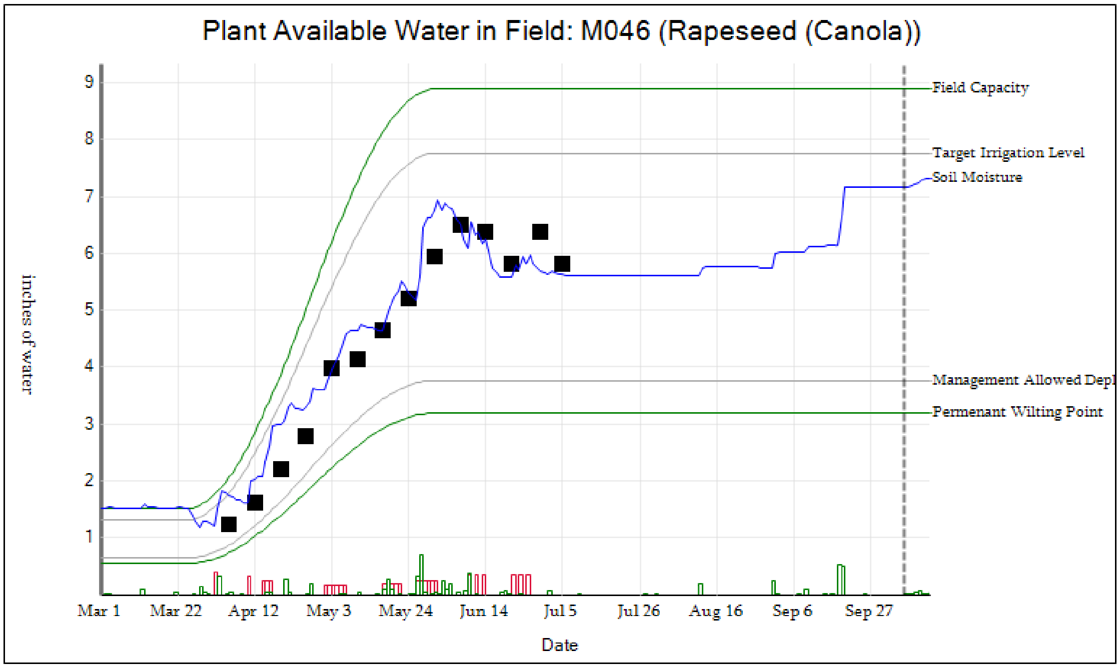


Figure 42 Field M046, uncorrected

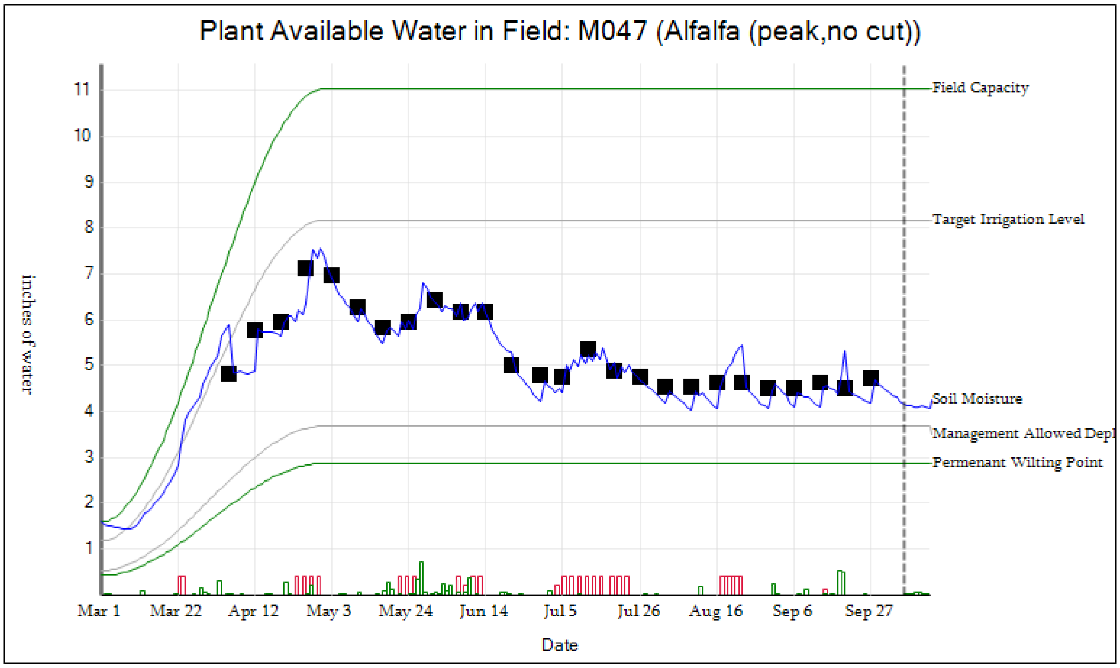


Figure 43 Field M047 with correction algorithm

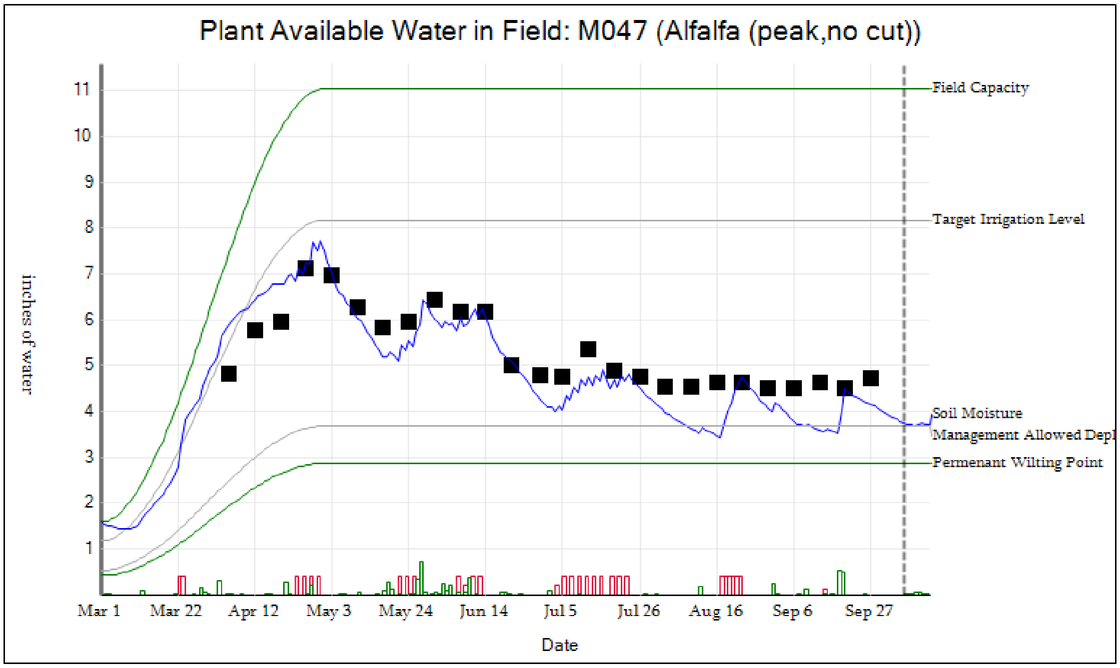


Figure 44 Field M047, uncorrected

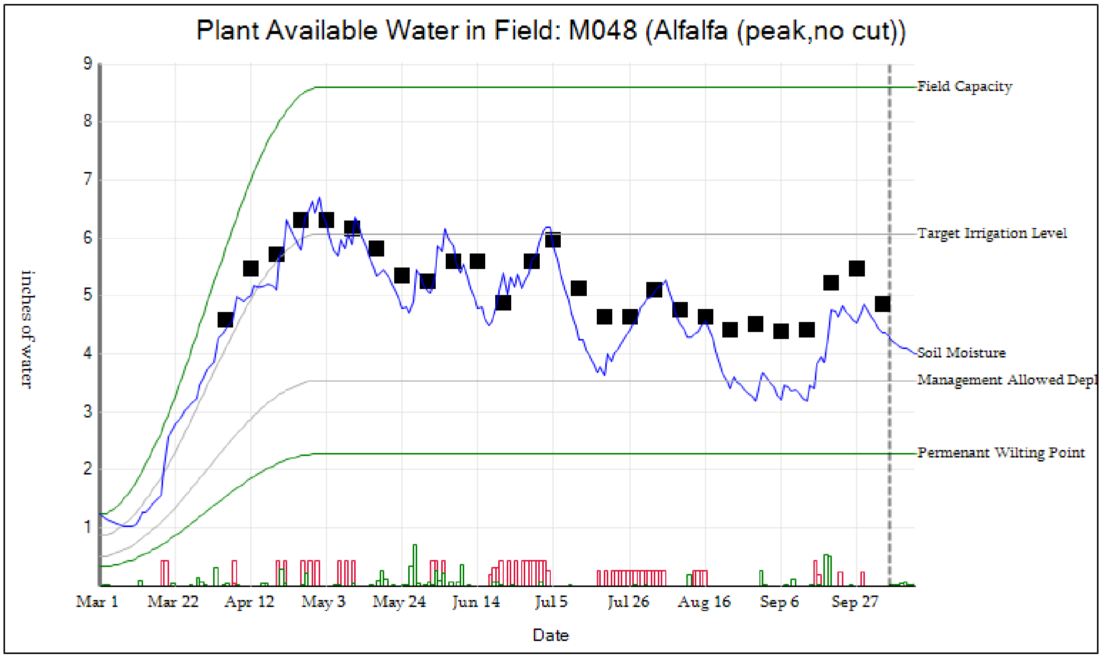


Figure 45 Field M048 with correction algorithm

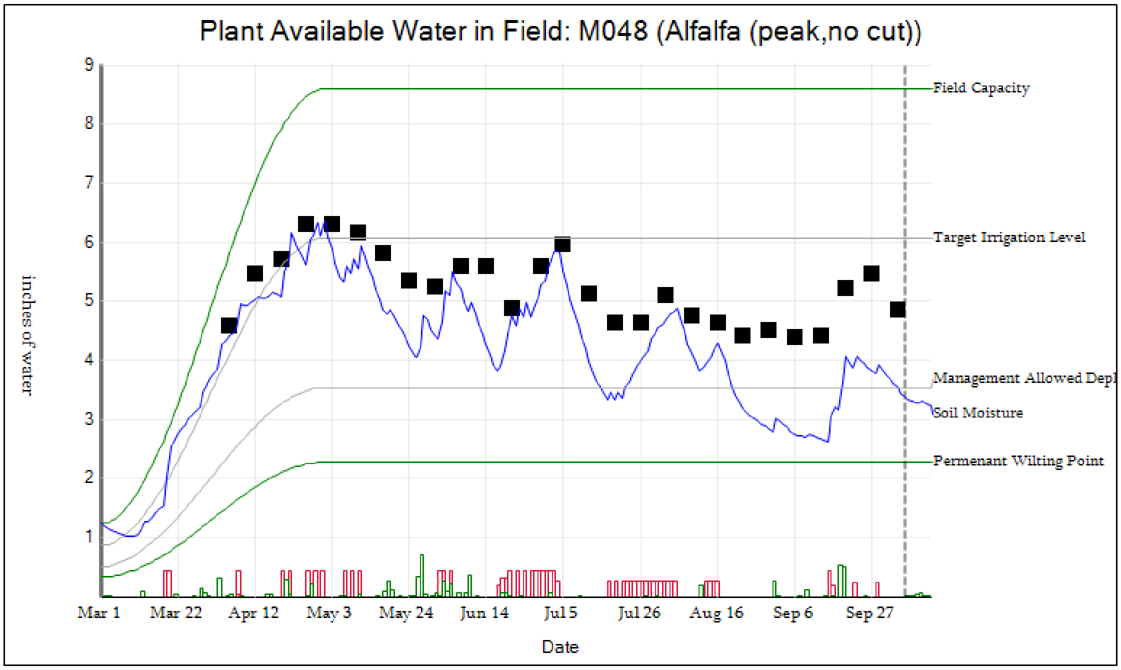


Figure 46 Field M048, uncorrected

Discussion

Field Trials

The field trails demonstrated that IEM can be accurately calibrated to a wide variety of conditions. The trials also demonstrated that the calibration process is critical. Initial attempts to calibrate IMO used some assumptions and approximations that are common to irrigation scheduling. In particular, the performance of the irrigation system must be known accurately and precise records of water use must be kept. In several instances we used assumptions about system runtimes based on the growers common practices (i.e. “I usually run 10 hour sets”, “I usually apply one inch per rotation”, “I irrigate every 5 days”, etc”). In practice, there were frequent variations in run times, gross depth applied, or days between irrigations, however these variations would typically be considered small relative to normal record keeping requirements. When the simulation results where compared to neutron probe measurements we were not able to obtain satisfactory results until more accurate records of water use where obtained. In one instance, the application rate of a pivot system was assumed based on the original design parameters. Calibration attempts repeatedly failed until it was discovered that the nozzles where too old to be considered reliable. After replacing the nozzles, calibration was adequate with subsequent neutron probe measurements.

Having access to all the simulation parameters also proved useful. During a trial in the Klamath Lake, OR area, crop coefficients for potatoes were not producing satisfactory results. This conclusion was based on early season discrepancies between simulated and measured soil moisture. These discrepancies diminished later in the season and satisfactory calibration was obtained on similar soils but different crops. The user was able to modify the early season crop coefficients (via the IMO Crop Characteristics interface) and subsequently obtained a reasonable calibration.

User Feedback

During the field trails attempts were made to solicit feedback from the trail participants. Users were generally satisfied with the accuracy of the system. The email feature was particularly popular and several of the trail participants have requested continued use of this feature. The most common complaints were that the system is complicated and that data entry was time consuming. A common request from more technically sophisticated users was to include some type of spread sheet interface so that Microsoft Excel could be used to manage data entry. The users who requested this were already using Excel for record keeping. Nearly all of the feedback was related to managing data and by the end of the field trails it was clear that ease of use and the time commitment required were the limiting factors for acceptance of the system.

Program Review

A panel of experts in September 2009 reviewed IMO. The panel consisted of researchers, farm advisors, and producers. The purpose of the review was to provide critical feedback and observations that will inform future development of IMO. A summary of the reviewer's comments follows.

IMO is complex and its complexity limits its useability. The model has more input parameters than most scheduling tools and the initial calculations required for setup and calibration are non-trivial for less sophisticated users. Using user interface components that are more visual than numerical would improve useability for less sophisticated users

IMO must incorporate new sources of data as they become available. New sources and types of measurements are becoming available as sensor and data collection technology becomes cheaper and more accessible. Additionally, IMO should be able to output simulated sensor readings to facilitate calibration. This will help maintain the level of accuracy needed for optimization. In particular, IMO needs to be able to use irrigation system instrumentation (e.g. pressure sensors, pump monitors, etc.) to reduce data input burdens on the user.

IMO should target specific groups of users. If the interface or complexity level is tailored to specific groups of users, more of that group is likely to use the system. IMO, in its current form, is most likely to be successful with growers who have already spent significant time considering irrigation management or have large operations. Motivation to use IMO will increase as water shortages increase. Eventually a broader audience will start using IMO and the system needs to be able to adapt to the new users in terms of useability and capacity.

IMO needs to include economic analysis. The system only needs enough data to compute *relative* changes in yield and costs of irrigation for given management options, not an economic analysis of the entire farm enterprise.

Conclusion

Optimal irrigation scheduling requires a robust set of analytical tools and an interface that is practical enough to facilitate the operational complexity and data management requirements of irrigation scheduling. IEM/IMO meets most, if not all, of the practical requirements for implementing optimal irrigation scheduling. IEM/IMO has been tested and validated as a tool for conventional and deficit irrigation scheduling. The data requirements for system setup were significant and could not rely on rough estimates. The data entry requirements were significant and, in some cases, a limiting factor for acceptance. Implementing methods for automating acquisition of data that is normally recorded by hand (particularly irrigation start and end dates) would significantly increase the likelihood that the scheduling system will be used. Throughout the field trails data entry was perceived as the most time consuming part of the process and that increased instrumentation (such as soil moisture sensors) was only helpful if the software systems could load and use the data without human intervention.

Irrigation Management Online is currently hosted on a server in the Biological and Ecological Engineering department at Oregon State University. The web application is free and available to the public at oiso.bioe.orst.edu. Development and enhancement of IMO is ongoing.

Envisioning the Next Generation of Irrigation Schedulers

Charles Hillyer, Peter Robinson

Written for presentation at the 5th National Decennial Irrigation Conference
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Phoenix, Arizona
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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 13. 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%	100%
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

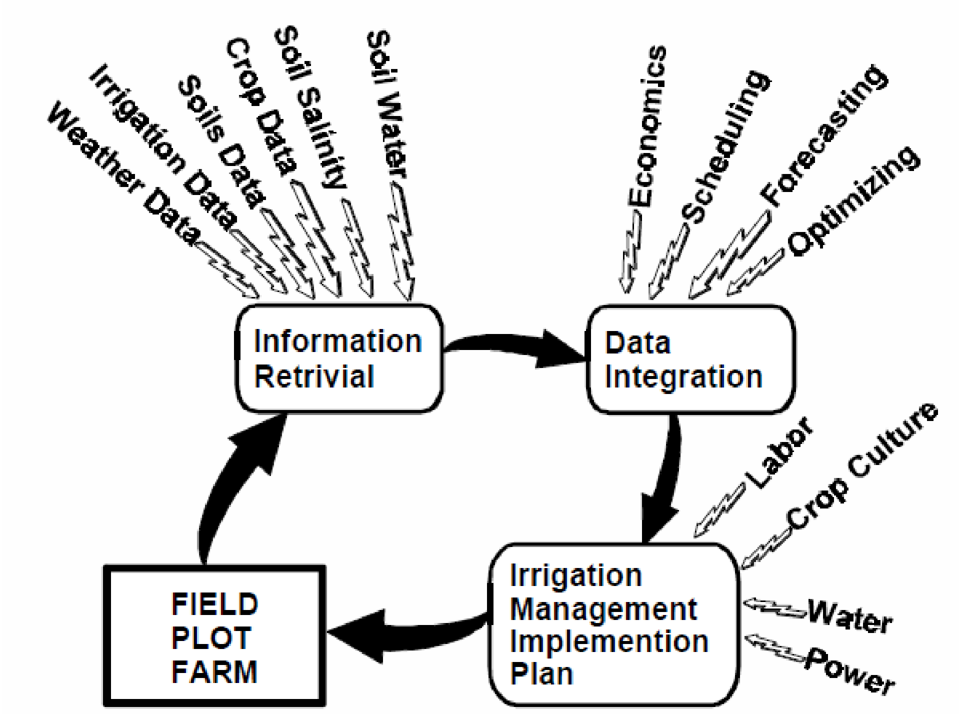

Figure 47 Irrigation Management Cycle (from Howell 1996)

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 47. 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 13 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 or '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 (Manas et al., 1999; Rodriguez et al., 2002; 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)

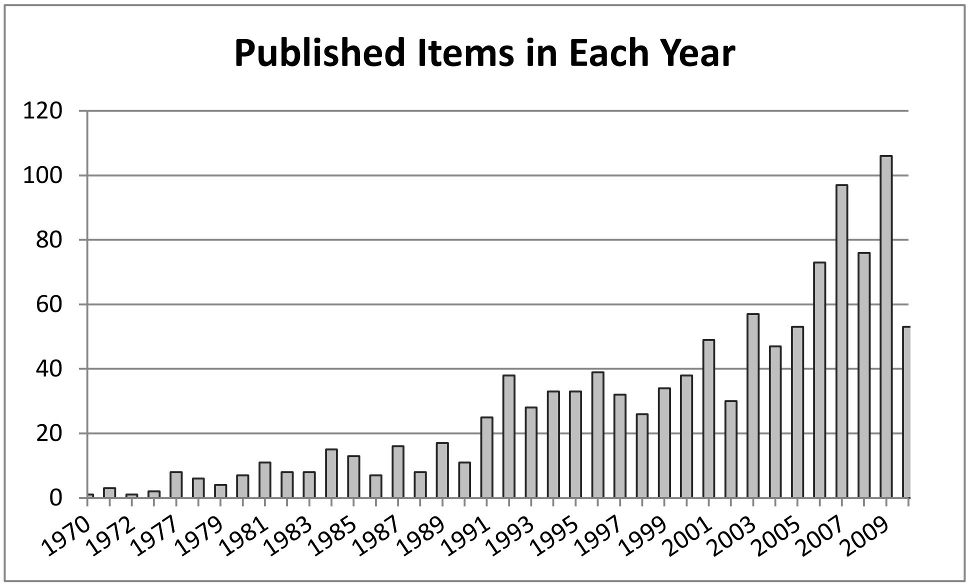

Figure 48 Search results from ISI Web of Knowledge using 'Topic=("irrigation scheduling")'

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 effect 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 introduces 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.

Development of IEM and IMO has triggered a national initiative for development of advanced irrigation advisory programs designed to meet the needs of irrigated agriculture under the severely water-limited circumstances anticipated in much of the world within the next two decades. The experience gained at OSU in development and pilot testing of IEM/IMO, in collaboration with NRCS, UC Davis, WSU and others has motivated establishment of a national task committee, under the auspices of EWRI, to promote and coordinate development of such a next 'generation system' and has informed the deliberations of that committee.

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