A Web-based Advisory Service for Optimum Irrigation Management

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Abstract

Optimum irrigation management generally involves partial irrigation of some crops to maximize net returns, particularly when water supplies are limited. This management paradigm is substantially more challenging than full irrigation to maximize crop yields, and few irrigators have the resources or capacity to deal with it quantitatively. Oregon State University and NRCS have created a web-based irrigation advisory system for optimum irrigation management. The system is being developed in two phases. The first phase, now largely completed, supports conventional irrigation scheduling. Key features of the first phase are: (i) application efficiencies are explicitly analyzed for each irrigation strategy considered; (ii) When water supplies or delivery system capacity are limited, the system provides simultaneous scheduling of irrigations in all fields that share a water source; (iii) the user interface permits farm managers to participate directly in searching for an optimal strategy using a robust, interactive web interface to stipulate objectives and constraints of irrigation strategies. A pilot advisory service was initiated in Central Oregon in 2006 and will be made available on the USDA national web farm for use by NRCS cooperators in 2008. The second phase is incorporating new analytical tools that will enable the advisory service to ore effectively support optimal irrigation management, including management of partial irrigation when water supplies are limited. Key elements of the second phase are (i) a statistical model of crop development and potential yield to estimate yields under partial irrigation; (ii) a feedback system to reconcile conflicting estimators of soil moisture depletion. Incorporation of the second phase will begin in 2008, but it is expected that refinement of these tools will continue indefinitely.

Introduction

This paper describes an irrigation advisory service that was developed specifically to support implementation of optimum irrigation management strategies. Optimum irrigation management generally involves partial irrigation of some crops to maximize net returns, particularly when water supplies are limited. This management paradigm can be substantially more challenging than conventional, full irrigation for several reasons: (i) because the ultimate disposition of applied water is significantly effected by irrigation management strategies, system application efficiencies cannot be assumed *a-priori*. Efficiencies must be explicitly analyzed for each irrigation strategy and weather year considered; (ii) since partial irrigation implies reduced crop yields an advisory service needs to anticipate and estimate such losses; (iii) optimal allocation of limited water or limited system capacity may require simultaneous irrigation scheduling of multiple fields and continuous tracking of total demands and system capacities; (iv) because an irrigation strategy that is optimal for one farm may not be optimal for another, farm managers need to participate directly in the formulation and evaluation of alternative strategies. This insures that the analysis will account for specific farm circumstances and bring the manager's local experience and preferences into the analysis.

To deal with these issues Oregon State University and NRCS have developed a web-based advisory system for economically optimum irrigation management. The system estimates application efficiency by simulating the spatially variable disposition of applied water as ET, percolation, spray loss, surface runoff and redistribution. A statistical model of crop yields will estimate both the expected values and the uncertainties of crop yields. Uncertainties of other aspects of the analysis are simulated in a variety of ways. One important element of the uncertainty analysis is a set of algorithms to reconcile estimates of soil moisture derived from different sources. The system facilitates allocation of limited water supplies by simultaneous scheduling of multiple fields, forecasting daily water demands to the end of the season and flagging any dates when farm irrigation system capacities will be inadequate to meet total farm water demands. The allocation of limited water to different fields is based on an iterative, user-directed search in which the farm manager stipulates irrigation strategies and operational constraints. The advisory service is accessed through a robust, interactive web interface.

This work is proceeding in two phases. The first phase provides the capability for conventional irrigation scheduling. The second phase will provide additional analytical tools for making best economic use of water, including in particular a yield modeling capability and algorithms for refining soil moisture estimates based on measurements of various kinds.

The system can be described in terms of four primary elements. The first is a general model of irrigation efficiency (IEM) that analyzes the disposition of applied water as spray losses, surface retention, runoff and redistribution, infiltration, percolation, evaporation and transpiration. The second element is a robust, user-oriented, web-based 'expert' interface (OISO). The interface obtains Penman estimates of reference ET from a regional weather station network, uses IEM to forecast irrigation requirements and analyze the disposition of applied water, communicates advisory information to client farms and obtains operational data (irrigation events, measurements of soil moisture) from them. These first two elements have been in beta testing with cooperating farms and are expected to be installed on the USDA web farm in the coming year. These first two elements, which constitute Phase I of the overall project, are operational and have been in beta testing on a pilot basis for one year for 35 fields on 20 cooperating farms in Oregon.

The other two primary elements are a yield model and a feedback system for soil moisture determinations. The yield model will provide estimates of yield reductions when irrigation does not meet crop water demands. The feedback system will provide a way of systematically reconciling different estimators of soil moisture depletion. These two elements, which are the key features of the second phase of the project, are to be integrated into the advisory service gradually over the next two years.

The advisory service is conceived as a dynamic system. While it is ready for use for conventional irrigation scheduling today, it is really being developed for irrigation management 20 years from now. The intention is to continue refining the analytical tools and user interface indefinitely in anticipation of a more challenging future when accelerating competition for water compels more widespread use of partial irrigation.

Phase I: Advisory Service for Conventional Irrigation Scheduling

The irrigation efficiency model (IEM)

The Irrigation Efficiency Model is designed to model the relationship between irrigation intensity, water losses and crop water use. IEM was originally developed by Oregon State University and the New Zealand Ministry of Agriculture and Fisheries (English 1992), then further developed and refined with funding from a USDA National Research Initiative grant (Isbell 2005). The model is implemented in C# and uses a variant of the MODCOM simulation framework (Hillyer, 2003). The implementation is modular and was designed with the anticipation of future extensions and modifications.

IEM functions as a soil water balance model, tracking irrigation and precipitation inputs, estimating potential crop ET, adjusting the potential ET to account for low soil moisture or wet surface conditions, and partitioning ET into its component parts of evaporation and transpiration using the algorithms outlined in FAO 56 (Allen 1998). When soil moisture reaches a user specified level of allowable depletion the model calculates the gross irrigation requirement, expressed as the duration of irrigation required to bring soil moisture up to a user specified refill level. Calculations of gross irrigation requirements are based on net irrigation requirement and an *assumed* application efficiency provided by the user. Subsequently, when an irrigation event takes place, IEM simulates *actual* application efficiencies by modeling the principal determinants of irrigation losses, including spatial variability of soil characteristics, irrigation timing and adequacy, patterns of applied water, wind effects on spray losses, wind distortions of sprinkler patterns, variability of surface infiltration rates, and surface water accumulations and redistribution. By simulating these factors, the model analyzes the disposition of applied water in terms of evaporative losses, percolation, and runoff.

Simulation of the variability of soil moisture in a heterogeneous field with non-uniform water applications is a particularly important aspect of IEM. Such spatial variability has important implications for irrigation scheduling, and can be an important factor in yield modeling. These points are illustrated by Figures 1, 2, 3 and 4. Figure 1 shows a histogram of measured 'field capacities' in a small area (one acre) of a silt loam soil that illustrates the innate variability of soil water holding characteristics. That variability has two important implications. First, since net irrigation requirements are commonly based in part on field capacity, the variability indicated by Figure 1 implies that net irrigation requirements depend upon which part of a heterogeneous field is considered the 'control' sector for scheduling purposes. Secondly, since it is common practice to rely on soil moisture measurements to determine 'true' soil moisture, the variability shown in Figure 1 implies that such soil moisture measurements must be treated as highly uncertain. These two conclusions will not be news to experienced irrigation managers, but they illustrate the rationale for simulating spatial variability.

The variability in Figure 1 is less useful as an indication of crop water availability. Given the integrating effect of root distributions and lateral flow of soil water, the true variability of crop available water is likely to be less than this histogram would suggest. On the other hand, larger scale variations commonly seen in field soils may cause much greater variations than suggested by Figure 1. Figure 2, taken from the NRCS soil survey for Oregon, shows a field comprised of two distinctly different soils, one with an available water capacity of 2.3 in/ft to a depth of more than 5.0 feet, the other with an AWC of 1.7 in/ft to 2.0 ft. These imply much greater field-wide variation than that suggested by Figure 1.

Variations in crop available water imply corresponding variations in crop yield. Figure 3 shows an IEM simulation of the spatial variability of ET in a relatively homogeneous field irrigated at 90% of cumulative ET. Histograms of transpiration in Figure 4 show the changing spatial pattern of ET in a relatively uniform field irrigated at intensities of 60%, 80% and 100% of potential ET (Isbell 2005). The variance of ET at 100% irrigation is small, but as irrigation is reduced, the variance of ET increases and the shape of the probability density function changes. If crop yields are assumed to be more or less linearly related to ET or T, these spatial patterns of ET imply corresponding patterns of crop yield. The importance of such patterns, if any, is being analyzed at this time.

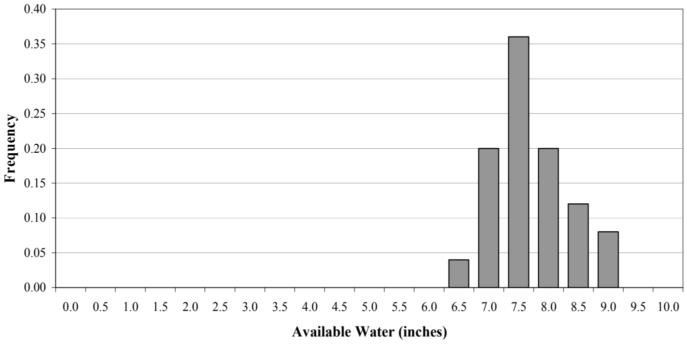
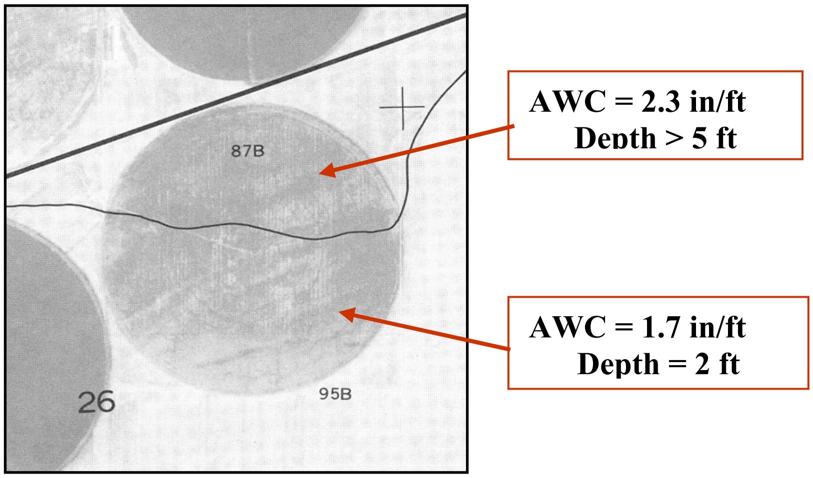


Figure 1. Variability of field capacity in a homogeneous silt loam soil



AWC = 2.3 in/ft
Depth > 5 ft

AWC = 1.7 in/ft
Depth = 2 ft

Figure 2. Two soil types in a single field

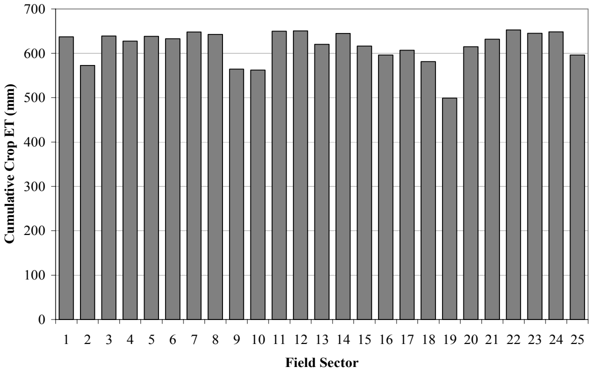


Figure 3. Distribution of Cumulative Crop ET

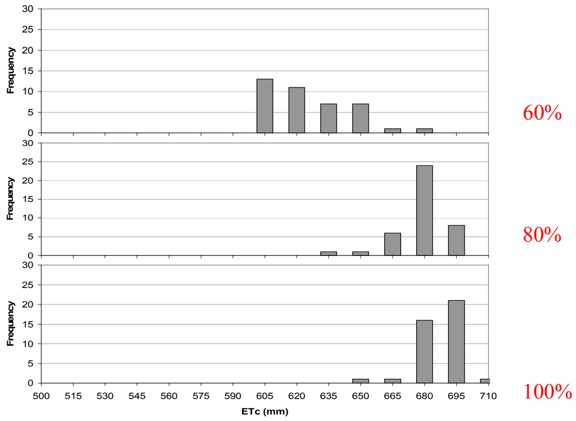


Figure 4. Simulated Distributions of Crop ET

Simulating the variability of soil water and crop available water provides a mechanism for explicitly accounting for these issues when formulating optimum irrigation strategies. That begs the question of how to determine the appropriate scale of variability for simulation purposes. At present that is left to the user's judgment, though default values are provided by the system.

Web based interface (OISO)

OISO analyzes operations for a single water management unit, or WMU, and multiple fields that share that are part of the WMU. By definition, fields that share a common water supply are part of the same water management unit. The program is initialized by specifying the WMU command area, delivery rates and volumes. The following inputs then define the fields and irrigation systems that share that water supply:

(i) area, crop type and development dates, soil depths, infiltration rates, water holding characteristics and antecedent moisture for each field

(ii) irrigation systems descriptions, including system type (e.g. pivots), application rates, nominal rotation times, estimated uniformity coefficients and sprinkler head configurations.

(iii) irrigation management strategies are described in terms of MAD, refill level, application efficiency (to be assumed for calculating gross irrigation requirements), and the field sector (defined by the total water holding capacity) to be used for scheduling purposes.

OISO downloads recent weather data, including daily Penman reference ET[1] then calls IEM to calculate spatially variable soil moisture on a daily basis, determine when irrigations are required and calculate the depths of water that need to be applied. When an irrigation event occurs IEM analyzes the disposition of the applied water as previously outlined. Outputs indicate current soil moisture status and recommendations for timing of upcoming irrigations. The program also forecasts crop water demand from the current date to the projected season end date. The system provides a daily email messages to individual clients.

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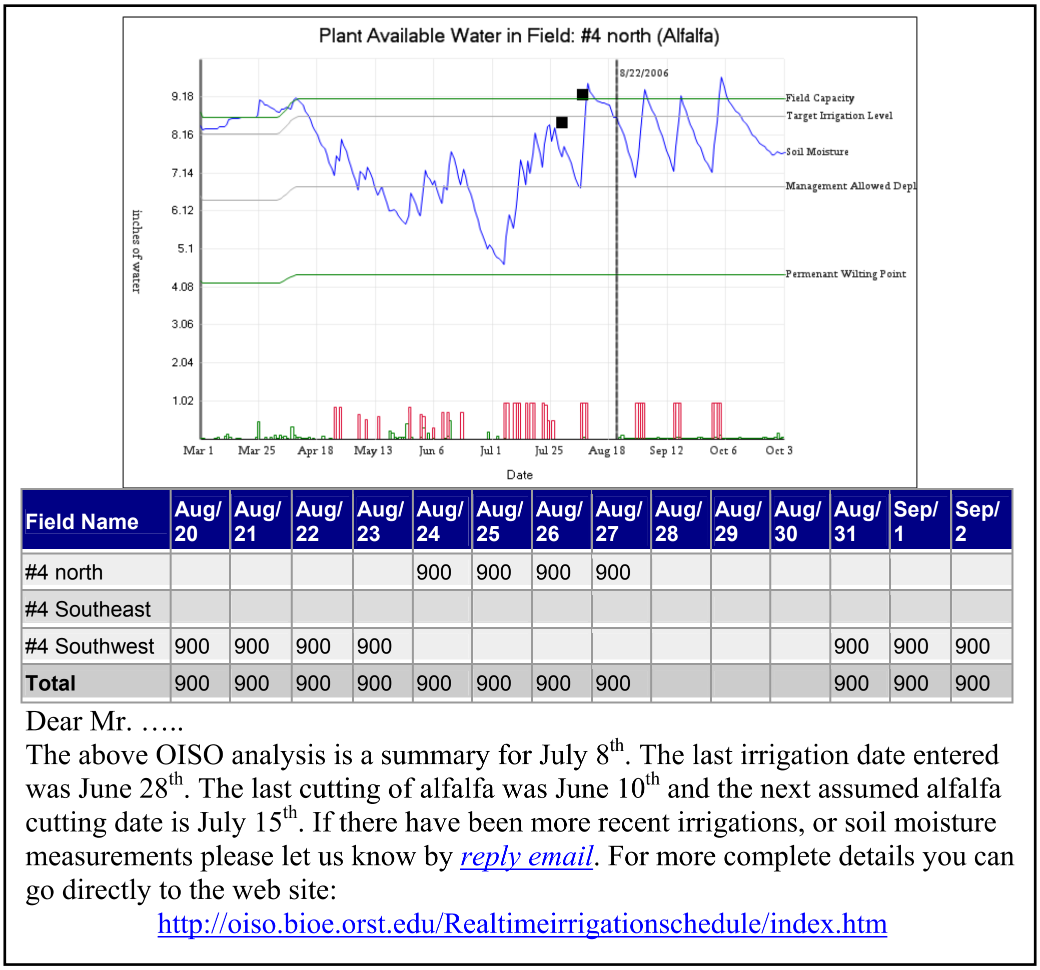
[1] At present the system is linked to the USBR Agrimet network.

A typical output for a single field is shown in Figure 5. This output is delivered to the user via email and is also available on the website in an interactive form. The graph shows a history of soil moisture to date for a single field. A record of irrigation events (red) and precipitation (green) is shown along the horizontal axis. Below the graph is a calendar of recommended upcoming irrigation dates and rates (gpm). The vertical broken line represents today's date. A forecast of future irrigation dates and soil moisture to the end of the season based on historical weather conditions is shown graphically to the right of today's date. The e-mail communication also inquires about recent irrigation operations. By simply picking the *reply email* hyper link, the client can easily send back current operational information such as recent irrigation events, soil moisture measurements or alfalfa cuttings. Clients wishing to see more complete analyses can access their individual web pages by following the URL.



Field Name	**Aug/ 20**	**Aug/ 21**	**Aug/ 22**	**Aug/ 23**	**Aug/ 24**	**Aug/ 25**	**Aug/ 26**	**Aug/ 27**	**Aug/ 28**	**Aug/ 29**	**Aug/ 30**	**Aug/ 31**	**Sep/ 1**	**Sep/ 2**
#4 north					900	900	900	900						
#4 Southeast														
#4 Southwest	900	900	900	900								900	900	900
Total	900	900	900	900	900	900	900	900				900	900	900

Dear Mr. …..

The above OISO analysis is a summary for July 8th. The last irrigation date entered was June 28th. The last cutting of alfalfa was June 10th and the next assumed alfalfa cutting date is July 15th. If there have been more recent irrigations, or soil moisture measurements please let us know by *reply email*. For more complete details you can go directly to the web site:

http://oiso.bioe.orst.edu/Realtimeirrigationschedule/index.htm

Figure 5. Sample daily output to client

The full potential of this system becomes clearer when allocating water among multiple fields. Figure 6 shows monthly crop water demand for each of four crops on seven fields during the 2002 crop year and aggregate demand for all fields on a cooperating farm in eastern Oregon. The horizontal line indicates the farm water supply.

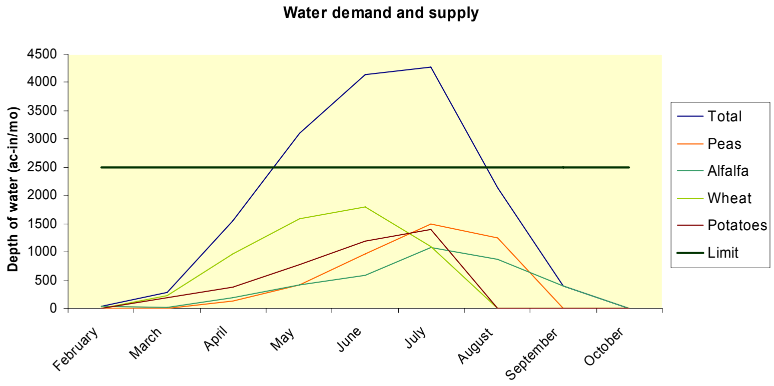


Figure 6. Nominal Crop Water Demand for four crops on Seven Fields

At peak of season, the water demand for full irrigation is about 80% greater than the supply. Clearly it is not possible to fully irrigate all seven fields, but strategic timing and deficit irrigation strategies have enabled this farm to manage these fields profitably in water short years. The present program is designed to deal with the unconventional strategies that farms such as this have chosen to use over the years. Since different managers have different objectives and tolerance for risk and face different local circumstances their irrigation strategies will differ. The procedure is as follows:

(i) propose a water management plan (cropping pattern, irrigation system configuration and irrigation management strategies) for each field
(ii) estimate daily water demand and resulting crop yields for each field for weather years of low, average and high water demand.
(iii) compare total demand with water supply and delivery system capacity
(iv) if the water demand exceeds available supply or system capacity, adjust the water-use plan and repeat the analysis until a feasible strategy is found such that the total demand is in-line with available water.

An example seasonal water use plan from the same cooperating farm[2] is shown in Figure 7. The color coded lines show projected irrigation dates and delivery rates (gallons per minute) for irrigation of five crops on seven fields of various sizes with a variety of irrigation systems. The resulting aggregate farm water demand, summed for all fields, is also shown (black line). Total farm water delivery capacity, about 2400 gpm, is shown as a horizontal line. As in the earlier example, the water demand would exceed supply for much of the season, particularly in May and June, so the initial water use plan shown here is not feasible. Several changes might then be proposed to deal with this water shortage; (i) a small field of alfalfa in its last year of production could be fallowed, (ii) a second field of alfalfa could be deficit irrigated, (iii) alfalfa cutting dates could be shifted slightly, and (iv) a circle of winter wheat could be deficit irrigated

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[2] This plan is for a different crop mix than was in place in 2002.

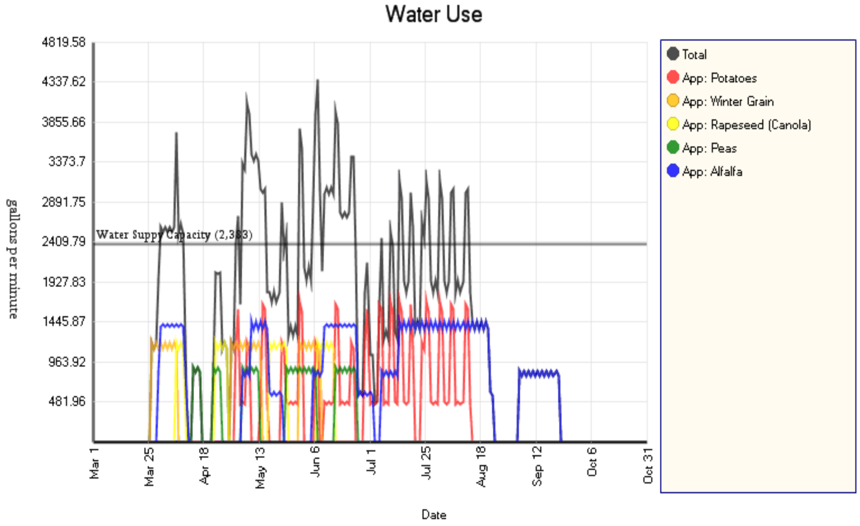

Figure 7. Seasonal Water Demand on a Cooperating Eastern Oregon Farm

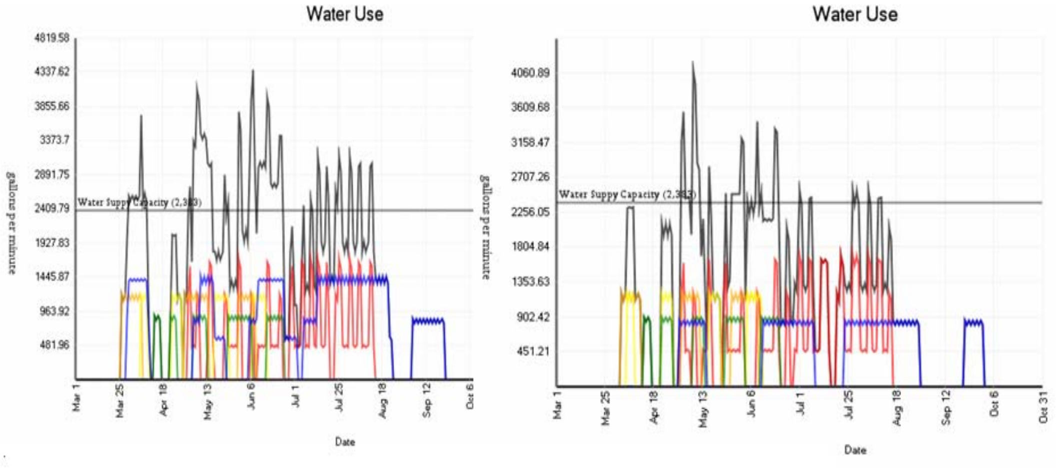

Figure 8. Original & Revised Water Demand Plots

Figure 8 compares the first water demand graph (left) with the resulting revised graph (right). The proposed changes would substantially reduce overall demand, and shorten most periods of excess demand which would make the water shortages more manageable. The next step would be to further refine the irrigation schedules on a day-by-day basis, shifting irrigations from specific high demand days to days when capacity is under-utilized.

Recall that the bottom row of the irrigation calendar shown in Figure 5 represents total water demand (gpm) for a set of fields that share a water source. When irrigation system capacities are not sufficient to meet total demand the total will be flagged by red highlighting. To facilitate allocation of limited capacity, the program will allow direct editing of this scheduling calendar, deleting or adding entries for specific dates or clicking and dragging strings of entries, until the total demand for each date is brought in line with supply. The concept is illustrated in Table 1 which shows two minor changes in a recommended schedule. Starting canola irrigation one day earlier and eliminating the last day of a scheduled irrigation of wheat would avoid the two days of excess demand.

Table 1. Calendar of Irrigation Dates & Rates

	Jun/4	Jun/5	Jun/6	Jun/7	Jun/8	Jun/9	Jun/10	Jun/11	Jun/12	Jun/13	Jun/14	Jun/15	Jun/16
43 potatoes									480	480	480	480	480
44 alfalfa										850	850	850	850
45 peas									900	900	900	900	900
46 alfalfa													
47 wheat	1200	1200	1200	1200	1200	1200	1200						
48A potatoes							1200	1200					
48B canola	←	1200	1200	1200	1200	1200	1200	1200	1200				
Total	1200	2400	2400	2400	2400	2400	**3600**	2400	**2580**	2230	2230	2230	2230

The procedures described above represent two different approaches for managing water use. The first involves preseason planning by way of an irrigation strategy. The second represents management of day-to-day operations. In both procedures the irrigation manager is a critical component of the system. The manager decides if a strategy is feasible and the manager decides which irrigation events can be changed. By relying on the irrigator as the primary decision maker OISO is a tool that supports –rather than supplants– irrigation scheduling. This pair of techniques, pre-season strategy and day-to-day operations management provides first part of a toolset for irrigation optimization.

Phase II: Optimum Irrigation Scheduling

Yield modeling

Initially, yield modeling has been based on FAO Irrigation and Drainage Paper No. 33. That model estimates relative yield as a function of relative evapotranspiration or relative crop water use by the yield response factor (K_y) (Doorenbos and Kassam, 1979):

$$\left(1-\frac{Y_a}{Y_m}\right)=ky\left(1-\frac{ET_a}{ET_m}\right)$$

Where: Y_a = actual harvested yield
Y_m = maximum harvested yield with no water deficit
K_y = yield response factor
ET_a = actual evapotranspiration
ET_m = maximum evapotranspiration

Though FAO 33 is perhaps the most widely used of all FAO Irrigation and Drainage papers, our experience and the experience of many others with the use of this model under ordinary field conditions has been unsatisfactory. During the last few years, a team of climate, crop, soil, irrigation and water scientists from various countries have been working under the auspices of FAO to develop a new crop-water production model to replace the FAO 33 model. The new FAO model, known as "AquaCrop", is a simple, accurate, robust, menu-driven and user friendly program that is designed for a wide range of users. It is expected that this new general yield model will be ready for distribution and available on the FAO website later this year. The model is still being calibrated for a variety of crops based on experiments done in different countries (Raes et al., 2006).

The AquaCrop development has been led by people of deep knowledge and broad experience, including Pasquale Steduto, Chief of FAO's Water, Development and Management Unit in Rome; Dirk Raes from the Department of Land Management and Economics at Katholieke Universiteit, Leuven, Belgium; Elias Fereres, Director of the Institute for Sustainable Agriculture, University of Cordoba, Spain; and Theodore Hsiao of the Department of Land, Air and Water Resources at the University of California in Davis. Given the credentials and experience of this team the new yield model should be a substantial improvement over FAO 33, and we are looking into the possibility of using it in conjunction with the irrigation advisory service outlined in this paper. At this point it appears likely that the existing IEM model described above will need to be modified in some respects to provide the input parameters and field data needed to support AquaCrop.

AquaCrop is composed of 3 submodels describing soil water balance, canopy development under water stress and yield response to water. The model requires minimal input and will be used to predict yield under water deficit conditions in different environments and regions where the other developed yield models require a lot of data that can be provided only by research stations and they need to be calibrated when they are used in new regions. AquaCrop describes the effect of irrigation amount and timing on crop yield. The model will include the crop response to saline water and different levels of fertilizers in addition to the effect of different irrigation methods (surface, sprinkler and trickle) and management types (supplementary and deficit irrigation) on the crop.

The model needs specific calibration for additional crops, including alfalfa. Work will be done at Oregon State University in collaboration with FAO to test the model for wheat and contribute to calibration for alfalfa. The alfalfa calibration procedure will be done using a combination of new field data from the Hermiston Branch Experiment Station in the Columbia Basin and existing data sets from other western states that link lysimeter-based measurements of ET with observed crop development.

Reconciling estimates of soil water depletion

Irrigation management depends upon continuous estimation of the amount of crop-available water stored in the active root zone. When the management objective is to avoid crop stress altogether, it is common practice to keep soil moisture relatively high, maintaining a certain amount of soil moisture in reserve to minimize risk. Given the margin for error in that approach, precise determination of soil moisture content is not critical. On the other hand, accurate estimation of crop-available soil moisture will become critical when the objective is to maximize net economic returns with limited water. The fourth element of the advisory service is therefore exploring algorithms to derive better real-time estimates of soil moisture. We are focusing on more effective tools for combining the information provided by two commonly used estimators of soil moisture depletion to minimize uncertainty of soil moisture determinations. The two estimators are cumulative calculated ET (as a proxy for cumulative depletion), and direct measurement of changes in soil moisture.

While it is common practice to regard soil moisture measurements as the final determinant of 'true' soil water content, the reality is that both of these estimators provide useful information and neither is perfectly accurate. The advisory service is therefore developing algorithms based on decision theory to combine these two estimators, extracting the maximum usable information from both in a hybrid estimator. Details of this work are to be presented at an EWRI Annual Conference in May, 2008, and will be incorporated into the advisory service during the coming year.

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