MANAGING FOR DEFICIT IRRIGATION

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ABSTRACT

This paper deals with budgeting of irrigation water for deficit irrigation – deciding how much water to use for a season and how much to allocate to each stage of crop development. When irrigation water is applied as needed to meet crop water demands (i.e. full irrigation) the amount of water to be used is determined by the crop itself, and irrigation timing is commonly based on real time observations of field conditions. But when a crop is deliberately under-irrigated the amounts and timing of water use need to be decided in advance.

The central theme of this paper is that success in deficit irrigation management will depend more on advanced and sophisticated modeling, and less on real time monitoring technologies.

Making the best use of limited water requires sophisticated modeling to assess alternative water use strategies, plan the allocations of water through the season to implement a preferred strategy, and adapt the implementation plan to accommodate the specific circumstances of individual fields. Modeling also provides a scientific basis for interpreting feedback data from the field as the season evolves. All of this involves substantial variability and uncertainty. It is a modeling challenge.

An advanced decision support system developed explicitly for deficit irrigation management addresses these challenges. Distinguishing features include:

(1) sophisticated modeling of the disposition of applied water enables derivation of field-specific crop production functions and long-range projection of crop water availability
(2) anticipated irrigation schedules can be routinely and continuously updated to accommodate unexpected circumstances or changing constraints
(3) adaptive feedback can be used to increase analytical precision, minimize uncertainty and provide insight into field-specific relationships between water use and crop production

The characteristics and performance of this decision support system will be outlined and the utility of the information it provides will be illustrated by two case studies, one involving optimum irrigation with high pumping energy costs, the other concerning deficit irrigation of an almond orchard under severe drought conditions.

INTRODUCTION

Systematic, science based procedures for irrigation management appeared about five decades ago with the advent of *scientific irrigation scheduling* (SIS). The prevailing management paradigm of the time was *full irrigation*; the objective was to maximize crop yields while minimizing water losses. But in recent years there has been increasing interest in partial irrigation, or *deficit irrigation*, an altogether different and more challenging management paradigm (English, et als, 2002). That increasing interest is reflected in the appearance of technical bulletins on the subject from diverse institutions worldwide (e.g. FAO, 2002; UCANR, 2016).

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The objective of deficit irrigation is to maximize net economic returns rather than maximizing yields *per se*. The focus on economic returns is increasingly motivated by competition for water. Farm water supplies are often simply insufficient for full irrigation, as forcefully demonstrated recently in the devastating California drought. But even when a farm has access to ample water, partial irrigation can be more profitable, especially when competing demands for water create opportunity costs for water. The forces driving this competition -- food shortages, energy costs and global water shortages -- will only grow stronger in the next few decades (English, 2010).

Deficit irrigation, the natural response to those forces, requires a fundamental change in the way irrigation is managed. Conventional, full-irrigation management has commonly relied on continuous monitoring of soil water depletion or crop stress to determine when to irrigate and how much to apply. We would characterize that approach as '*real time scheduling'*. And, significantly, with conventional SIS the total amount of water to be used for the season *is not a management decision*, it is determined by crop water demand.

Deficit irrigation management is altogether different and more complicated. The manager must decide *in advance* how much water to use for the season, when to use that water and *when to withhold it*. That requires analyzing how a sequence of irrigations will play out months into the future. For purposes of this discussion we will refer to such long range projections of irrigation schedules as 'forward scheduling'.

The central theme of this paper is that success in deficit irrigation management depends less on real time scheduling technologies and more on advanced and sophisticated modeling for forward scheduling.

Optimal management of deficit irrigation requires: (i) evaluating expected outcomes for alternative management strategies; (ii) testing the feasibility of preferred strategies (iii) translating preferred strategies into detailed, full season irrigation plans; (iv) customizing those plans to accommodate the unique circumstances and constraints of specific fields; (v) tracking implementation of scheduling plans to assure adherence to the overall strategy; and (vi) updating plans as conditions evolve during the season. These capabilities will be illustrated in the present paper.

Advanced technical support is needed for dealing with these analytical challenges, and incremental improvements in current technologies will not meet that need. While current management technologies largely rely on instrumentation to monitor field conditions in real time, deficit irrigation management will require sophisticated modeling -- in future time -- of the whole complex system; irrigation hardware performance; management preferences; operational constraints; the disposition of applied water in heterogeneous fields; and the physiological responses of the crop.

Recognizing the need for a new generation of management modeling, the USDA and other agencies funded development of a practical decision support system for deficit irrigation[2] known as *Irrigation Management Online* (IMO) (Hillyer and Sayde; 2010). This paper reviews the experience and general insights gained from beta testing of IMO for two cases; irrigation with high cost energy in the Columbia Basin, and management of a severely limited water supply for almonds in the California drought.

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A DECISION SUPPORT SYSTEM

Development of IMO was based on three key design objectives. The first design objective was that the system should *embrace analytical complexity*. Simple water balance modeling cannot adequately represent the whole complex of dynamic, interacting processes involving soils, climate, crop, water supply, irrigation system and management practices that relate applied water to crop development and yield.

The second design objective was to *streamline the computational process* to facilitate rapid analysis of alternative irrigation strategies. Computationally efficient analytical tools such as linear programming or genetic algorithms have not been capable of dealing with the complexity of deficit irrigation management. Optimization will necessarily involve simulation and iterative search which will entail heavy computational burdens. The analytical software must therefore be designed for maximum speed and efficiency.

The third design objective was to *fully engage the user as a direct participant* in the analytical process. Any seasonal water use plan generated by IMO must align with the objectives, experience and preferences of the farm manager. To account for such subjective factors requires direct input from the client/manager.

These design objectives are reflected in the following key features of the IMO system:

- sophisticated modeling of the disposition and fate of applied water enables more accurate simulation and long-range projections of crop water availability
- modeling of application efficiency coupled with general, ET based yield models can realistically simulate crop response to applied water, an essential capability for optimum management.
- efficient analytical algorithms and advanced software design enable rapid search for optimal strategies and rapid updating of seasonal plans as circumstances change
- an editable calendar enables the farm manager to make short term modifications to irrigation schedules without compromising overall seasonal planning
- record keeping, integrated displays of alternative sources of field data and retrospective analysis of past seasons provide insight into field-specific relationships between water use and crop production, and facilitate system re-calibration for increased analytical precision.

Applications for deficit irrigation management

We will address four analytical tasks to which IMO has been applied for optimum management of limited water:

- Budgeting water; deciding how much water to use for a coming season
- Forward scheduling; planning the seasonal irrigation schedule to make best use of the limited water
- Error detection and recalibration
- Assessment

BUDGETING WATER

Example 1: deciding how much water to use when pumping costs are high

The question of how much water to use for a given field may be moot if the water supply is strictly limited, but when a farm has ample water this can be a challenging economic question. As a general rule the profit maximizing level of water use will be somewhat less than the yield maximizing level. The optimum amount to use may be based on the experience of individual farm managers. Some research leaders have offered general guidelines on the optimum. For two examples, Keller and Bleisner, 1990;

English and Raja, 1996) have suggested that when water supplies are limited or costly the economic optimum point will be on the order of 10% or 20% less than full irrigation.

If water has a significant opportunity cost, the optimal level of irrigation may be considerably less (English and Raja, 1996). In that case a production function relating applied water to crop yield may be needed to evaluate alternative water use strategies.

Given the variability of weather, soils, antecedent moisture, distribution uniformity, root distributions and other factors, it is difficult to predict how much applied water will actually be used by a crop, and what potential yield will be. When combined with other factors, such as crop response to chemical use, weather conditions, disease, pests and so on, the yield that will be produced by a given level of applied water is virtually impossible to predict with certainty.

Nevertheless, estimation of yields is important for optimal management of deficit irrigation. It is our position that the analytical engine at the heart of IMO realistically represents the complex relationship between applied water and crop yield on a field scale. Having been derived from first principles, it is sufficiently accurate and robust to guide management decisions. An example follows.

Developing a crop production function

A general relationship between crop consumptive use of water, ET and yield is illustrated in Figure 1 (Raes and Geerts; 2009). Zones (c) and (d) of this function are the economically rational range of interest for deficit irrigation. Yields will increase more or less linearly in zone c. Then, for some crops, yield response rates will decline near maximum potential ET (zone (d)). Beyond that point, zone (e), yields will generally decline with the adverse consequences of excess water use.

Figure 2 indicates how ET relates to applied water (NEEA, 2013). As indicated, applied water tracks ET fairly closely in the range corresponding to zone (c). As applied water approaches the yield maximizing point, progressively increasing losses from surface accumulation and runoff, percolation and surface evaporation will cause the applied water curve to depart progressively farther from the ET curve.

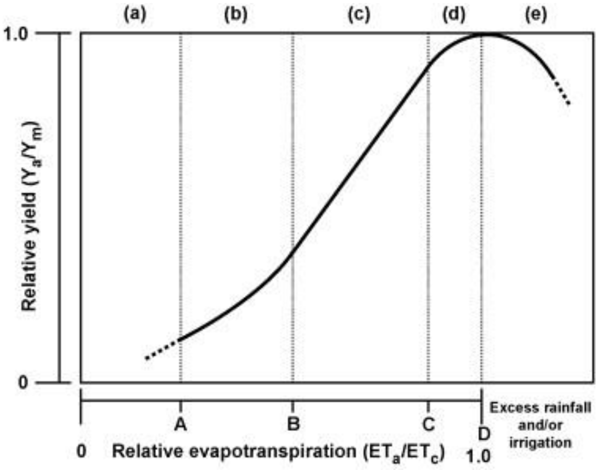


Figure 1: yield response to ET

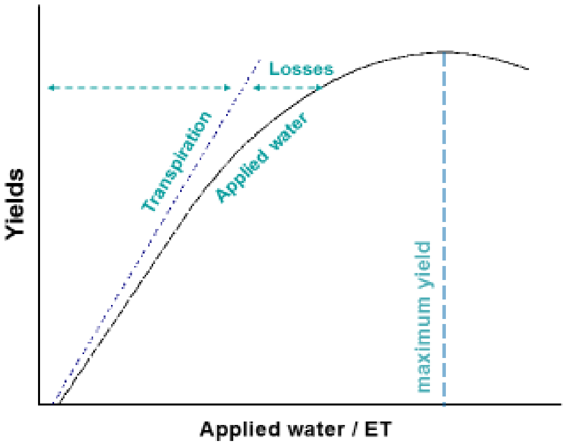


Figure 2: yield response to applied water

IMO estimates yields by modeling these two relationships in tandem. When an increment of water is applied to the field IMO estimates the resulting pattern of incremental ET that across a heterogeneous field. The physiological response of the crop to incremental ET is then used to estimate yields on a field-wide basis.

The IMO system was used for partial irrigation of a circle of alfalfa on a cooperating farm in the Columbia Basin. The analysis considered alternative levels of water use ranging from 50.5 inches (full irrigation) down to 20 inches (67% below full irrigation). The specific management strategies employed for each level of water use were defined in terms of the following five management parameters, each combination of which would result in a specific level of water use:

i) *Irrigation adequacy*, the percentage of the field to be fully irrigated when water is applied
ii) *Management allowed depletion (MAD);* the amount by which soil water content is allowed to be reduced before an irrigation takes place.
iii) *Target refill level*; the target soil moisture level to which the root zone will be refilled during irrigation (expressed as a percentage of available water holding capacity in the root zone)
iv) *Assumed application efficiency*; the estimated application efficiency to be used in calculating gross irrigation requirements.
v) *Critical growth stage applications*, the seasonal pattern of applying or withholding irrigations according to stages of growth.

Note: in the case of alfalfa the growth stages are associated with the sequence of cuttings, since yields tend to decline with later cuttings. The discontinuity of data points between 27.7 inches and 43.60 inches of applied water derived from elimination of the last cutting.

Nineteen specific combinations of these parameters were used in this analysis to generate paired values of applied water and yields, as summarized in Table 1. The seventh column shows seasonal water use for each instance. The tenth column shows yields as estimated using the FAO 33 algorithm. (However the yield reduction factor derived by calibrating the FAO 33 algorithm (Doorenbos and Kassam, 1979) with water use and yield data from partial irrigation of six fields on the cooperating farm was 1.17, rather than the FAO published factor of 1.10. The derived production function is shown in Figure 3.

Table 1: yield response to applied water

Case	Adqcy	MAD	Refill Target -------	nominal effncy -------	irrigation ending date	Gross applied (inches)	ET	Losses as perc, spray, RO	FAO #33 yields (tons)
1a	87.5	50	100	85	20-Aug	49.9	44.4	6.9	8.99
1b						50.6	44.5	7.4	9.00
1c						50.6	44.5	7.1	9.00
2a	50	50	100	100	20-Aug	49.3	44.3	6.3	8.96
2b						46.1	43.4	5.2	8.91
2c						49.3	44.4	6.3	8.97
4a	nil	50	100	100	20-Aug	48.7	44.2	5.5	8.90
4b						48	44.2	5.3	8.89
4c						48.7	44.2	5.6	8.90
5a	nil	50	80	100	20-Aug	45.5	43.6	4.2	8.80
5b						45.5	43.3	4.3	8.79
5c						44.8	42.9	4.3	8.71
6	nil	60	80	100	20-Aug	43.6	42.2	4.1	8.52
7	nil	70	80	100	20-Aug	42.9	41.2	4	8.00
8	nil	50	80	100	9-Jul	27.7	29.6	2.3	8.08
9	nil	60	80	100	9-Jul	26.4	28.6	2.2	7.83
10	nil	70	80	100	9-Jul	25.1	27.3	2.1	7.32
11	nil	80	80	100	9-Jul	21.3	24.2	1.6	6.35
12	nil	85	60	100	9-Jul	16.8	19.7	1.3	4.66

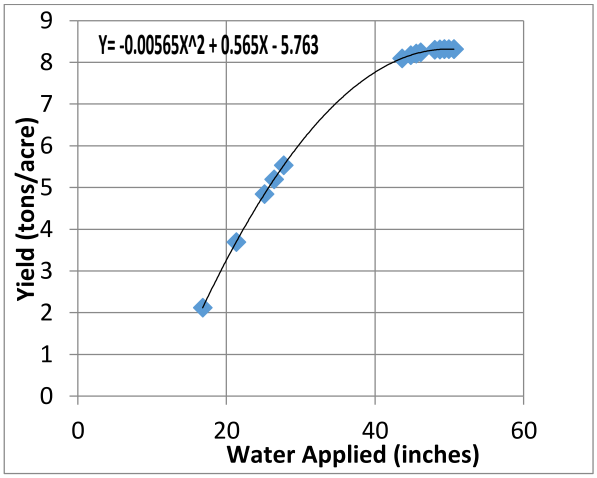


Figure 3: crop response function

Alternative irrigation strategies

This function was used to determine optimum water use for a 125 acre field of alfalfa under a center pivot system on a cooperating farm in the central Columbia Basin with high pumping head (300 ft) and energy costs of $0.09/kwh. Estimated harvest costs were $42 per ton, and crop sale price $220 per ton.

We considered three alternative management objectives; first, to maximize yield per acre; second, to maximize net income per acre; third, to maximize net economic returns to water. Since this farm has more land than water, the water saved by deficit irrigation could be used to increase irrigated acreage, with opportunity costs corresponding to net returns to irrigation. The results are indicated in table 2, below. Net income at full irrigation would be $143,000. If water and energy use is reduced net income would be increased until water use goes below 42.9 inches.

If water use is reduced below 42.9 inches the net income from the single 125 acre circle would be less than that from full irrigation. However if additional income were derived from sale or use of the water conserved, net farm income could continue to increase. In this case we assumed the opportunity cost of water could be captured by irrigating additional land with the same net economic return to water. At the point of maximum net returns to water (27.7 inches) the profit from cropping on the 125 acre pivot would be reduced by $43,148, as indicated. But if the conserved water (22.9 inchesx125 ac = <u>2863 ac-in</u>) were used to irrigate additional land it would yield an additional profit of (2863 ac-in x $28.93/ac-in = <u>$82,726</u>). Total farm profits would then be increased by (-$43,148 + $82,726 = <u>$39578</u>).

Table 2: Analysis of alternative optimization strategies

Applied water	Crop yield	Revenue	Energy use (kwh/ac)	Energy Cost ($/ac)	Haying costs ($/ac)	Net income ($/acre)	Net for 125 ac	Change in net farm income	net returns to water ($/ac-iin)	(
16.8	2.134	470	1260	113	90	$267	$33,314	- $110,001	15.86	
21.3	3.708	816	1598	144	156	$516	$64,534	-$78,781	24.24	
25.1	4.859	1069	1883	169	204	$695	$86,933	-$56,382	27.71	
26.4	5.215	1147	1980	178	219	$750	$93,763	-$49,553	28.41	
27.7	5.552	1222	2078	187	233	$801	$100,167	-$43,148	28.93	
42.9	8.077	1777	3218	290	339	$1,148	$143,520	$205	26.76	
43.6	8.131	1789	3270	294	341	$1,153	$144,118	$802	26.44	
44.8	8.209	1806	3360	302	345	$1,159	$144,855	$1,540	25.87	
45.5	8.248	1814	3413	307	346	$1,161	$145,118	$1,803	25.52	
45.5	8.248	1814	3413	307	346	$1,161	$145,118	$1,803	25.52	
46.1	8.276	1821	3458	311	348	$1,162	$145,246	$1,930	25.21	
48	8.339	1835	3600	324	350	$1,160	$145,052	$1,736	24.18	
48.7	8.352	1838	3653	329	351	$1,158	$144,751	$1,436	23.78	
48.7	8.352	1838	3653	329	351	$1,158	$144,751	$1,436	23.78	
49.3	8.359	1839	3698	333	351	$1,155	$144,396	$1,081	23.43	
49.3	8.359	1839	3698	333	351	$1,155	$144,396	$1,081	23.43	
49.9	8.362	1840	3743	337	351	$1,152	$143,950	$635	23.08	
50.6	8.360	1839	3795	342	351	$1,147	$143,315	$0	22.66	

🟨	maximize yield per acre
🟦	maximize profit per acre
🟩	maximize profit per acre-ft

FORWARD SCHEDULING

Example 2: planning a deficit irrigation schedule for almonds

The second example involves an almond grower in the San Joaquin Valley of California whose available water supply in the fourth year of the recent drought was limited to 250 ac ft for 93.5 acres, or 32 inches, about 60% of full irrigation.

Identifying a research-based strategy

The first step was to review the past practices and experience gained by the producer herself, and to consult with research and extension professionals about recommended general strategies for deficit irrigation.

One primary resource used is shown in Figure 4, from a bulletin prepared by Doll and Shackel (2015) outlining the effect of water stress at various stages of almond development. This provided a general guide to how water should be allocated during the season. A key observation from that bulleting is that deficits can be most easily tolerated during June, the period approaching hull split.

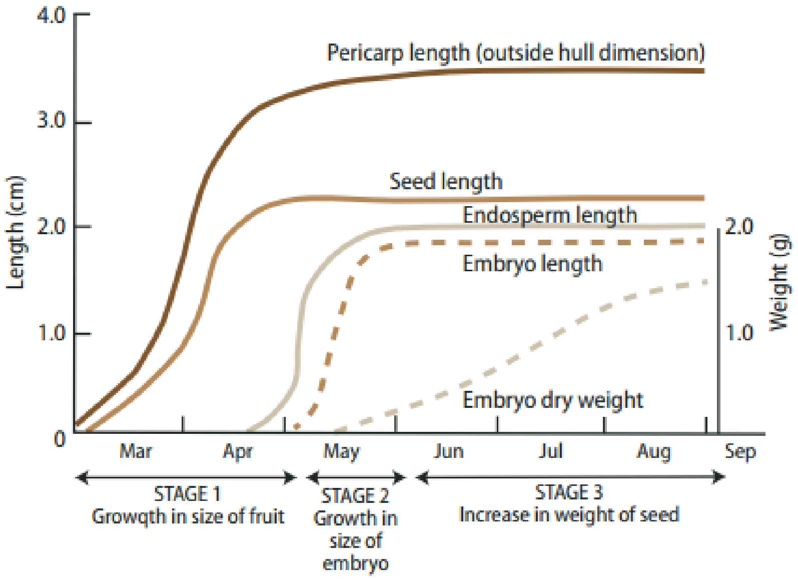


Figure 4: Almond sensitivity to water stress at various stages of development

A second primary source of advice was recommendations for various levels of partial irrigation of almonds, expressed as percentages of PET (PPET) (Goldhammer, IN FAO 66, Steduto, et al., 2012) for each of five phases of crop development. The specific recommendations when available water is 63% of full irrigation, comparable to the cooperating farm situation, are summarized in Table 3.

Table 3: recommended percentages of PET to be applied when the seasonal water supply is 63% of full irrigation

Phase 1: 70% of PET … the first two months or so following bloom; March and April;

Phase 2: 50% of PET ….. shell hardening, kernel expansion; fruit maturity; May – early June
Phase 3: 25% of PET (later changed to 50%): .... hull split, late June
Phase 4: 100% of PET …. Approaching harvest
Phase 5: 60% of PET …. Post-harvest

This schedule indicates a tolerance for more stress in June, which is consistent with Doll's graph. It also advises more water use in July, approaching harvest.

A third key source, Ken Shackel at UC Davis, advised a generally uniform pattern of stress through the entire season, with the exception of increased stress approaching hull split.

The final strategy was a version of the pattern in Table 3, with two modifications: the first was to allocate less irrigation water to Phase 1, relying on antecedent moisture for a significant fraction of crop water use. The second was to increase water use in Phase 3 to 50% of potential PET.

The strategy thus derived then needed to be translated into specified irrigation dates and set times. The challenge was to allocate 32 inches of water over a seven month season, according to the water use pattern stipulated in Table 1, to maximize crop production, ensure good crop quality and minimize detrimental effects on the following season's crop.

Allocations according to stages of development

IMO was used to downloaded all historical weather data from the California Irrigation Management Information System (CIMIS) Los Banos station and compile a day-by-day profile of average reference ET. These were converted to crop potential ET and Monthly allocations of water were calculated according to the prescribed values in Table 1. The bar chart in Figure 5 shows crop potential ET (blue) and recommended allocations (yellow) for each of the five prescribed stages of crop development.

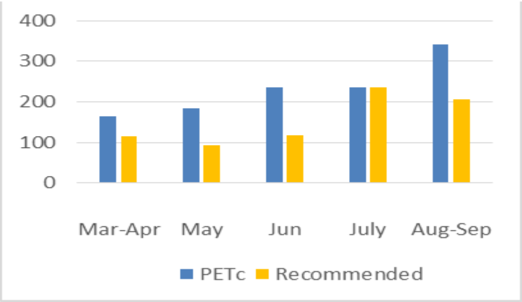


Figure 5: Potential ET and recommended allocations of water

Forward scheduling

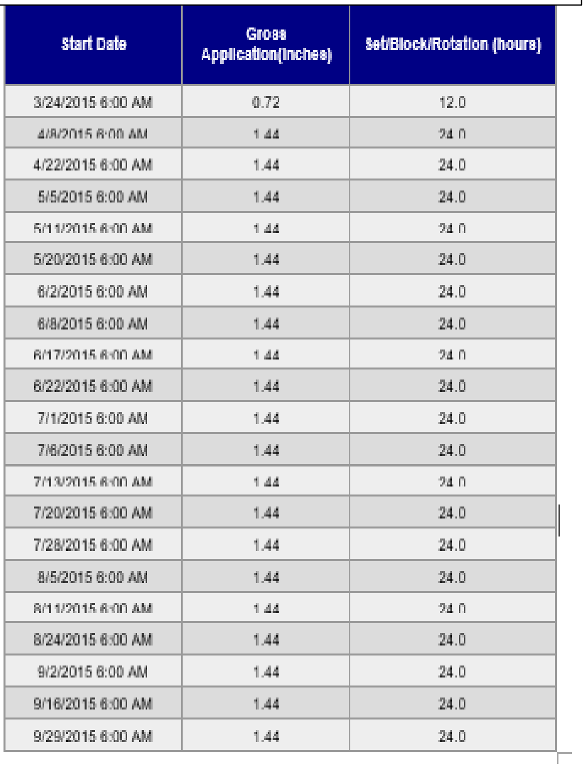
A detailed irrigation schedule was generated using IMO in an iterative search. A preliminary schedule was first generated automatically by IMO to use the 32 inches of available water in a pattern approximating that shown in Figure 5. Successive iterations in a guided search by an analyst until a sequence was found that would adapt the schedule to the specific circumstances of the farm to ensure that it was feasible, practical and consistent with irrigation system capabilities, constraints and normal farm practices.

The resulting schedule is shown in Table 4. A season-long projection of crop available water in a five foot root zone is shown in the accompanying graph (Figure 6). The black data points in upper left are neutron probe measurements to determine antecedent moisture. The red bars represent dates and amounts of irrigation events.

Tracking and updating the plan

As the season evolved IMO was used to track water use and field conditions and revise the schedule as needed to ensure adherence to the intended management strategy. The plan was revised during the season to account for weather anomalies and changing forecasts of available water. Figure 7 shows

Table 4: Suggested irrigation dates and set times



Start Date	Gross Application(Inches)	Set/Block/Rotation (hours)
3/24/2015 6:00 AM	0.72	12.0
4/8/2015 6:00 AM	1.44	24.0
4/22/2015 6:00 AM	1.44	24.0
5/5/2015 6:00 AM	1.44	24.0
5/11/2015 6:00 AM	1.44	24.0
5/20/2015 6:00 AM	1.44	24.0
6/2/2015 6:00 AM	1.44	24.0
6/8/2015 6:00 AM	1.44	24.0
6/17/2015 6:00 AM	1.44	24.0
6/22/2015 6:00 AM	1.44	24.0
7/1/2015 6:00 AM	1.44	24.0
7/6/2015 6:00 AM	1.44	24.0
7/13/2015 6:00 AM	1.44	24.0
7/20/2015 6:00 AM	1.44	24.0
7/28/2015 6:00 AM	1.44	24.0
8/5/2015 6:00 AM	1.44	24.0
8/11/2015 6:00 AM	1.44	24.0
8/24/2015 6:00 AM	1.44	24.0
9/2/2015 6:00 AM	1.44	24.0
9/16/2015 6:00 AM	1.44	24.0
9/29/2015 6:00 AM	1.44	24.0

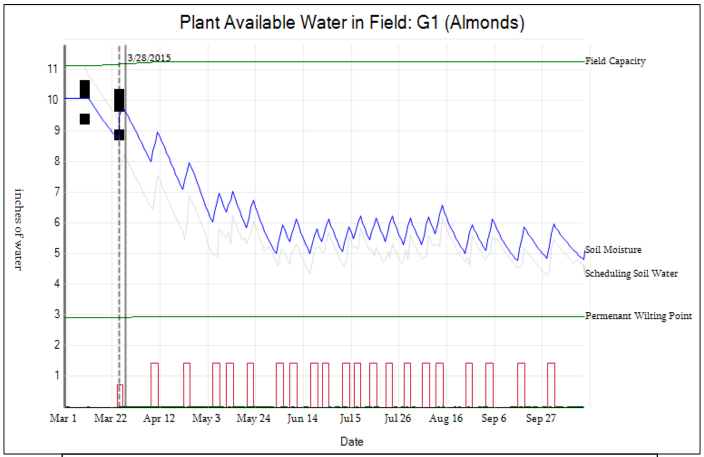


Figure 6: Anticipated seasonal pattern of crop water availability

historical daily average PET as derived from the CIMIS station at Los Banos (plotted in red) and specific 2015 daily values (plotted in blue). The 2015 data departed substantially from expected values in May and July. The reduced ET was also compounded by unexpectedly high rainfall early in May. Additionally, the available water supply was increased slightly during the season. Consequently, some of the water originally allotted for May was shifted to July.

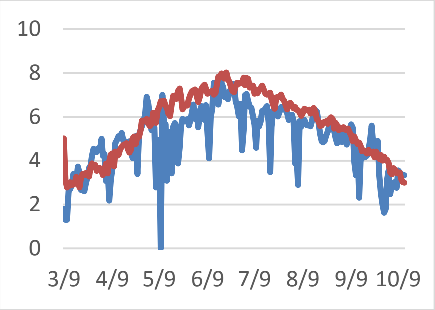


Figure 7: Estimated daily potential ET and observed daily PET

ERROR DETECTION AND RECALIBRATION

Error detection

The long range projections of crop water availability are subject to several sources of error. One factor, antecedent moisture, can often be a significant fraction of a water budget, but how much antecedent moisture will contribute to crop water use over the course of the season can be difficult to predict. Other important uncertain factors are estimates of the *potential* crop ET, upon which the plan is based, particularly due to the variability of k_c, the crop coefficient. Another parameter, K_s, which accounts for the reduction of actual ET when the crop is water-stressed is intrinsically uncertain, and algorithms for estimating K_s are generally linked to soil water holding capacity, which is itself uncertain.

Given these and other elements of uncertainty, deficit irrigation management should include error trapping and recalibrating of the analytical engine as routine operations. The detailed and integrated records of water use, soil moisture conditions and weather produced by IMO, combined with observations of crop development, crop stress and yield, provides an opportunity for systematically processing a mass of potentially valuable information from which a manager can gain insight and refined understanding of optimal water management.

IMO provides two ways to deal with these issues. One is by tracking soil moisture conditions to detect errors in long range projections of actual crop ET. The other is by integrating feedback data from alternative, independent sources. These are illustrated below.

Tracking soil moisture

In the case of the almond producer, it was clear early in the season that pre-season projections of crop available water were significantly lower than indicated by neutron probe measurements, and the error became progressively greater with time. Figure 8 illustrates the cumulative error by mid-May. The error was initially traced to two sources; the crop coefficients for early season ET were too high, and the estimated emitter discharge rate was about 6% low. The crop coefficients were revised in mid-season based on research done separately by Sandon, Ayars and Goldhammer (Goldhammer; IN FAO 66, Steduto et als, 2012). The emitter discharge rate was revised based on District measurements of water deliveries. Subsequently the assumed effective root zone available soil water holding capacity were adjusted. Figure 9 shows how model estimates (blue) would have compared with neutron probe measurements of soil moisture by the end of the season if not calibrated during the season. Figure 10 illustrates the revised soil moisture plot after recalibration.

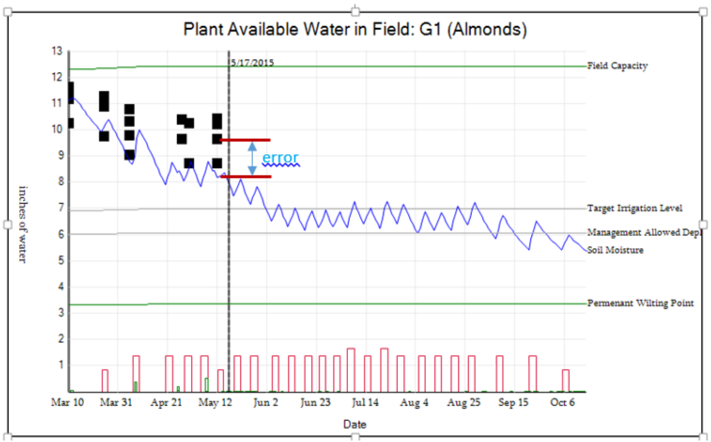


Figure 8: Error in projected soil moisture as of May 17, 2015

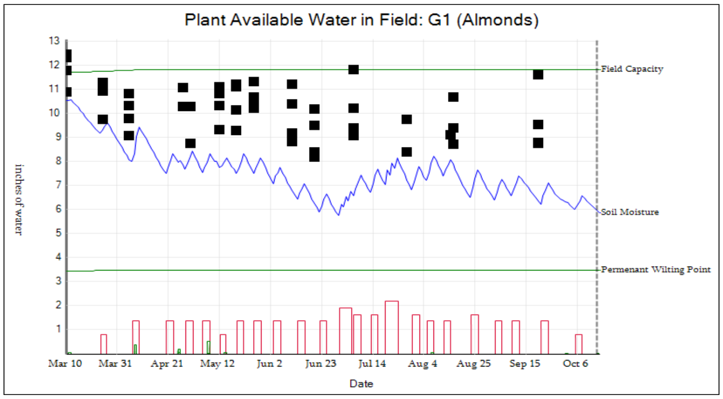


Figure 9: Uncalibrated soil moisture estimates

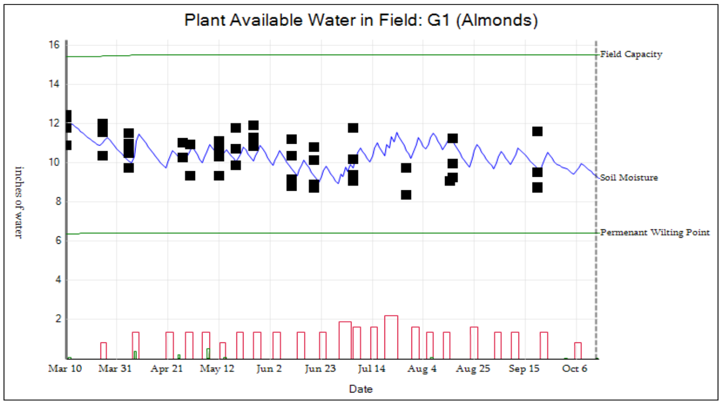


Figure 10: Calibrated projection of season soil moisture

Such recalibration will be an iterative process, with further refinement of model parameters in succeeding years.

Integrating alternative feedback data

Displaying multiple, independent sources of information about crop water status provides a basis for informed judgement of the quality of each data source. Figure 11 displays three independent data sets in a single graph: soil moisture estimates (derived from ET data), neutron probe readings and, along the bottom of the graph, annotated values of stem water potential.

As an example of the utility of integrated displays, a stem water potential reading of 16.0 in late March indicated incipient stress, indicating that the trees should be irrigated earlier than originally planned. But ET based modeling and neutron probe readings indicated there crop water availability was high. The consistent progression of the soil moisture data was judged to supersede the stem water potential readings and no additional irrigation was called for. (It was later concluded that the SWP readings had not been done correctly.)

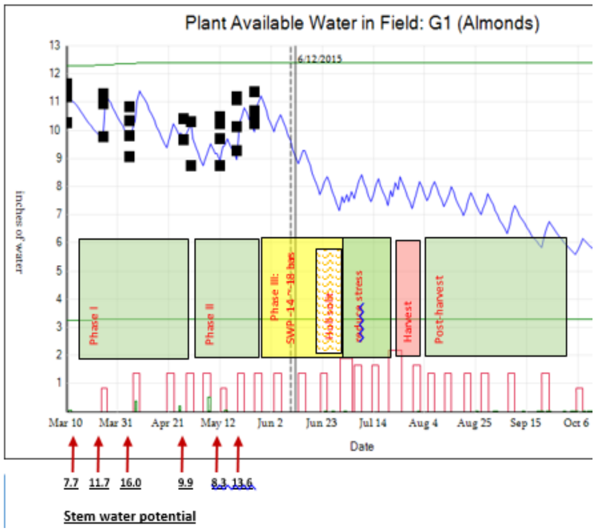


Figure 11: Comparing ET based estimates, neutron probe readings and stem water potential

While this example involves subjective use of independent data, we have also experimented with a more systematic procedure for combining alternative types of information using Bayesian Decision Theory (English and Sayde, 2008).

ASSESSMENT

It is not possible to quantify the benefits of this decision support system in terms of improved crop production, since there was no 'control' field. Nevertheless we can take note of the farm manager's subjective assessment of the system. Additionally we can describe in detail how well the actual irrigation schedule conformed to the advice of the research and extension community.

The manager's perspective

The value of the forward scheduling with IMO, expressed subjectively by the farm manager, was that it 'takes the guesswork out of it". Early in the season she was concerned that neighbors had begun irrigating and she wondered if she should also. With the seasonal plan in place she delayed starting for about two weeks, which enabled one additional irrigation at a more propitious time later in the season. As the season went on the question of whether to irrigate or delay recurred continuously. Ultimately she was comfortable following the plan precisely for the entire season, with the exception of shifting a day or two on one or two occasions because of conflicts with other activities.

Another important advantage from her perspective was knowing when to order district water.

Conformity with research guidelines

A second question was whether the pattern of water use was aligned with the research-based guidelines from which the irrigation strategy was originally derived. Figure 12 compares the recommended pattern of allocations (blue), the applied irrigation water (red) and the net crop water use (irrigation plus net change in soil water content at each stage, providing a visual indication of how well the pattern of actual allocations tracked the recommended pattern. Total water use for the season was 248 ac ft, almost exactly the original allotment of 250 ac ft.

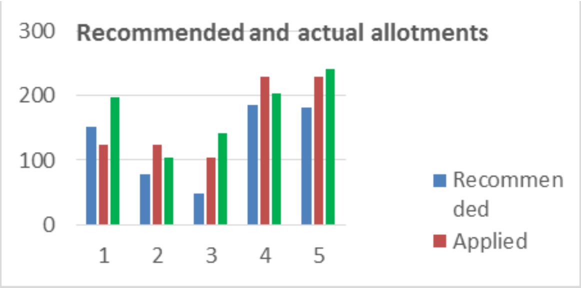


Figure 12: Actual patterns of crop water availability (green) and recommended pattern (blue)

Figure 13 shows a stress index (calculated ratio of actual ET to potential ET) plotted in parallel with Doll and Shackel's graphic of stress sensitivity, providing a general indication of the effectiveness of the stress management strategy. The stress pattern indicates that there was ample water until late May, then increasing stress approaching hull split, and quick recovery approaching harvest.

Yields

Yields in 2015 were 10.5% less than 2014. About 6% less water was applied in 2015 than in 2014**,** but the lower ET and unanticipated rain in 2015 may have offset that difference.

Our understanding is that the harvest volume was about the same in 2015 as 2014, but kernel weights were slightly lower for nonpareils and significantly lower for two other varieties. One possible explanation for the reduced kernel weights might be that early season (April and May) water supplies were higher than planned relative to late season water use. As a rule, water stress should be more or less balanced throughout the season (Shackel, personal Communication), and some degree of stress early in the season would condition the trees to later stress. But unexpected rainfall and lower than expected potential ET resulted in high levels of crop available water until mid May, followed by significant stress through June. From Doll's graph in Figure 13, early season high crop water availability may have induced full growth of the outer shell early in the season, but the subsequent water supply was unable to support full growth of the kernels later in the season. We did adjust the plan in May to account for the anomalous weather, but perhaps not aggressively enough. There may also have been been an echo effect from stress in the preceeding three years of intensive drought.

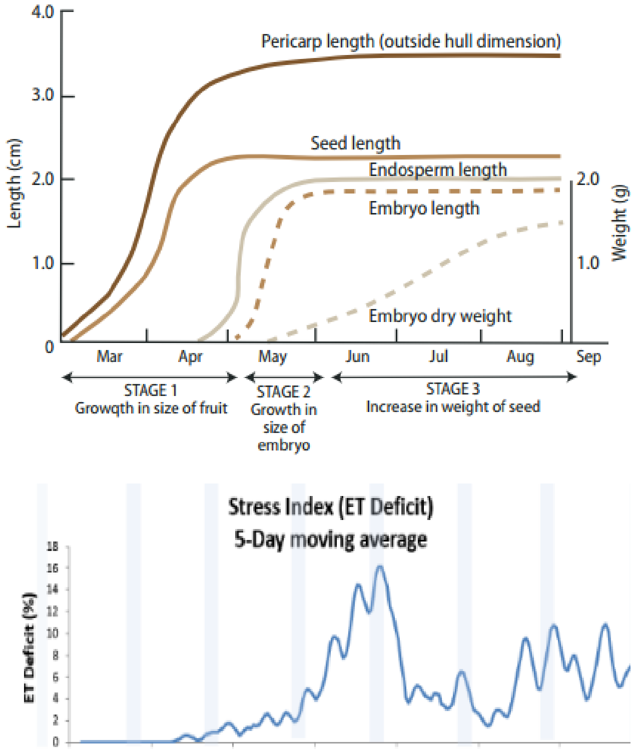


Figure 13: Comparing seasonal sensitivity to water stress to the seasonal pattern of estimated stress moisture with neutron probe data

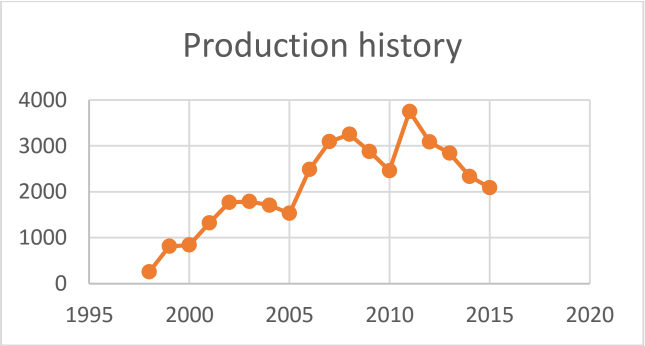


Figure 14: history of orchard yields since planting

CONCLUSIONS

Modeling of crop yields in response to partial irrigation, though intrinsically uncertain, provides science-based guidance for deciding how much water to allot to a particular field when water is limited or expensive. Example 1, illustrated value derived from modeling a field specific relationship between applied water and crop yields in order to examine in more precise detail the benefits of conserving water, and determine well defined optimal levels of water use.

Example 2 also illustrated the process of forward scheduling by which an irrigation manager was able to plan in detail for implementing a recommended irrigation strategy under drought conditions. The planning allowed the farm manager to envision an entire season.

The continuation of example 2 illustrated a necessary element of deficit irrigation management, the systematic and continuous processes of error detection and recalibration of the analytical system. The process of error detection, though predominantly based on the quantities that are modeled ((i.e. soil water depletion) can also be enhanced by systematically comparing independent sources of feedback data.

Comparison of uncalibrated and calibrated system analysis indicated that the error in initial estimates of antecedent moisture was about 3.5 inches, or 10% of the anticipated water supply.

The implementation of the intended strategy tracked well with the chosen strategy. The pattern of water use over the season was close to the originally stipulated pattern, after adjusting for the recommended increased water use approaching hull split. Yields were less than in previous years, but it is difficult to ascertain the cause.

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