Opportunities for Energy Demand Management in Irrigated Agriculture

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Introduction

The California Energy Commission (CEC) is supporting development of a decision support system for irrigation management to facilitate on-farm participation in energy demand management incentive programs. Balancing on-farm irrigation and energy needs with the dynamic energy markets is becoming increasingly important to energy users, energy producers and California's energy infrastructure.

This paper will outline linkages between operational imperatives of the energy grid and irrigation energy demands. Economic opportunities for on-farm energy conservation and energy load shifting will be discussed. Potential economic benefits and challenges of demand management programs will be illustrated, including: (i) timing of pumping energy use to take advantage of favorable utility rates at off-peak hours; (ii) responding to interruptions in energy supplies for a farm with limited system capacity. We will present an overview of an irrigation planning and management tool designed to facilitate participation in demand management programs.

Energy supply issues and opportunities in irrigated ag in the San Joaquin Valley

California's electricity system is undergoing unprecedented change. California's current goals call for meeting 50% of California's retail electricity sales with renewable energy by 2030 and reducing greenhouse gas (GHG) emissions to 40% below 1990 levels by 2030 (CARB, 2016). A 50% renewable electricity system in California will have a high penetration of variable solar and wind generation. Fluctuations and uncertainty of variable generation will make the operation of an already complex electricity system even more complicated. One way to offset the unpredictability of renewable resources is through demand response programs (DR), by which end users are induced to change their electric usage to match demand to supply. Historically, DR resources have been used to reduce the system level peaks (e.g. hot summer days). As California moves closer to its target of 50% renewables, traditional DR can provide local reliability, but more importantly faster time scale DR services (also referred to as Ancillary Services) will be more important for facilitating the intermittency of renewable generation.

A significant resource that can provide DR services to the grid and contribute to its stability is agricultural irrigation pumping. Agricultural irrigation pumping is a significant component of California's electric demand. In addition, agricultural distribution feeders often have low diversity in their types of customer loads, and exercise of a large number of irrigation pumps on

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a single feeder can cause over-voltage issues (Olsen 2015). In 2016, the peak demand of the California's electricity grid was 46 GW (CAISO 2016). In the same year, the peak demand for agricultural irrigation pumping was 1.3 GW (3% of California's total peak electricity demand) (CAISO 2016). As of 2015, California Investor Owned Utilities' (IOUs) total DR portfolio added up to 2.1 GW (Alstone, et al., 2016). Theoretically, 62% of the current IOU DR portfolio can be satisfied through agricultural irrigation DR alone.

The changing picture; how energy demand and availability are changing;

With higher penetration of intermittent renewable sources, the grid needs to deal with generation variability. Intra-hour variability and short-duration ramps are one of the immediate challenges faced by a 50% renewable California grid. However, other challenges arise as the California grid becomes greener over time. Historically peak hours were defined as the hours between 12pm-6pm (PG&E, 2016). Proliferation of solar generation in California (especially rooftop solar) is forcing those peak hours to shift to later hours in the day (4pm-9pm)[3]. This is most commonly referred to as the "Duck Curve" (Figure 1), where the increased solar generation is significantly dropping the net electricity demand during the day, which in turn results in significant ramps in the later hours (CAISO, 2016).

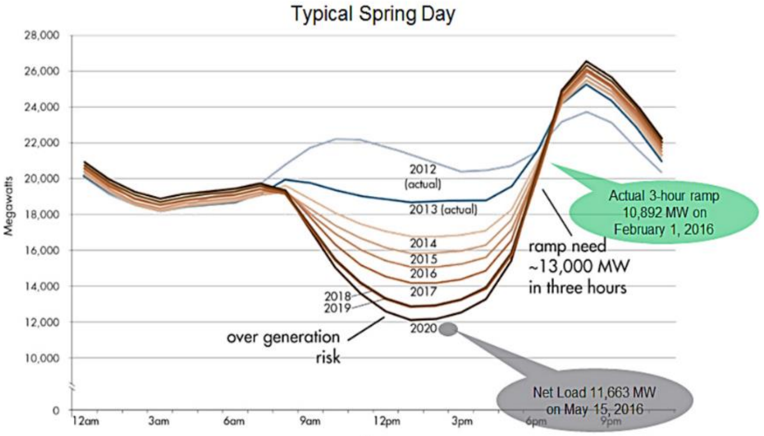

Figure 1: The duck curve shows steep ramping needs and over-generation risk (CAISO 2016)

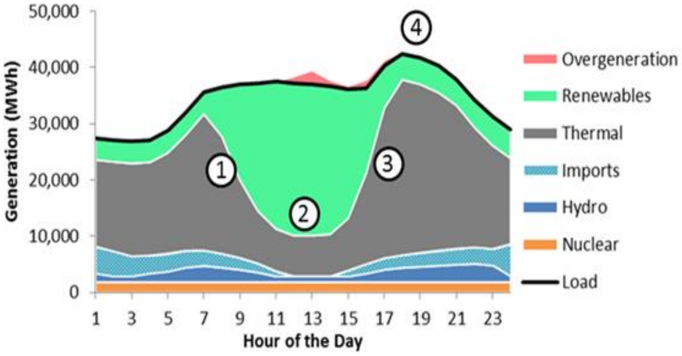

Figure 2: California grid under 50% RPS (E3 2014)

The Duck Curve might be better explained by looking at the generation mix of California's grid under a 50% renewable portfolio standard (RPS) shown in Figure 2. In a 50% RPS scenario, thermal power plants will ramp down as solar resources come online early in the day (1). However, they cannot drop to zero since a minimum capacity need to remain spinning for contingency as well as the evening ramp up, and in the absence of cheap energy storage, excess solar generation must be curtailed to maintain grid stability (2). As solar resources stop generating electricity in the evening (3), thermal power plants (mostly natural gas) need to ramp up to make up for the lost solar generation, and the evening ramp up will become more pronounced with increasing solar penetration (4).

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[3] Although there are no updates to agricultural customer TOU periods, PG&E has announced new residential and commercial TOU rates with 3pm-8pm and 4pm-9pm as new peak hours.

Agricultural irrigation can help address several challenges highlighted in Figure 2. As shown in Figure 3, agricultural load is highly concentrated in the summer months, coincident with the peak demand of the grid as a whole. In addition, highest daily demand for agricultural irrigation occurs during hours with highest levels of evapotranspiration, which are coincident with highest levels of solar electricity generation. On the other hand, solar curtailment, whereby solar generators are disconnected from the grid to protect the grid from being overwhelmed, occurs between the hours of 12-6 PM, hours of peak irrigation demand.

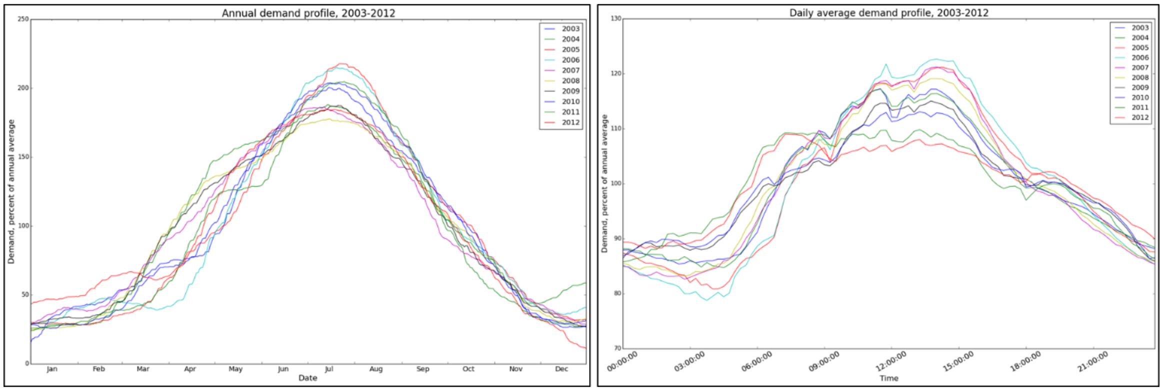

Figure 3: Estimated daily demand for a subset of PG&E agricultural customers, relative to daily average, 2003-12 (Left), and average daily demand profiles for interval meters, 2003-12 (right)

Therefore, a flexible and dynamic irrigation system can take excess load off the grid by over-irrigating during certain hours of the day (and less in other hours) in order to facilitate higher levels of solar integration into the grid and eliminate solar curtailment.

Most agricultural irrigation systems operate in a manual or semi-automated fashion which require long notification periods in order to participate in DR programs (Olsen 2015). A dynamic irrigation system (e.g. irrigation pumps equipped with variable frequency drives) can modulate its demand based on the instantaneous grid needs (e.g. variability of renewable generation) and provide fast response with shorter notification periods.

Currently agricultural irrigation pumping can only participate in traditional DR programs offered through utilities (also referred to as demand side DR). In the near future, fast responding DR services that can participate directly into the electricity markets will become more valuable. Automated DR (Auto-DR or ADR), another DR strategy in which loads are shed automatically in response to grid control signals unless the customer opts-out, allows quicker, more reliable load sheding with less effort required by grid operators and growers alike. ADR has the potential to be used for ancillary services, which are growing in importance due to the load uncertainty and variability caused by the integration of large shares of renewables (Watson et al. 2012). Such services are referred to as supply side DR. In order to provide supply side DR to the grid, loads should directly interact with the California Independent System Operator (CAISO). There are currently no mechanisms in place that allows pumping loads to directly provide supply side DR, so agricultural customers can only provide resources to the grid by enrolling in a TOU, DR, or ADR program offered by their local utility.

Time of use (TOU), demand response (DR) and automatic demand response (ADR) strategies; incentives/criteria/constraints; Time of Use (TOU) pricing is the most cost effective option for modifying load shapes because there are no site-level technology enablement costs and while the load reduction at any given site is typically small, the breadth of participation if the rates are default or mandatory provides a substantial statewide effect. TOU can contribute substantially to overall DR potential. The impacts of TOU pricing on agricultural accounts is clearly distinguishable in average daily demand profiles recorded by Pacific Gas and Electric's SmartMeters as shown in Figure 4.

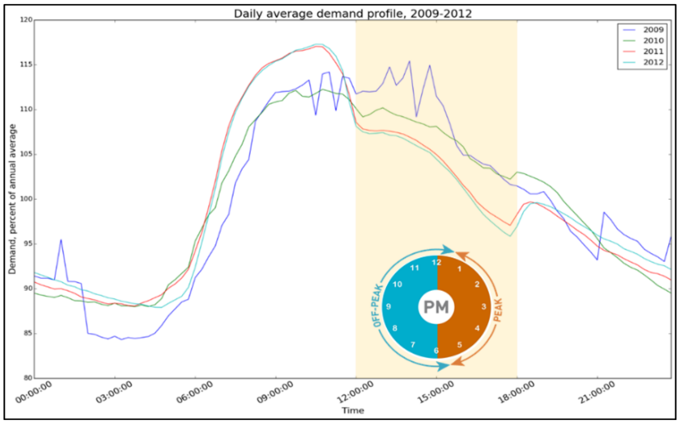

Figure 4: Average daily SmartMeters demand profiles, 2009-2012

In addition to TOU, several utilities offer various DR programs tailored toward agricultural irrigation customers with a combined load shed magnitude of 0.7 GW dating back to 2004 (Olsen 2015). Although largely successful, challenges faced by agricultural DR programs include unreliable shed rates (35%-85% relative to baseline load), low participation rates (20%), lack of automation, communications, and controls, as well as farm operational limitations (irrigation capacity, water delivery schedules, and labor).

Case-specific Illustrations of TOU and DR from cooperating farms

The examples presented below illuminate the nature of the demand management challenges from the irrigators' perspective. This limited overview of demand management for irrigated agriculture in the San Joaquin Valley illustrate the management decisions that must be made.

Example 1: Time of use management (TOU): The first case involves shifting time of use for a 92 acre almond orchard with ample delivery system capacity, a readily available water supply and on-farm water storage. The orchard is irrigated in three sets. Most irrigation events were 24 hours or more, so most irrigation events span three days. The actual sequence of irrigation dates and durations in 2017 is indicated by the darker histogram in Figure 5. The wide spacing between irrigation events indicates ample irrigation system capacity, allowing the farm to easily shift irrigation dates and durations. This represents an ideal opportunity for energy load shifting. It is simple to plan and implement, and presents a clear financial benefit.

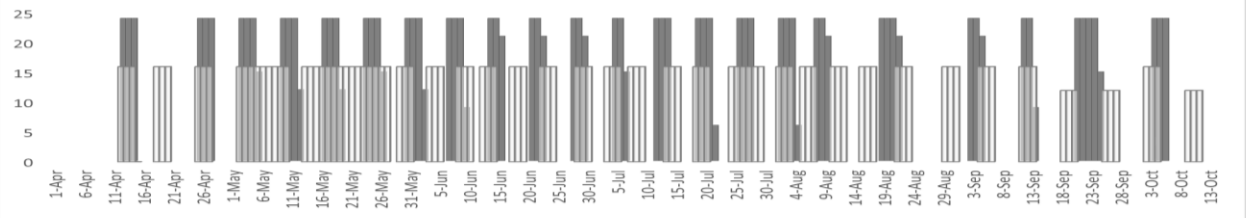

Figure 5: Alternative time of use (TOU) management

Energy rates for the farm are $0.195 per kWh for off peak hours and $0.445 per kWh for 8 peak hours daily. An alternative schedule, indicated by the lighter bars in Figure 5, would restrict irrigations to the 16 off-peak hours each day. The alternative schedule would have achieved virtually the same seasonal pattern of crop water availability as the actual schedule. Estimated pumping energy use in 2017 was 75 kW for 1908 hours, a total of 143 MWh. Pumping costs would then be $39,681 for the actual schedule and $27,834 for the off-peak pumping strategy. This simple TOU strategy would have achieved a saving of $11,847 in 2017.

Example 2: Interruptible power and limited pumping capacity: Now let us suppose the same farm also participates in a DR incentive program involving interruptible energy use. If the farm were also following the above TOU schedule it will be operating close to maximum pumping capacity. The incentive program stipulates that interruptions will last no more than four hours, with no more than one interruption per day nor more than ten per month. The analysis begins with the irrigation schedule based on 16 hour sets presented in the previous example (the darker bars in Figures 5 and 6). A modified schedule with occasional interruptions generated at random times is overlaid on the intended schedule (the lighter bars in Figure 6). An energy interruption is represented as a gap in the lighter bars. If an interruption is called when no pumping was planned it is indicated as a negative four-hour bar. On those days when no pumping was planned additional pumping for 8 to 12 hours can be inserted to compensate for up to preceding interruptions.

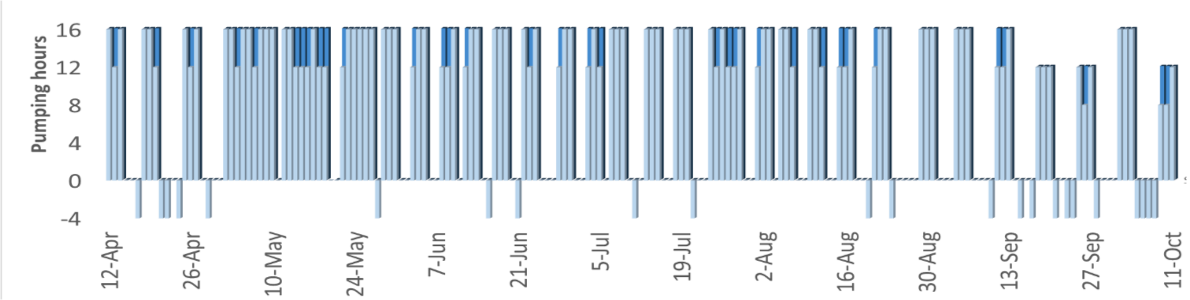

Figure 6: combining TOU and DR management

It appears from Figure 6 that the irrigator could compensate for most interruptions shown in by shifting irrigation dates by a day or two. Estimated impacts of such limited delays on crop production should be minimal (as will be discussed in the following example).

This example can also illustrate an important constraint common to demand response programs, which is that a farm shall only be compensated for DR participation in months when they would normally be using a significant percentage of pumping capacity. For example, the requirement might stipulate that the farm would normally be irrigating 75% of the time. In this case the TOU seasonal pumping from May through August would exceed the 75% level. If the financial incentive for participating in the DR program were $8 per kW per month and the farm qualifies for four months the payout would be an additional $2400 per year. However it is important to note that interruptible energy use could entail capital investment for remote system control and variable speed pumping, which are not considered here.

Example 3: Yield impacts of interruptions: Figure 7 shows a schedule for another orchard in which a similar TOU strategy was developed for a maximum of 15 off-peak hours per day. However, in this case the irrigation capacity could not meet scheduled crop water demands on six dates in late July and August, indicated by negative bars, each representing 15 hours of additional pumping needed to maintain the intended soil moisture pattern. The cumulative irrigation deficit during that interval would be 6% of intended seasonal water use.

Scheduling of additional irrigations to compensate for the 6% deficit would involve significant shifts of in the timing of applied water. Compensating irrigations will necessarily be delayed by two weeks or more until late August. Additional irrigations that late in the season will not mitigate the month long period of stress from mid-July to mid-August.

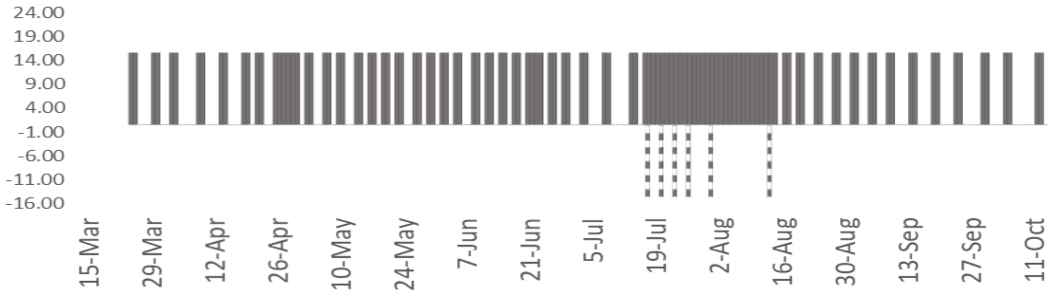

Figure 7: Deficits caused by pumping interruptions

The consequences of such periods of stress will depend on the complex relationships between irrigation timing and amounts, crop water availability and crop response to available water. The ability of a crop to recover from a delayed or missed irrigation will depend on the stage of growth, the reserves of water in the soil, atmospheric conditions and the physiology of the crop.

In this case we used an advanced irrigation management model, discussed later in this paper, to estimate the effect that reduced crop water availability would have on the cumulative daily ET. ET deficit is a widely used parameter for estimating yields under limited irrigation conditions. Figure 8 shows estimated daily ET for the two alternative irrigation schedules, indicating an ET deficit until August 20. The resulting cumulative ET deficit reached a maximum of 0.45 inches, approximately 1% of normal seasonal ET, before the compensating irrigations began. Because that deficit is concentrated in a one month interval it would represent a 4% ET deficit roughly coinciding with the onset of harvest, which could result in a more significant effect on yields. On the other hand, some degree of deficit irrigation may actually increase farm profits by reducing costs and increasing management flexibility. Modeling of the impacts of ET deficits is therefore a central issue for DR management.

Figure 8: Comparison of estimated crop ET under alternative management scenarios

Example 4; Conjunctive management of multiple fields: Figure 9 illustrates the greater complexity involved in conjunctive management of multiple fields. Figure 9 shows pumping demand for four fields on another cooperating farm in 2017. The stacked bars represent hours of pumping in each of the four fields. The highly irregular pattern indicates this farm could reduce peak demands substantially by shifting most irrigation dates by a day or two.

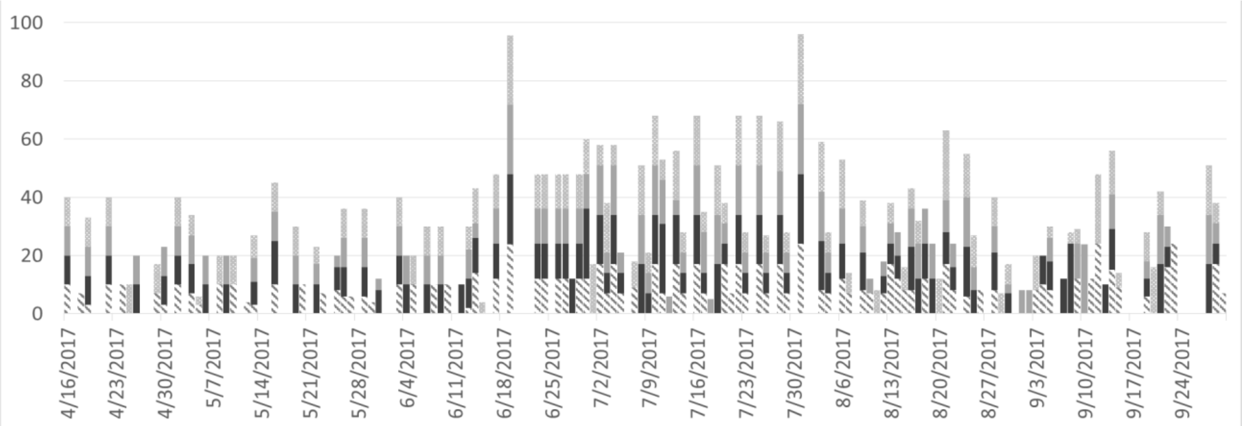

Figure 9: Conjunctive management of four fields

However such re-scheduling can be complicated by the need to re-allocate limited water among different and competing applications, such as different crops, differences in field characteristics (e.g. soil parameters) and differences in irrigation system characteristics in the different fields.

A decision support system to facilitate demand management

As indicated above, irrigation planning to accommodate TOU and DR strategies will need to anticipate occasions of high water demand weeks or months ahead of time, especially when allocating water among multiple fields that share a common water supply. If optimal water use involves some degree of deficit irrigation, the planner will need to assess the possible yield impacts of delaying, reducing or eliminating some irrigations.

Meeting these challenges will require accurately modeling the disposition and fate of applied water over extended periods of time and modeling crop response to available soil moisture. And long range plans need to be easily and quickly updated when and as changing weather, the availability of water, disease problems and other factors evolve during the season. And planning needs to account for farm-specific constraints due to contractual arrangements, operating practices, risk tolerance and other factors that differ from one farm to another.

Current irrigation management technologies, which focus on monitoring current conditions and simple water balance modeling does not provide adequate support for such management challenges. The CEC is therefore funding adaptation of an existing decision support system. Known as *Irrigation Management Online* (IMO), the system was originally designed for optimal long range planning and management of irrigation strategies, including deficit irrigation, to deal with these complex management challenges (*Hillyer at als, 2015*). IMO utilizes comprehensive and sophisticated modeling of the disposition and fate of applied water in order to accurately project crop water availability well into the future. The software maximizes analytical efficiency and speed to minimize the computational burden in order to facilitate iterative analysis of alternative management practices under variable and uncertain field circumstances.

The IMO system supports five phases of irrigation management;

- *Planning seasonal water use*; consulting with the farm manager is an essential first step to account for the manager's prior experience, tolerance for risk or uncertainty, contractual arrangements, incidence of disease or pests and other ancillary factors that influence irrigation management. Researchers and extension leaders are also consulted to identify the best seasonal pattern of water use based on local field circumstances.
- *Seasonal scheduling;* generating a full season irrigation plan, with anticipated dates and set times for all irrigation events to implement the intended seasonal pattern of water use (as illustrated in Table 1).
- *Dynamic scheduling;* tracking measured and estimated soil moisture (illustrated in Figure 10) and updating the irrigation plan continuously to account for actual seasonal weather, changing farm objectives or other changing circumstances.
- *Recalibration;* using incoming field data to check the accuracy of the analysis and recalibrate model parameters.
- *Yield modeling;* in some applications water use and crop yield data have been combined to calibrate a farm-specific crop yield models for estimating yield deficits (see Example 3).

Start Date	Gross Application (inches)	Set/Block/ Rotation (hours)
7-Apr	1.91	28
17-Apr	1.91	28
24-Apr	1.91	28
1-May	1.63	24
8-May	1.91	28
15-May	1.91	28
22-May	1.91	28
29-May	1.91	28
5-Jun	1.91	28
12-Jun	1.63	24
19-Jun	1.63	24
26-Jun	1.63	24

Table 1: a seasonal irrigation schedule

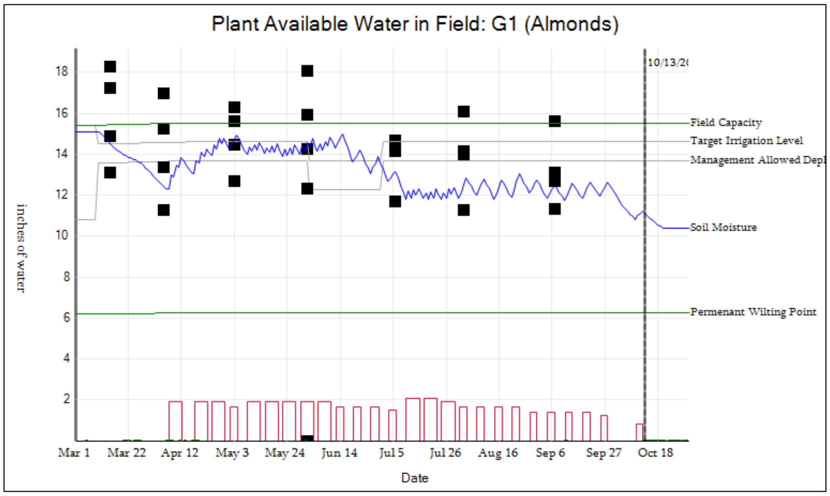

Figure 10: estimated and measured soil moisture

Two additional algorithms are being developed to simplify use of the IMO system. The first, an auto-scheduling algorithm, will automatically generate an irrigation schedule for an upcoming season and update the schedule quickly when circumstances change. If an interruption in a planned irrigation schedule renders the original schedule infeasible, as illustrated in Example 3, the algorithm will generate alternative new schedules, reject schedules that violate operational constraints, evaluate the outcomes of feasible schedules in terms of a specified objective function, and repeat this sequence in a systematic search for a 'best' schedule.

The second new algorithm will automate the process of re-calibrating the analytical engine, a procedure that currently depends upon a trained analyst. We are currently in the conceptual development phase, exploring alternative machine learning tools and formulating specifications for the objective function[4].

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[4] We have been guided in this effort by Profs. John Bolte and Steven Goode of the Biological and Ecological Engineering Department, Oregon State University