Case Study: Managing Center Pivot Irrigation Using Municipal Reclaimed Water

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ABSTRACT

Secondary and tertiary treated municipal wastewater has been used to irrigate alfalfa and grains on approximately 4,000 acres in Southern California via center pivots. In addition to coordinating fluctuating treated water supply and crop demands, this program has focused on balancing two competing goals: (a) maximizing crop yield and (b) maintaining compliance with relatively strict environmental discharge permit requirements that limit the transport of nutrients, such as nitrates, past the root zone. For example, minimizing nitrate movement through precise irrigation promotes salts accumulation in the root zone. Subsequently, crop yield and nutrient uptake rates are impacted. In that context a combination of good management strategies, excellent irrigation hardware, and the selective use of technology have proven to be essential tools for success. This paper will detail some of the short and long-term challenges of managing soil health and crop production under local regulatory obligations.

RECYCLED WATER USE IN CALIFORNIA

Municipal sewer systems are designed to collect and treat wastewater. The level of treatment and fate of the treated wastewater is the result of balancing regulatory landscapes, local land uses and economics.

With few exceptions, un-disinfected secondary treatment is the minimum level of wastewater treatment required by federal regulatory agencies. In addition to primary treatment, which removes the majority of settable and floating debris, secondary treatment further reduces suspended solids and most biological nutrients.

The scarcity of water with sufficient quality, among other drivers, have produced incentives for water reuse. The primary objective of treated water reuse is to displace the use of new water with an existing treated water supply. Potential uses of treated wastewater are listed in California Code of Regulations Title 22 as summarized in Table 1.

Table 1. Generally acceptable uses of recycled wastewater in California (adapted from California Code of Regulations, Title 22, Division 4, Chapter 3, Article 3)

Disposal/Use	Undisinfected secondary	Disinfected Secondary-23	Disinfected Secondary-2.2	Disinfected Tertiary
Food crops, including all edible root crops, where recycled water comes into contact with the edible portion				X
Parks and playgrounds				X
School yards				X
Residential landscaping				X
Unrestricted access golf courses				X
Surface irrigation of food crops where edible portion is produced above ground and not contacted by the recycled water			X	X
Cemeteries		X	X	X
Freeway landscaping		X	X	X
Restricted access golf courses		X	X	X
Ornamental nursery stock; sod farms were access by the general public is not restricted		X	X	X
Pasture for animals producing milk for human consumption		X	X	X
Any nonedible vegetation where access is controlled so that the irrigated area cannot be used as if it were a park, playground or school yard		X	X	X
Orchards were the recycled water does not come into contact with the edible portion of the crop	X	X	X	X
Vineyards where the recycled water does not come into contact with the crop	X	X	X	X
Non food-bearing trees	X	X	X	X
Fodder and fiber crops and pasture for animals not producing milk for human consumption	X	X	X	X
Seed crops not eaten by humans	X	X	X	X
Food crops that must undergo commercial pathogen-destroying processing before being consumed by humans	X	X	X	X
Ornamental nursery stock and sod farms provided no irrigation with recycled water occurs for a period of 14 days prior to harvesting, retail sale, or allowing access by the general public	X	X	X	X

Intuitively, there are more potential uses for water treated to higher degrees. On the other hand, there is a trade-off. Significant investments in construction, operations and maintenance are required to achieve incrementally higher treatment levels. Therefore, local wastewater authorities must find a balance between treatment costs and the benefits of recycled water use. In general, there is a trend towards increased treatment levels. As of 2011, about 75% of the US population is connected to a sewer system, of which about 40% of the connected networks are fitted with tertiary treatment (OECD, 2018).

While Title 22 limits the potential application of recycled water, additional restrictions and quality standards were historically determined by regional water quality boards through a permitting process. The permitting process would consider additional constraints of local and pre-existing conditions.

In 2014, the California State Water Resources Control Board issued a General Order intended to streamline the permitting process for recycled water use due to ongoing drought conditions (California Water Boards, 2014).

GENERAL ADVANTAGES OF AGRICULTURAL IRRIGATION WATER RECYCLING

Agricultural irrigation is one of many potential uses of recycled water. Naturally, without agricultural irrigation nearby, it is more economical for some municipalities to deliver recycled water to uses more fitting of local land uses. Some examples of urban wastewater uses are as golf courses, landscaping, parks and other recreation.

For municipalities near irrigated agriculture, there are advantages to directing recycled water to that purpose:
1. Water quality requirements are lower and therefore treatment costs are less
2. Water demand per acre can be higher than other uses. Similarly, parcel sizes are also larger and therefore fewer delivery points are needed
3. Annual water demand is relatively easy to estimate if cropping patterns are similar
4. Installation costs are less per linear foot in rural areas

Because of these advantages and preexisting irrigated crop production nearby, among other drivers, agricultural irrigation continues to be the primary use of recycled water throughout California (CA SWRCB, 2015).

PROJECT INTRODUCTION

Multiple municipal wastewater treatment plants (WRPs) in Southern California are operated by the Sanitation Districts of Los Angeles County (SDLAC). Two of the WRPs collectively treat about 30 million gallons per day (mgd). The WRPs:
- are fitted with large storage ponds to help balance flows of treated effluent and demand.
- deliver treated effluent for irrigation, primarily for agricultural uses. Recycled water use via agricultural irrigation was identified in multiple environmental impact reports (EIRs) as the recommended option considering various alternatives. (Lancaster and Palmdale EIR executive summaries). Recycled water is also sent to wildlife wetlands and urban uses.

Recycled wastewater is applied via center pivots for commercial crop production on about 4,600 acres in the Antelope Valley of Southern California. The primary crop rotation is alfalfa and oats. Typical crop yields are 8 tons per acre of alfalfa in 7-8 cuttings. Alfalfa was selected as a primary crop because of its ability to consume relatively large amounts of nitrogen when available, but also sourcing its own (through fixation) when necessary.

Climate and Soils. The Antelope Valley is relatively arid, with predominantly sandy loam soils receiving about seven inches of average annual precipitation. Therefore, the majority of water needed to meet crop evapotranspiration requirements is provided by irrigation.

Water Quality. Initially, about one-third of the water supply was treated to non-disinfected secondary standards with an average of total nitrogen concentration of about 35 mg/l, equivalent to about 95 lb/AF (Cass and Plazlak, 2006).

Subsequent upgrades have been undertaken to elevate all water treatment levels to disinfected tertiary. The entire recycled water supply is now treated to disinfected tertiary levels. Current water constituents are listed in Table 2 and compared to more typical agricultural surface water values such as State Water Project supplies.

Table 2. Key water quality constituents and average annual concentrations for the project's WRP recycled outflows compared to State Water Project sources, which supplies a large portion of irrigated agriculture on the western side of the Central Valley

Constituent	WRP 1 (mg/l)	WRP 2 (mg/l)	SWP (mg/l)
TDS[1]	489	444	300
Chloride[1]	158	128	85
Nitrate as N[1]	3.07	6.31	0.9
Ammonia as N[2]	15.7	22	
Potassium[2]	17	14.1	
Sodium[2]	167	125	

[1] Source: LADPW, 2014
[2] Source: Kennedy/Jenks, 2006

The water quality from the two recycled water WRPs are similar. The WRP recycled water contains higher concentrations of most constituents, which can be an advantage and potentially problematic. One advantage to the recycled water is the additional nitrates that, when managed properly, can partially displace commercial fertilizer applications. On the other hand, higher concentrations of total dissolved solids can require more leaching over time to minimize the accumulation of plant stress inducing compounds (e.g., chlorides) and elements (e.g., sodium).

Water Quantity. Current recycled water demand and availability and projections for the year 2020 is listed in Table 3, using the following assumptions and data:

1. Projected increases in treated water supplies as a result of treatment plant upgrades and population growth (Kennedy/Jenks, 2006)
2. The same average agricultural demand (same acreage and cropping)
3. Urban and environmental uses:
    a. The same environmental flows to Piute ponds as part of a memorandum of understanding to maintain a target range of wetted acres
    b. Increased urban recycled water use as additional pipelines and delivery points are constructed

Table 3. Current recycled water demand and projections for 2020

Description	Current average value (AF)	Projected average value in 2020 (AF)
Annual tertiary recycled water supply	25,550	48,750
Annual agricultural irrigation demand (based on 4 AF/acre)	18,400	18,400
Annual urban and environmental recycled demand	7,000	24,500
Supply minus total demand	+150 (negligible)	+5,850

Annual average combined treated outflows from both WRPs is about 70 acre-feet per day, equivalent to 25,550 acre-feet per year (Kennedy/Jenks, 2006). Agricultural irrigation is one of many current recycled water uses. On average, about 4 feet of recycled water is applied on the 4,000 acres of irrigated agriculture representing about 16,000 AF/year. The remainder, perhaps 9,550 AF per year, are delivered to environmental and urban uses.

Recycled water is stored in reservoirs to buffer the relatively fixed recycled water supply with variable agricultural and urban demands. Agricultural demands vary with crop rotations, growth stage, harvesting and cultural operations. In addition, weather patterns affect both agricultural and urban irrigation demand.

On the lands with applied recycled water, seeding, cultural activities and harvesting are completed by local farmers, who competitively bid for 5-year operations contracts. An engineering consultant is also hired to schedule irrigations and fertilizer applications, as well as document compliance with relatively strict discharge permits. The discharge permits regulate the fate of certain treated wastewater constituents, including nitrogen and salts. Additional operational constraints are balancing inflows, available pond storage and crop water demand.

REPORTING REQUIREMENTS OVERVIEW

The SDLAC recycled water project is unique because of the relatively intense level of agronomic management, regulatory compliance and reporting required to comply with the WDR permits. For example:

1. On a weekly basis, irrigation schedules are developed in order to determine gross irrigation application requirements.
2. On a quarterly and annual basis:
    a. Nitrogen and water balances are calculated for each field.
    b. A farm management plan is developed and updated to justify and report major agronomic interventions (not including cultural practices) such as anticipated cropping patterns, macro and micro nutrient applications and soil amendment recommendations.
    c. Regular Sampling and laboratory testing is conducted to verify the theoretical nitrogen balance computations, and ultimately to avoid groundwater/soil degradation:
        i. One crop sample per alfalfa harvest (about 200 per year)
        ii. 220 soil samples are taken annually
    d. Soil and weather sensing
        i. 25 soil sensing stations with five sensors each, at different depths. Four soil moisture sensors are installed per station (depths: 2,3,5 and 10 feet below ground surface)
        ii. One local CIMIS weather station data
3. Every five years, system distribution uniformity analyses are conducted on each pivot to benchmark and identify improvements, if necessary.

In contrast, many other agricultural irrigation projects using recycled water report far less details of on-farm practices. It is presumed that the extra sampling and reporting obligations were developed for the following reasons:

1. The aquifer was sensitive to further degradation due to pre-existing local conditions, including contaminant leaching of native soils.
2. SDLAC was a relatively early adopter of agricultural recycled water use in California, so an abundance of caution was justified.
3. Initially, about one third of the recycled water applied to crops was treated to non-disinfected secondary levels. Eventually, a transition to 100% disinfected tertiary treatment was made.

CHALLENGES AND SOLUTIONS

A number of challenges were confronted and overcome during the duration of the project related to meeting regulatory obligations and their subsequent impacts. In general, this challenge was resolved through well-defined operational constraints, excellent hardware performance and selectively applying appropriate technical tools.

Efforts to resolve other challenges have proven more difficult because they are managed by economic and legal teams, yet result in real engineering problems in the field.

CHALLENGES AND IMPACTS OF REGULATORY COMPLIANCE

Maximizing the productivity of most commercial crops involves minimizing plant stress by managing soil water tension in the root zone and the availability of specific elements and compounds within target ranges. In practice, it is relatively difficult to accurately determine actual crop water and fertilizer demand. It tends to be less expensive and less time-consuming to estimate crop demands with conventional farming operations. A small amount of excess water and fertilizer can also be applied to cover the uncertainty in crop demand estimates.

In contrast, agricultural operations for SDLAC follow additional constraints that require a greater degree of certainty in determining crop demands and accurate applications within tighter tolerances. It is therefore critical to properly define the constraints.

THE IMPORTANCE OF DEFINITIONS

Some aspects of the project are constrained by the definition of specific terms, such as “agronomic rates” within the WDR permits. Because irrigation water and plant nutrients are key factors in maximizing crop production, properly defining the term “agronomic rates” has been a critical component to the success of the project.

At the beginning of the project in 2005, the most complete definition of “agronomic rates” was irrigation water that “is applied at a rate that does not exceed the demand of the crop plant, with respect to water and nitrogen, to minimize deep percolation of applied recycled water from the root zone to the groundwater table” (LADPW, 2014).

The definition is problematic. First, it is not sufficiently clear to the reader what quantitative limits are placed on irrigation scheduling, which is a task that depends on numbers. Secondly, the definition can be interpreted as a mandate to under-irrigate, which for alfalfa results in a proportional decrease in yield. As such, there was justification for a modified definition of agronomic rates to avoid future issues. An alternative definition of "agronomic rate" was proposed:

> The agronomic rate, as defined in this application, is the potential maximum recommended amount of recycled irrigation water that can be applied to a field. Agronomic rates include ETc of irrigation water (total crop evapotranspiration minus evapotranspiration of precipitation), water needed to overcome irrigation system non-uniformity, plant establishment, plant germination, suppression of wind erosion, frost protection, and the leaching requirement to maintain the soil salinity below a threshold that can cause crop damage. Spray losses (evaporation of water being applied during the irrigation) are also included. (LADPW, 2014)

The improved definition of agronomic rates are estimated using the following formula:

$$\text{Agronomic Rate} = \frac{\text{ET}_\text{c} \text{ of Irrigation Water}}{\text{DU} * (1 - \text{LR})}$$

Where,

DU = the irrigation system distribution uniformity (unitless)

Distribution uniformity (DU) is a measure of how uniformly water is being applied to a field. Typically, irrigation is performed such that the area of the field receiving the least amount of water still receives sufficient water to meet its agronomic needs. Satisfactory DU for center pivot systems ranges from 0.70 to 0.85. For planning purposes a DU of 0.80 was used. Field studies and interventions designed to improved center pivot DU are detailed later in the report.

LR = the leaching requirement to maintain soil salinity below a threshold that can cause crop damage (unitless). The leaching requirement is the amount of irrigation water applied after the soil has reached field capacity in order to remove excess soil salinity within the root zone. The average salinity of the irrigation water has an electrical conductivity (EC_{iw}) of approximately 0.76 dS/m. The threshold electrical conductivity of the soil extract (EC_e) to prevent crop loss is based on alfalfa salinity sensitivity (EC_e = 2 dS/m).

ETc of irrigation water = estimated evapotranspiration of the crop.

Other components of agronomic rate (e.g., water needed for germination, frost protection, etc.) are difficult to quantify because they are dependent on management and environmental factors. Therefore, these other components are not included in the formula by default, but are incorporated in irrigation scheduling calculations when necessary.

The alternative definition was ultimately approved by the regional water quality board. The suitability of the new definition of "agronomic rates" was further reinforced with the adoption of

California State Water Resources Control Board Order WQ 2014-009-DWQ General Waste Discharge Requirements for Recycled Water Use, which includes a similar definition:

> The rate of application of recycled water to plants necessary to satisfy the plants' evapotranspiration requirements, considering allowances for supplemental water (e.g., effective precipitation), irrigation distribution uniformity, and leaching requirement, thus minimizing the movement of nutrients below the plants' root zone. (CA Water Boards, 2014)

Once clear operating constraints were determined, attention was directed to the performance of hardware impacting the uniformity of fertilizer and water applications.

APPROPRIATE TECHNOLOGY

A variety of technological tools have been used to more accurately determine crop demands and verify that applications are on target:

1. An excellent weather station was constructed in the project vicinity and integrated into the California Irrigation Management and Information System (CIMIS) network. While the hardware and installation was funded by the project, ongoing support, communications, data hosting and quality control are provided by CIMIS staff. The new CIMIS station provides accurate, local weather conditions and an estimate of reference evapotranspiration (ETo).
2. A network of soil moisture sensors were installed. The soil moisture sensors are a combination of Decagon EC-5 and 5TE sensors
3. Magnetic flow meters were installed at each pivot to provide accurate flow measurement and volumetric accounting
4. Remote pivot monitoring and control systems were installed to provide farmers with a greater degree of control and flexibility.

Despite these significant investments in robust and industrial equipment, reliability and accuracy issues were experienced. For example, each center pivot was fitted with permanently installed volumetric soil moisture sensors at two locations per pivot. Each soil moisture sensing location has three sensors installed at various depths within and below the managed six-foot root zone.

Most of the time, the soil moisture sensor data reasonably fit expectations. More specifically, most irrigation events are measured by the sensors and the volumetric water content decreases with sensor depth. One example of reasonable data collection from soil moisture sensors is shown in Figure 1. Each line represents a single sensor reading at distinct depths. The blue line is a sensor reading installed at 2 feet below the soil surface. Trend lines with lower values represent moisture measurements further from the soil surface, with the maximum sensor depth at 10 feet.

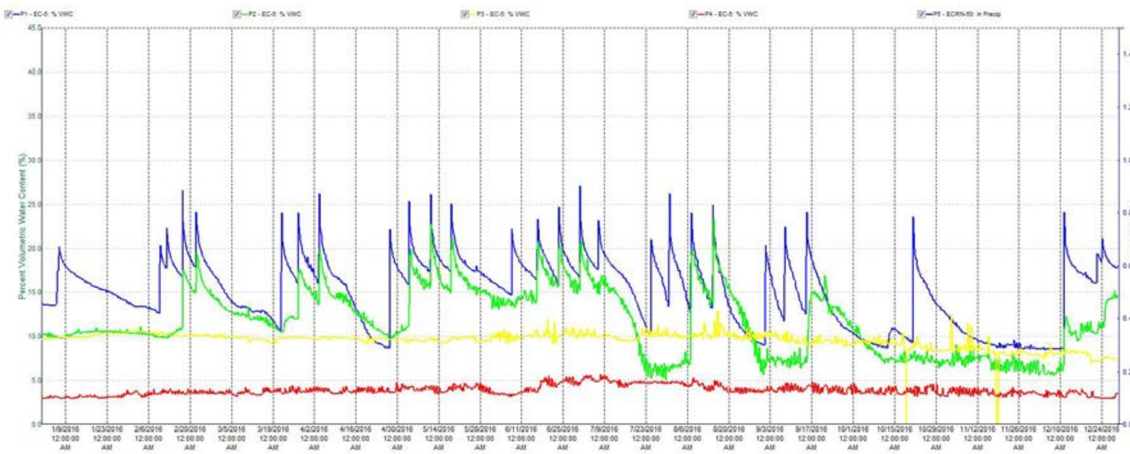

Figure 1. Reasonable soil moisture sensor readings and trends representing irrigation events and depths. Sensor depths range from 2 feet to 10 feet.

On the other hand, the same hardware can experience failure or confusing readings as shown in Figure 2.

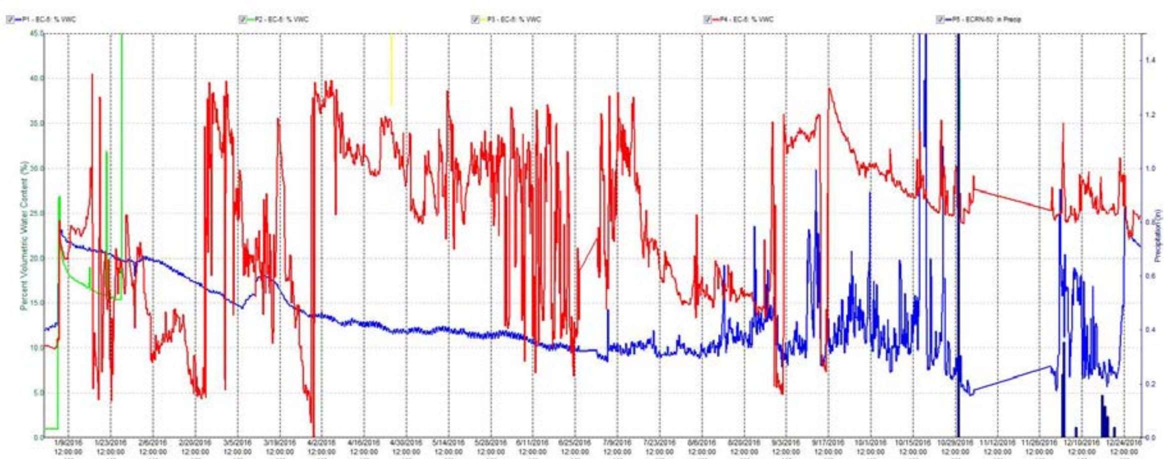

Figure 2. Sensor failures and unreasonable volumetric soil moisture measurements at different depths on alfalfa. Sensor depths range from 2 feet to 10 feet.

Based on these results, the sensor data has not impacted irrigation scheduling, but have been used for verification when sensors are functioning.

EVALUATING AND IMPROVING DISTRIBUTION UNIFORMITY

The efforts and expense of accurately determining crop demands are wasted without the ability to uniformly apply target water and fertilizer volumes. As such, efforts were directed to irrigation system distribution uniformity (DU) evaluations.

Extensive evaluations were conducted on all of the project's center pivots, resulting in catch can DU scores of 0.62 to 0.73. A variety of recommendations focused on improvement were developed. The data reinforced the concept that even relatively new irrigation systems can perform at sub-optimal levels when designed or fitted improperly. Recommendations for improvement included:

1. Raise sprinklers from 3.5 feet to 5.5 feet on average
2. Stagger adjacent sprinkler heights to avoid stream collision.
3. Fix new weights and drop tubes to each sprinkler to ensure the sprinkler plates are level
4. Replace broken sprinklers and clean debris from functional sprinklers
5. Replace nozzles to ensure design application rates

After the recommendations were implemented, uniformity evaluations were repeated. The post-intervention data indicated that the DU increased to 0.89, a marked improvement and considered excellent for center pivots. Figure 3 illustrates the catch can data collected before and after the improvements.

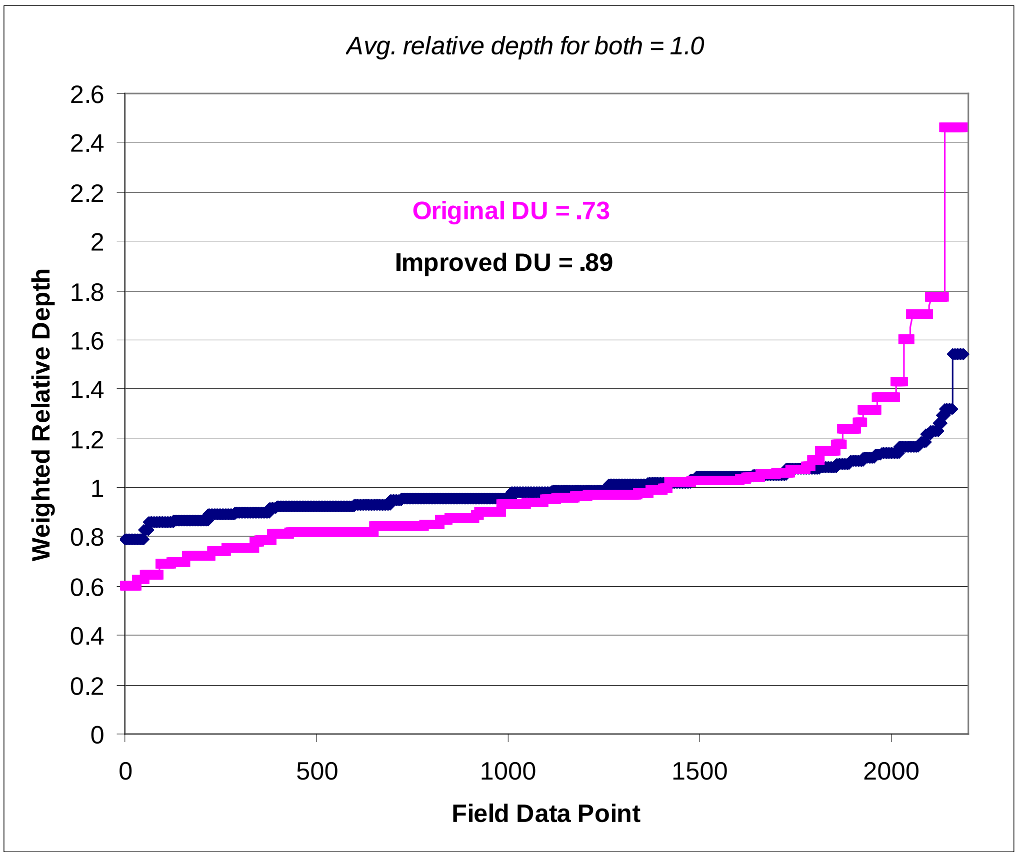

Figure 3. 2007 catch can data for one of many project pivots, before and after improvements

The improved DU values provided the ability to apply water and fertilizer through the irrigation system with relatively good uniformity. In order to maintain excellent performance, regular DU evaluations and an extensive maintenance program were prescribed and followed.

CONTRACTUAL CONSTRAINTS AND INCENTIVES

Currently, entities competitively bid on 5-year farming contracts while paying volumetrically for water. The relatively short term of the contract, and no guarantee of contract renewal does not incentivize long-term on-farm management that might normally occur under a different set of circumstances.

It is likely that a longer-term farming contract would incentivize investments to improve future yields. For example, it is typical to apply additional irrigation water for the benefit of leaching salts past the root zone, or to apply soil amendments such as gypsum. Unfortunately, the contract terms have not lengthened, and field conditions have suffered.

CONSEQUENCES OF GOOD PRACTICES

The combination of excellent hardware and data made farming operations under well-defined and stringent regulatory obligations possible. The farming operation had the ability to achieve excellent yields while also minimizing deep percolation. However, without regular leaching an accumulation of salts occur within and just underneath the managed root zone. Similarly, an accumulation of nitrogen occurs just past the root zone.

Over time, crop yields have slightly declined. An additional and comprehensive round of soil sampling was conducted at depths of 1, 3 and 5 feet below ground surface. Soil sample locations are shown in Figure 4.

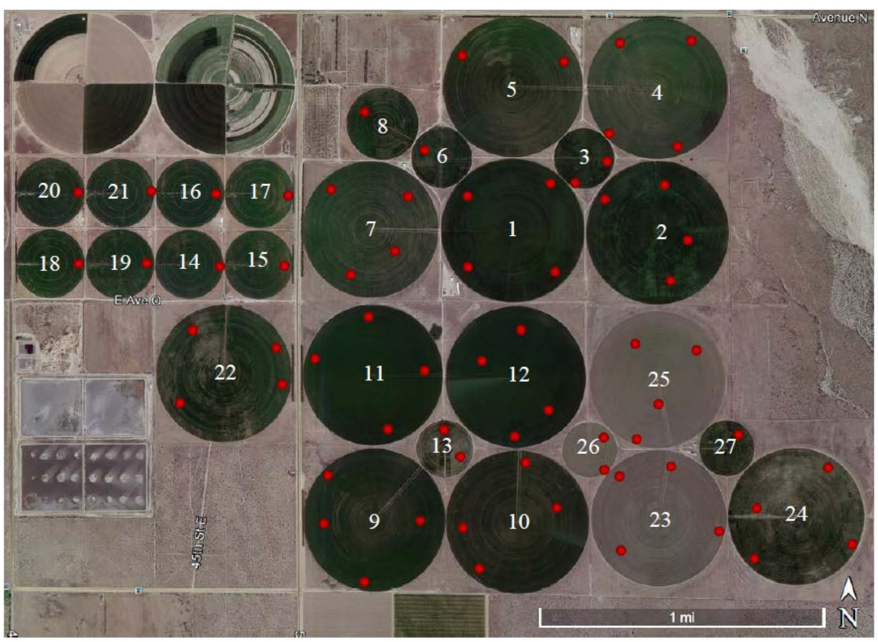

Figure 4. Soil sample locations

A dataset of laboratory test results from a single field and sampling event at different depths (1 foot, 3 foot and 5 foot) is listed in Table 4; the results are representative of similar data from other fields.

Table 4. Lab results from multiple soil samples and different depths at the same location

Sample #	Sodium (ppm)	Computed percent cation saturation from sodium (%)	Soluble Salts (mmhos/cm)
1	89	9	0.4
2	308	86	0.5
3	660	13.5	1.1
4	183	13.9	0.5
5	297	21.4	0.3

This data, the exchangeable sodium percentage (ESP) and soluble salt (in dS/m), was plotted with historic data to get a sense of changes over time, as shown in Figure 5.

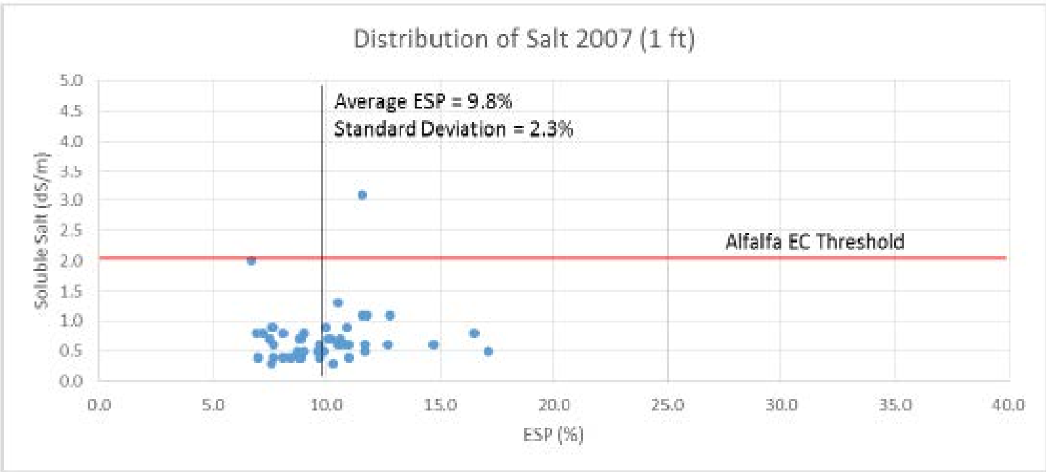

Figure 5. 2007 soil sample results from all fields at 1 foot depth. The average ESP was about 10%.

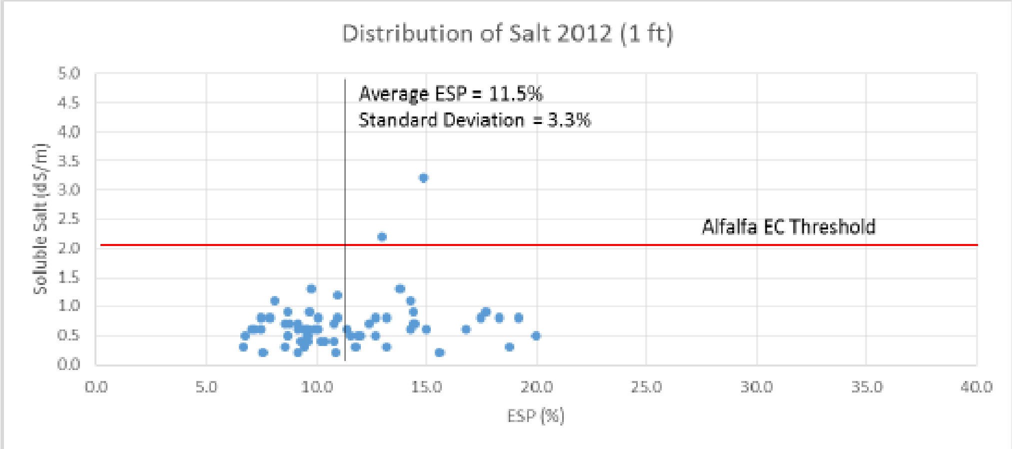

Figure 6. 2012 soil sample results from all fields at 1 foot depth. The average ESP was about 12%.

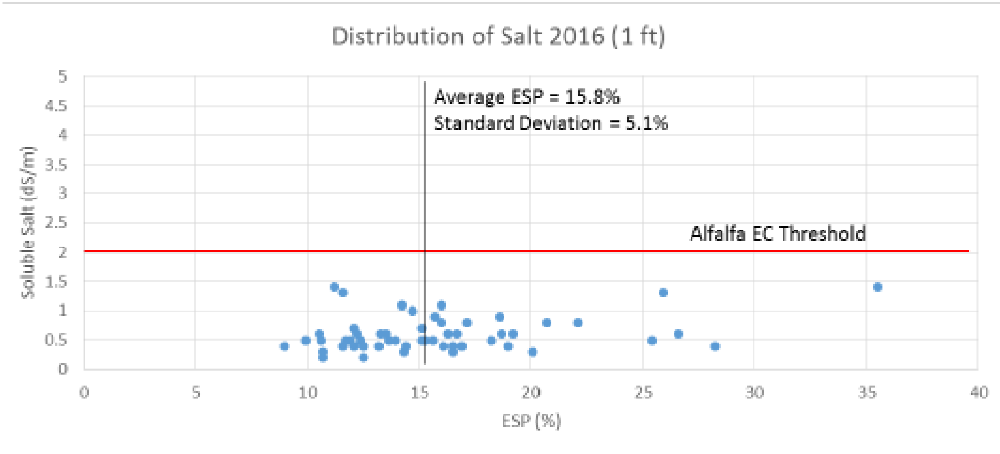

Figure 7. 2016 soil sample results from all fields at 1 foot depth. The average ESP was about 16%.

The data from the soil sampling indicate that indicate that:

1. Salt has accumulated in the managed root zone over time, likely due to insufficient maintenance leaching, appropriate soil amendments, and ongoing application of recycled water with an average sodium concentration of 140 mg/l.
2. Sodium concentrations in the soil are nearing and sometimes surpassing published tolerance threshold values.
3. Based on published threshold values for alfalfa of 2 dS/m, a slight decrease in yield can be expected. This tends to match with the small amount (approximately 10%) of variation in yield throughout different fields.

To further prove or disprove the hypothesis of salt stress affecting yields, a firm was contracted to map soil conductivity. Samples of the resulting maps are shown in Fig. 8.

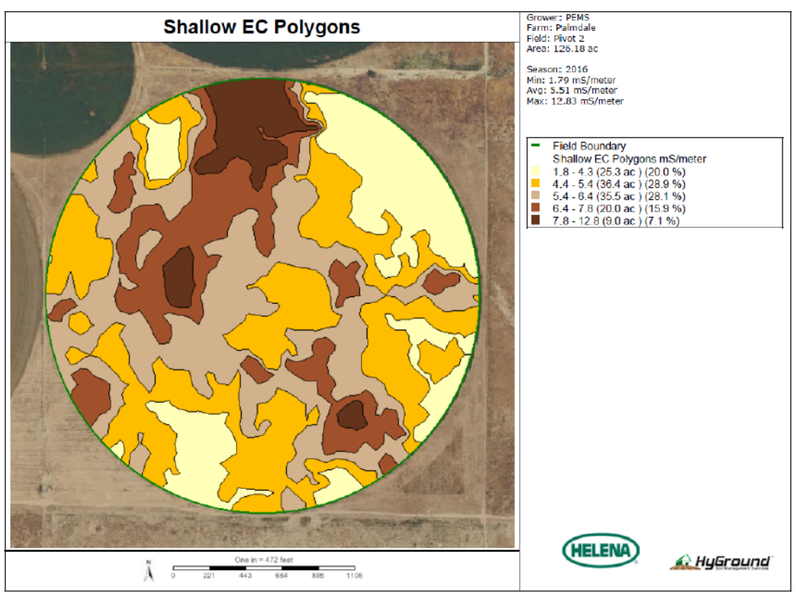

Figure 8. Soil electroconductivity mapping example for one pivot; units in mS/meter

The data output from the soil conductivity mapping are informative, but provided an incomplete assessment when considered separately because:

1. The distribution of conductivity between fields is presented with a different color scale. It may be easy to identify the magnitude of variance within a field, but it is difficult to compare different fields
2. Almost no correlation was found between the soil sample results and the soil conductivity mapping. One possible reason for the lack of correlation is that the mapping involves averaging many points throughout the soil matrix, while the laboratory testing measures constituents from a very limited volume.

The soil conductivity maps provided by the contracted firm were overlain with crop yield and actual crop evapotranspiration maps as shown in Figure 9. Actual crop transpiration maps were developed through satellite imagery analysis following the METRIC-ITRC method.

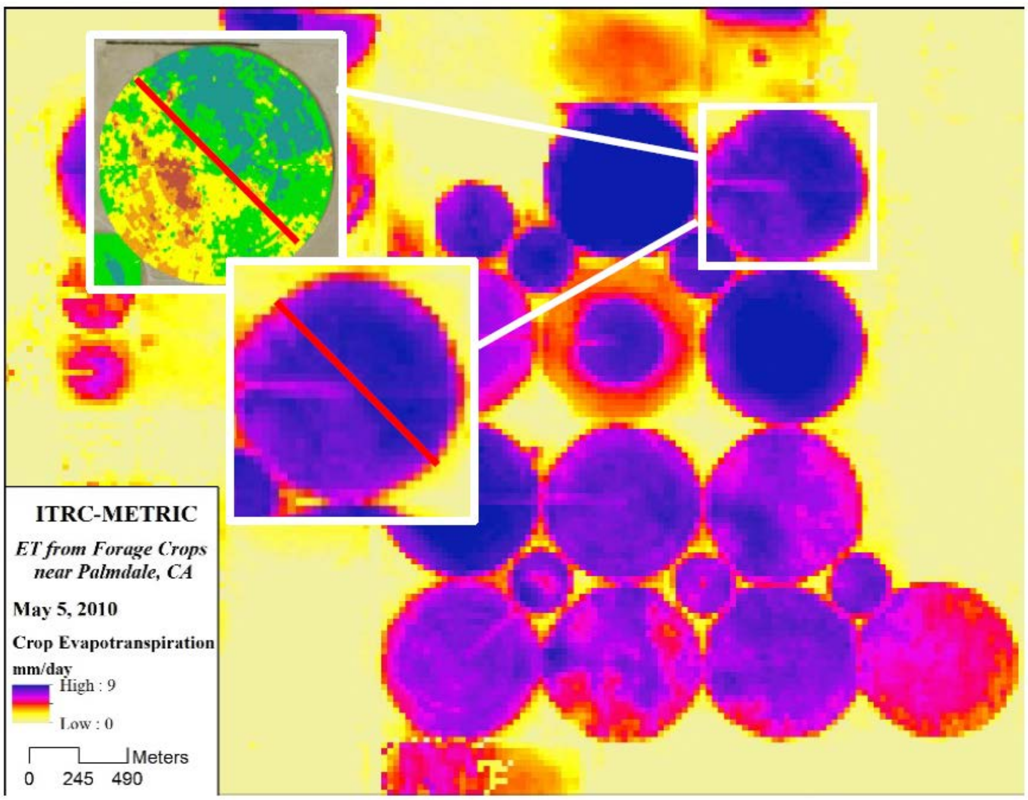

Figure 9. A comparison of crop ET and soil salt maps

The data indicate that there is some correlation between increased salt concentrations and about 10% decrease in yields, which resulted in a recommendation to apply gypsum in order to displace sodium on the cation exchange sites with calcium and subsequent leaching.

Despite the weak correlation between the EC readings and crop yield, it is clear that the sustained use of recycled water in the project results in accumulated salts in the root zone, when less-than-ideal rates of maintenance leaching are performed.

CONCLUSION

Recycled water use for irrigated agriculture can be successful even under strict regulatory oversight. Irrigating with non-conventional water sources also presents new challenges dealing with unique constituents and respective concentrations.

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