Improving Irrigation Water Management — Latest Methods in Evapotranspiration and Supporting Technologies

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Preface

The papers included in these Proceedings were presented during the **USCID Ninth International Conference on Irrigation and Drainage**, held October 11-14, 2016, in Fort Collins, Colorado. The Theme of the Conference was ***Improving Irrigation Water Management — Latest Methods in Evapotranspiration and Supporting Technologies***.

Agricultural producers in irrigated areas of the U.S. are facing significant water supply challenges due to drought, climate change, declining groundwater levels, water demands for environmental uses, and increasing urban and industrial demands. Possible climate change can potentially exacerbate those water supply problems. Critical to managing this challenge is the development of basic knowledge and technologies that allow producers to better quantify and manage crop water demands at the field and irrigation district levels. Likewise, regional water managers need better science and tools to quantify consumptive use and its impact on the regional hydrologic balance.

The Conference aimed to generate discussions on concepts and technologies for measuring and predicting evapotranspiration at different spatial scales, for a range of irrigation management strategies, including limitations. The Conference also addressed issues dealing with institutional aspects of evapotranspiration, as well as other topics of interest to the profession.

The authors of papers presented in these Proceedings are professionals from government agencies, the private sector and academia.

USCID and the Conference Co-Chairs express gratitude to the authors, session moderators and participants for their contributions.

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REAL-TIME MONITORING OF SOIL MOISTURE SENSORS: A TOOL TO MAXIMIZE WATER USE EFFICIENCY

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Tom Penning[1]

ABSTRACT

Irrigated agriculture faces tremendous pressure to maintain yield while maximizing water use efficiency. Global weather uncertainty, along with overdraft of groundwater, has further exacerbated this issue and brought to the forefront the importance of water use efficiency. The irrigation industry in collaboration with the research community have brought many new products and technologies to the market place to increase the efficient use of water. Crop evapotranspiration and soil moisture monitoring being two popular forms of irrigation scheduling. Evapotranspiration (ET) is the measure of two separate but simultaneous process, where water is lost through evaporation from the soil surface and from the crop by transpiration.

The ET estimates for irrigation scheduling, which are available from the various sources, do a great job of providing broad scale irrigation recommendations. However, it is also important to monitor soil moisture status on a field scale during the growing season to maximize yield and reduce plant stress. Availability of moisture stored in the soil profile is dictated by soil texture, bulk density, organic matter content, tillage practices, etc.

Soil moisture monitoring using in-situ sensors is one of the more popular options, used by growers to manage and maintain the moisture in the field. To access the moisture status, the grower has to rely on in-field spot measurements using hand held meters or data loggers. However, it would be easier for the grower to have access to the moisture data in real-time so they could be reactive to change as it occurs. Self-powered, compact "Mesh" networks, can provide real-time access of data from remote field locations, while minimizing the need to run wires in the field. This presentation will cover real-time monitoring of soil moisture sensors and demonstrate associated returns on investment.

INTRODUCTION

Water is an essential component of our everyday life. Both agriculture and urban users compete over water use, while agricultural and urban users compete and debate over water use in arid and semi-arid regions, agriculture accounts for 80% of developed water resources (Letey et al, 2002; Rijsberman, 2006;). In the drought prone Western United States, groundwater is often used to fill the gap between available surface water and water demand for urban, agriculture, environmental, and industrial needs (Gutzler and Robbins, 2011). Additionally, as the world's population continues to grow, achieving global food security—producing enough nutritious food that everyone can access, and doing so sustainably—is one of the greatest challenges we faced by todays farming

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community (Binns, and Lynch,1998). One of the major input into farming practices is irrigation or amount of water applied to crops. In order to apply water to the crop efficiently, various irrigation scheduling methods are used. The most predominant methods of irrigation scheduling are: experience, calendaring, evapotranspiration (ET) based or soil moisture sensor (SMS) based.

This paper explores the potential of taking advantage of soil moisture based irrigation scheduling to maximize yield while minimizing the water footprint.

APPROACH

Irrigation scheduling involves making decision on when and how much water to apply to meet specific agronomic objectives, generally to optimize yield without inducing crop water stress. Effective irrigation scheduling helps augment profit while minimizing inputs such as energy, water, labor, fertilizer etc. The factors that affect irrigation scheduling include the type of crop, stage of development, soil properties, soil-water relationships, availability of water supply, and weather conditions (Aguilar, 2015; George et. al 2000).

This paper focuses on how the use of soil moisture sensor and ET data for irrigation scheduling are complimentary.

Evapotranspiration or ET is the sum total of evaporation or water lost to atmosphere and transpiration from plants. So in a typical irrigation scheduling regime based on ET, we need to replace the amount of water lost in the form of ET as irrigation, on a timed basis (Snyder et. al, 2008).

On the other hand, Soil Moisture based irrigation scheduling relies on detecting the amounts of moisture available in the soil and assists an irrigation manager in applying irrigation so that adequate moisture threshold are maintained (Evett, 2006).

Soil moisture sensor data from a site/sensor could be collected manually using a handheld reading device; recorded using a datalogger; or sent to the cloud at timed intervals using telemetry. Real-time data as well as data that is logged frequently can provide lot of additional useful information which is otherwise lost when data is collected sporadically using a manual collection system. Some of this information includes the wetting and drying trends as dictated by the rate of change or slope of the data.

RESULTS AND DISCUSSION

Here are the findings of this paper:

-ET data provides us the information on the amounts of water needed for irrigation, but a soil moisture sensor working in conjunction could confirm if the amount of water supplied has been efficiently applied and is sufficient in the root zone.

-ET data is mostly available on a regional scale and does not account for site specific conditions, unless a local station is installed. Whereas, soil moisture sensors are installed on site and provide in-situ information.
-Multiple soil moisture sensors are normally installed in a field to encompass soil variability, which could be adjusted with a smart irrigation system or manually by the irrigation manager.
-Real-time monitoring and access to soil moisture status allows for the irrigation manager to be reactive to change, and act accordingly
- Soil moisture sensors are normally installed at various depths in the root zone, using this data the irrigation manager can decide if a shallow or deep irrigation set is required.
-Numerous studies have shown that properly configured soil moisture sensors can significantly save water.
-Granular matrix sensor does not need site specific calibration.

CONCLUSION

Irrigation scheduling tools that can be tailored to a site's specific soils can greatly facilitate the irrigation scheduling decision process. However, in order to tailor site specific soils to the irrigation tools requires calibration of the sensors. Granular matrix sensors like the Watermark sensors do not need site specific calibration and are easy to adapt for decision making process. In implementing an irrigation schedule, all the irrigation manager needs to consider is the rooting depth and the soil type of the site, which helps dictate when and how much water needs to be applied to avoid crop-water stress and maximize yield.

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DEFICIT IRRIGATION STRATEGIES FOR STRAWBERRY IN CALIFORNIA: YIELD PERFORMANCES AND WATER SAVINGS

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Guillaume Sauvageau[1]
Oleg Daugovesh[2]

ABSTRACT

Worldwide, water is a precious resource that is becoming increasingly scarce as the population grows and water resources are depleted in some locations. It obviously affects strawberry production and water cuts are being imposed to many strawberry growers to save water, with limited information on the impact on crop yield and economic performances. Studies were conducted on the sandy loam over 2 years testing different deficit irrigation strategies in comparison with irrigation based on crop evapotranspiration (ET). The most appropriate set points for initiating irrigation was found to be around -10 kPa for both years and resulted in maximum yield relative to irrigation based on crop ET. Deficit irrigation initiating water applications at about -35 kPa resulted in water savings around 25% but caused yield drops around 6% for both years. Meanwhile adopting a variable threshold approach to initiate irrigation generated yield decrease of 2% to 3%, while saving 14% of the applied water. Hence, this crop appears highly sensitive to any hydric stress and given the high value of the crop, further investigation should look at the economies of minor hydric stress on this crop productivity.

INTRODUCTION

In North America, 86% of the strawberry is grown in California, along with Florida (7%), Québec (3.5%) and Ontario (3.5%). Through the whole cycle, the crop is mainly drip irrigated, which provides water savings relative to overhead irrigation. Despite the high efficiency of such an irrigation system, water is becoming increasingly scarce in California, and cuts are being imposed in that production. Irrigation of strawberries is also under increasing control elsewhere. Hence, cuts may be imposed to strawberry growers to save water, but limited information is available on the impact of these cuts on crop yield.

Irrigation approaches

Irrigation can be managed in several ways using timer, personal judgment, weather, plant or soil-based measurements. Among all of them, two approaches are widely used in practice: weather and soil-based measurements. Weather data are used in combination with crop evapotranspiration models to estimate water used by the crop in the past period

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and provide irrigation guidelines on the amount to be applied (Grattan et al., 1998). Indeed, when weather data obtained from meteorological station are combined with a field estimate of crop coefficients, irrigation requirements are calculated and further applied based on the on such information. Alternatively, such estimates may also be used as guidelines relative to personal judgement as it answers the question about how much water to apply over the season. Since this approach requires limited data and equipment to implement it at large scales, it is widely used. However, weather based irrigation scheduling suffers from several limitations. First, it gives an estimate of crop requirements with no field based or soil-based data sets. Ends, the accuracy of this approach varies from field to field due to differences in personal judgment, soil type or other factors leading to over or under watering, as there is no mean to estimate whether the soil is already too dry or too wet when irrigated, which may cause either oxygen or water stresses to the plants because of a bad irrigation timing. Second, this method only provides a global field estimate of the water requirements. However, the soil's capacity to supply water varies from one location to another, but the spatial variability is difficult to identify at the global level without any soil or plant measurements (Périard et al., 2012). Such a global approach could be improved by giving information on the uniformity with additional tools. Drones or satellite aerial imagery can be used with GPS equipped yield monitor or sensor networks. Real time soil sensor could also fit that function. On top of providing information on uniformity of soil moisture, real-time soil data help anticipate water stresses before they are experienced by the plant, and real-time soil based sensors can often lead to significant yield increases (Périard et al., 2012). Thus, some physiological disorders can be avoided by having real time data to anticipate stresses (Périard et al., 2015, Périard et al., 2012). Therefore, improvements in water use efficiency, crop performance and water use are expected by either using a soil based only method or a combination of crop evapotranspiration estimate and sensing technologies to save water. Using real-time sensing technologies do have short comings too; it requires investment in equipment, including fees for service, installation and maintenance. Sensors may shift and water content and tensiometer sensors may need calibration.

Deficit Irrigation

Although strawberry irrigation management has been extensively studied comparing several approaches by different authors (El-Farhan and Pritts, 1997) very few studies have addressed the efficiency of deficit irrigation strategies in strawberries. The recent drought in CA and resulting mandatory reductions in agricultural water use dictate the need to improve irrigation efficiency.

In the weather based irrigation management, the 100% Crop ET requirement is generally calculated on wind speed, relative humidity, irradiance and temperature and a field estimate of crop coefficient from tables or plant coverage estimates (Grattan et al., 1998). In one of the soil sensor based irrigation management approach, the flux of water from the soil to do plant is theoretically linked to a critical soil matrix potential (tension) at which the flux of water coming from the soil to the root may limit plant growth and result in stresses being imposed to the crop (Rekika et al, 2014). The functional link between the two has been described elsewhere (Rekika et al., 2014, De Jong, Van Lier et al.

2006). Rekkika et al. (2014) showed that the critical matrix potential (h_1 asymptotic) at a given depth can be related to the crop transpiration (S_0), the rooting depth (L) as well as the soil capacity to supply water under unsaturated condition (the shape of the unsaturated hydraulic conductivity, described by the alpha α parameter and K_{sG} the field saturated hydraulic conductivity) through Eq. 1.

$$h_{1,\text{asymptotic}} = \frac{1}{\alpha^*}\ln\left(-\frac{1}{\alpha^* K_{sG}}\begin{pmatrix} q_0\alpha^* e^{-\alpha^* L} - q_0\alpha^* \\ +S_0 e^{-\alpha^* L}\alpha^* L \\ +S_0 e^{-\alpha^* L} - S_0 \end{pmatrix}\right) + L \tag{1}$$

Then, a critical matric potential for irrigation h_c is derived from h_1 (Rekika et al, 2014) and is simply the matric potential at the point of insertion of a tensiometer used to manage irrigation and is the point at which the plant uptake is met through the whole rooting depth L. The benefit of an irrigation management approach where the measurements are taken at the beginning of the soil plant atmosphere continuum is the capacity to anticipate stresses before they have occurred. Hence, maintaining the soil water matric potential above the critical threshold within the rooting zone aims at insuring a supply of water fast enough to meet the root uptake. Périard et al. (2015, 2012) have shown that by using this strategy to avoid stress and water limited field conditions, there is a yield gain and reduction in tip burn with lettuce.

Adjusting Critical Irrigation Threshold

The critical matric potential may vary though as the soil hydraulic parameters, like K_{sG}, and α, shown as constants in Eq. 1, evolve in time and space and are difficult to fully characterize (Caron et al. 2016). Indeed, by Eq. 1, h_c is expected to vary during the season because rooting depth (L) and crop ET (S_o) vary. However, as real-time monitoring systems software and controllers can now allow adjustment for increasing root and increasing ET, such adjustments can now be implemented for managing irrigation and generate increased accuracy. Alternatively, a simpler approach would consist in maintaining a lower (-35 kPa) threshold when the roots and the plants are small and move to a higher (-10 kPa threshold) when the plants gets bigger to save water.

The first objective of this study consisted in determining if adjusting the irrigation threshold h_c could increase water productivity without affecting yield for real-time tension based irrigation systems. A second objective consisted of assessing the accuracy of simpler adjustment of critical thresholds to initiate irrigation.

MATERIAL AND METHODS

The five irrigation treatments of Figure 1 were applied through the growth cycle, on a Hueneme sandy loam, in the Oxnard area in California, in a completely randomized block design with 5 replicates. The experimental set up was part of a strawberry grower ranch and the grower managed all cultural operations associated with strawberry production, but the specific irrigation treatments imposed. All replicates consisted of a full length bed 100 m long feet long. Two Subplots located along the bed direction at 33 and 66 m from the beginning of the drip line were marked and consisted of a total of 16 strawberry plants each.

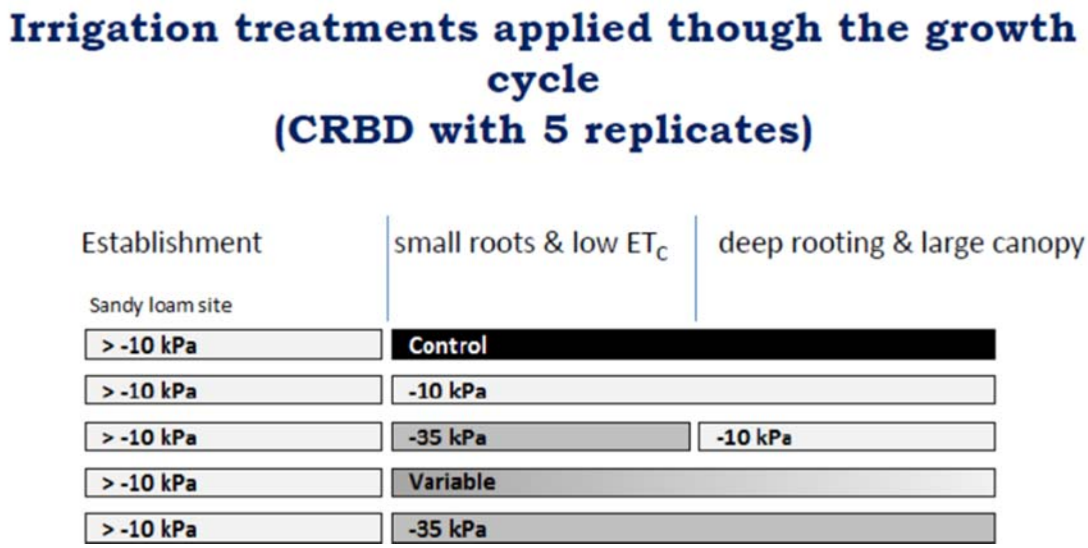


Figure 1. Critical irrigation threshold imposed to initiate irrigation for the different treatment on both years.

Plant Performance and Hydric Stress Measurements

Such measurements were performed weekly from January to June of both years. Yield measurements were conducted on the sub-plots. Fruits were harvested weekly for yield and quality data on the subplots but were harvested for production once or twice a week on alternate other days. Size of the fruits (caliber) and quality (Brix index) were measured once a week on fruits collected on subplots. Plant size (canopy area) were measured with a ruler (Grattan et al. 1998), leaf water potential (LWP) with a pressure chamber, and leaf temperature with an infrared thermometer on four plants per subplot once a week. Yields obtained in both years corresponded to those obtained by top growers from the area.

Soil Sampling and Soil Analysis

These analysis were performed on 3 soil samples per plot taken at the beginning of the experiment for texture, saturated hydraulic conductivity (Ksat), soil water retention curves, electrical conductivity (EC_e or EC_{sw}) and pH. Soil electrical conductivity was measured using the saturated soil extract (SSE) method (1: 1 suspension) to provide an estimate electrical conductivity of soil extractor (EC_e) or that of the soil soclution (EC_{sw}) on soil water samples obtained with a suction lysimeter taken every week within each replicate. The amount of water per ha was measured using flowmeters on the main lines of each irrigation treatment and readings taken weekly (non replicated though).

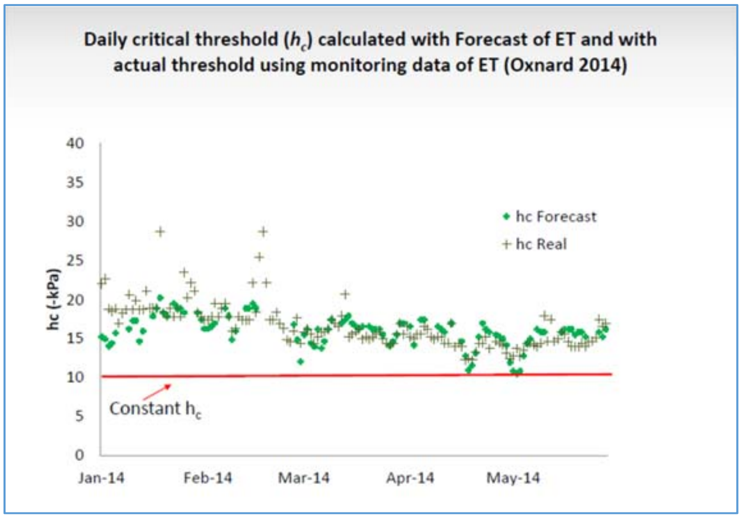
Irrigation Management

From January to June of both years, real time soil water potential were measured at 15 cm and 30 cm (3 reps) using wireless tensiometers collecting data every 15 minutes. Irrigation were either initiated by the irrigator (2014) or fully automated (2015).

RESULTS AND DISCUSSION

Water Use

Previous work has indicated that -10 kPa was the most appropriate irrigation management for day neutral strawberries grown on raised beds (Letourneau et al, 2015). Figure 2 clearly illustrates that this -10 kPa threshold was a little bit on the wet side for 2014 as the critical h_c appears closer to -15 kPa through the whole season. However, such estimate was appropriate for 2015, as the critical h_c line was close to -10 kPa most of the time. Data also indicated that early in the season drier thresholds may have been used, as plants were smaller. Correspondingly, h_c estimate was also closer to -20 and then -15 kPa early in the season.



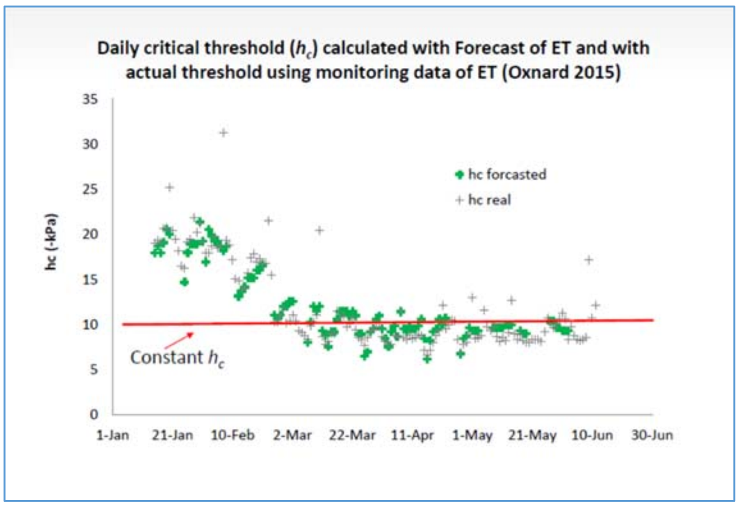


Figure 2. Evolution of the critical threshold h_c during the 2014 and 2015 season in strawberry field in Oxnard, California

This, however, indicated that irrigation management could be initiated at dryer conditions and that maybe water savings be obtained. Figure 3 illustrates the different amount of water used for both years. As expected, the driest treatment (-35 kPa) used 25% less water than the wettest treatment (-10 kPa), which used the highest amount. Partial deficit irrigation were in between, generating savings of 14% relative to the wettest treatment. The grower control was closer to the driest treatment (-35 kPa), possibly because of a general tendency observed now for trying to use less water in agriculture, as a result of a general drought than campaign through the state of California. Relative to crop ET, the wettest treatment used more water on both years, for possibly two reasons. First, the beds were compacted and sometimes run off was observed. Second, differences in variety and growing conditions may explain differences in real uptake in comparison to crop coefficient estimates derived from independent studies performed elsewhere and under different varietal and growing conditions. Data indicated that between 1 and 2 acre foot were necessary to meet crop requirements during that period. As expected, the two partial deficit irrigation treatments generated water savings with values between the wettest and the driest treatment. When averaged on both years (Table 1), the trend remained the same.

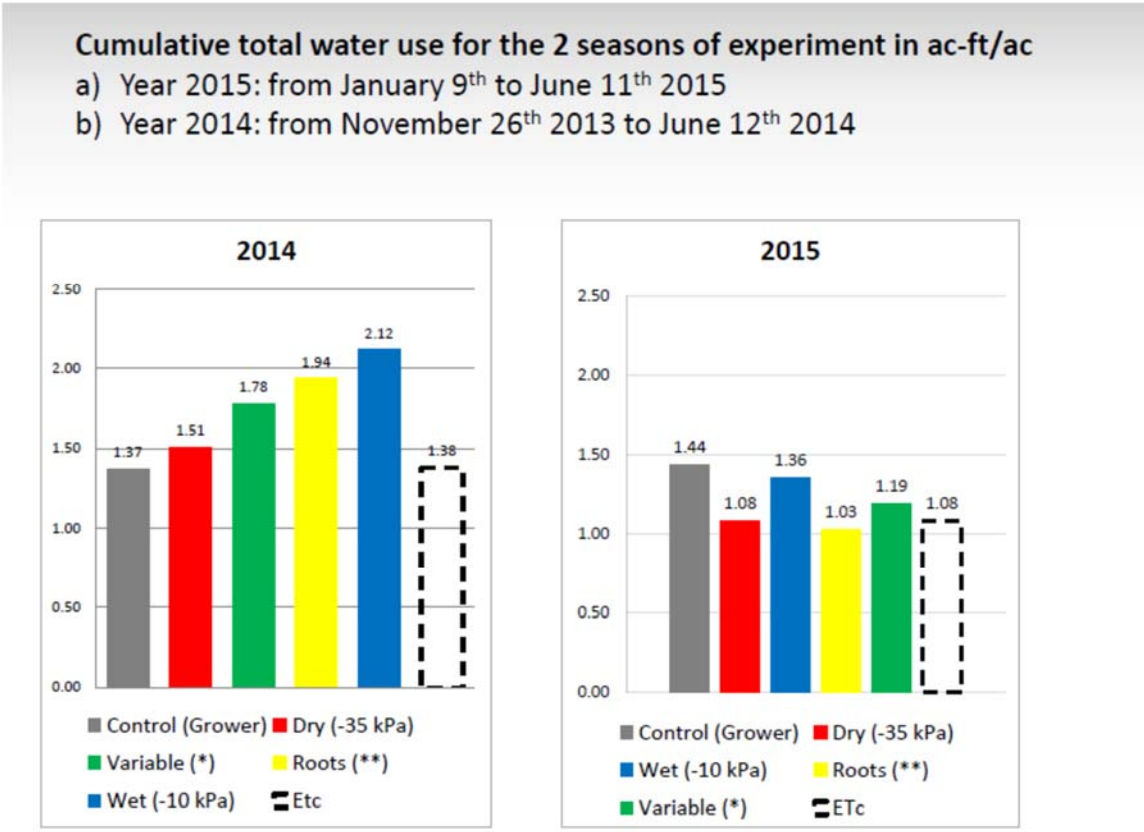


Figure 3. Water use for the wet, the dry and the deficit irrigation treatments for 2014 and 2015.

Effects of crop and soil properties

Despite an impact on water applied, using these different thresholds to manage irrigation, had no visible impact on soil salinity and plant general appearance (data not shown). These thresholds did have an effect on yield though (Table 1). As reported elsewhere, the yield was the highest in the wet (-10 kPa) irrigation treatment relative to the grower (significant at $p = 0.05$), possibly as a result of a more uniform irrigation (Gendron, 2016). The driest treatment also resulted in a yield decrease, not significant though relative to wet treatment. Both partial deficit irrigation generated yield decrease of 2 to 3% on average for the two years. While such decreases were not significant on this site, a more complete study confirmed significant yield decrease with decreasing thresholds from -10 kPa and that decreases of 2 to 3% had a severe impact on the net margin of the crop (Gendron, 2016). Hence, additional work should be performed on additional sites to increase accuracy on yield drops associated with limited stresses to evaluate more precisely the effect of these mild stresses.

Table 1. Yield and water use average for both years

Irrigation treatments	Relative yield [1]	Water used
	%	acre-foot per acre
Grower	92b	1.41
-10 kPa	100a	1.74
-35 kPa	94ab	1.30
Partial deficit		
Roots	97ab	1.51
Variable	98ab	1.49
Reference ET	-	1.23

[1]Numbers with the same letter do not differ significantly at p=0.05 using a protected LSD test.

With respect to the first objective, partial deficit irrigation generated significant water savings. However, data presented here suggest that imposing a deficit irrigation strategy may result in important loss of productivity given the high price of the commodity. This aspect should be given more attention in the future when implementing water cuts and additional work performed to increase precision on the economics of minor water cuts on additional sites, as conclusion may be site-specific. Nevertheless, the crop appears sensitive to any stress. With respect to the second objective, it appears that for strawberries, a simple adjustment of the critical matric potential h_c appears as effective as a more complex one for this sole type. Such conclusion should be tested further though as to crop responds to stress may be soil texture dependent.

CONCLUSIONS

Strawberry appears as a sensitive crop to any water stress as imposing stresses even mild, resulted in 2 to 3% yield decrease with 14% less water than the control. A small deficit irrigation then appears as a strategy which may have an important financial impact for the crop, given the high price of the commodity.

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EVAPOTRANSPIRATION MEASUREMENT AND MODELING IN MID-SOUTH IRRIGATED RICE

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ABSTRACT

Nearly 75% of US rice is grown in the humid mid-South. Rice requires more water to produce than other crops (corn, soybean, and cotton). The identification of rice evapotranspiration and irrigation demand is paramount to understand regional water use and water allocation. Drill-seeded, commercial sized rice fields in Northeast Arkansas were observed under two irrigation managements: continuous flood (CF) and alternate wetting and drying (AWD) in the 2013 and 2015 production seasons. The initial flood after post nitrogen fertilizer application occurs at the same time in CF and AWD. After two weeks AWD fields are permitted to dry intermittently. Two eddy covariance (EC) systems measured evapotranspiration (ET) and CO_2 flux. ET demand averaged 4.36 mm d^{-1}, and 8.66 mm d^{-1} during vegetative and reproductive in 2013 and 2015 respectively. During ripening compounded with a drained field, ET demand was 0.86 mm d^{-1} and 5.51 mm d^{-1} in 2013 and 2015. Measured ET from the EC method was compared to Penman-Monteith/FAO56 and Hargreaves models. The Penman-Monteith model underestimated ET by 5% possibly due to energy gap closure bias from soil heat flux or high humidity. The Hargreaves model overestimated ET especially on cloudy and rainy days. Both models show bias early and late in the production season as field conditions changed from non-flooded to flooded conditions. Daily ET was measured at decreased 25-45% with removal of the floodwater indicating ET may be influenced more by climate and management practices than growth stages. AWD reduced ET demand during draw down events due to decreased evaporation. There was no significant reduction in yield between AWD and CF.

INTRODUCTION

Rice requires more water than other crops produced in the mid-South (corn, soybean, and cotton). Annually, there is enough precipitation and surface water to meet all agricultural demands in this region. However, the production season does not occur during periods of high precipitation which can replenish surface water sources. As a result, most irrigation water is drawn from the Mississippi River Alluvial Aquifer (MRVA). An estimated 80-95% of aquifer withdraws were for irrigation, which decreased groundwater storage via lower storage minima (Arkansas Natural Resources Commission (ANRC), 2014; Döll et al., 2012). Groundwater modeling of MRVA suggests only a fraction of water demand in 2050 will be met with groundwater. Arkansas governance promotes practices that encourage water use efficiency through integrated water management and conservation

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practices to address groundwater decline (Arkansas Natural Resources Commission (ANRC), 2014).

Typically, rice in the mid-south is grown in a continuous 8-10 cm flood after emergence until harvest to meet evapotranspiration (ET) demand and suppress weeds (Smith and Fox, 1973). The flooded conditions mean rice uses more water than cotton and soybeans, so the quantification of water used to produce rice is needed for mid-South irrigation requirements. Cotton ET demand has been measured in the humid southeastern US at 500-600 mm for the growing season (Fisher, 2012), while soybean was measured at 510-660 mm for a fully irrigated crop (Kranz and Specht, 2012). A Mississippi rice study, which follows typical Arkansas rice growing practices, found mid-South rice production requires 355-635 mm of water depending on the cultivar, soil type and weather (Pringle, 1994). Mean annual rainfall in Northeast Arkansas is about 1200 mm, but mean rainfall during the growing season (June-August) is 360 mm, not enough to meet rice crop water requirements alone, so supplemental irrigation is needed. From 2003 to 2012, rice producers in Arkansas applied an average of 763 mm irrigation water (Henry et al., 2016). Therefore, producers apply greater amounts of water needed for rice production with a 46-83% irrigation application efficiency.

One alternative irrigation practice to continuous flooding (CF) is alternate wetting and drying (AWD), also known as alternate submergence-non-submergence (ASNS) or intermittent flooding (Belder et al., 2004; Lampayan et al., 2015; Linquist et al., 2015; Tabbal et al., 2002; Yao et al., 2012). Previous studies in the mid-South concluded rice produced under non-flooded conditions with furrow and sprinkler irrigation are not as economically viable compared to AWD due to yield penalties and increased blast and weed susceptibility (Hoek et al., 2001). AWD can reduce irrigation applied and increase water use efficiency. The increased water use efficiency and reduction in energy use can be attributed to higher capture of rainfall compared to CF rice, and decreased water loss from evaporation, seepage, and runoff (Li, 2001). Clay soils, such as the Sharkey-Steele complex soil have slow percolation which makes the region ideal to grow rice (McKimmey et al., 2008).

Actual amounts of water saved implementing AWD depended on soil type, hydrological conditions, rainfall, and water management practices, particularly the timing and degree to which the soil was dried or how low the water level was allowed to drop below the surface. A review of 31 AWD implementation studies in central-north India, the Philippines, and Japan found an average 23±14% (the second number represents the error if multiple trials were conducted in the experiment) water savings with a 6±6% yield reduction. On-farm experiments in the Philippines found 60% water savings and 25% yield reductions in AWD (water reapplied after disappearing from surface) compared to CF fields (Tabbal et al., 2002). In China, AWD adoption by maintaining groundwater tables no lower than 35 cm below the surface and above rooted depth of soil most of the time during non-submerged periods preserved similar plant biomass and yields and reduced irrigation input by 15-18% (Belder et al., 2004). AWD implemented by allowing the water level to drop 15 cm below surface before re-flooding kept comparable yields to CF, saved 15-38% irrigation water compared to CF in field trials (Lampayan et al., 2015;

Yao et al., 2012). Plot trials of varying degrees of AWD irrigation measured by percent of saturated volumetric water content until flood was reestablished in Arkansas reduced water use by 18% with 0-13% yield declines (Linquist et al., 2015).

Despite potential water savings reported from previous studies, producers hesitate to adopt AWD because of concerns about grain yields, grain quality, and their ability to reestablish a flood in a timely manner. Lack of adoption can also be attributed to conflicting information on AWD management; i.e. how low soil moisture can be without substantial yield loss, when to start and end alternate wetting and drying treatments, land owner/tenant agreements, and limited incentives to adopt AWD practices to discourage water use (Nalley et al., 2015). Groundwater depth, 'severity of treatment' and ability of the soil to hold water greatly affect water use and possible water savings with AWD implementation. Conflicting conclusions of several irrigation studies 'create a demand' for regional studies and hydrological/water use characterizations to assess the extent and magnitude of global water savings with AWD implementation. Previous studies on smaller size plots are easier to monitor and control than production field scales. However, the water usage on the plot scale may not represent field scale usage (Linquist et al., 2015). By monitoring ET, producers can time supplemental irrigation to capture higher amounts precipitation while preventing water stress. Until recently AWD had not been evaluated in mid-South U.S. rice production sized systems (Massey et al., 2014).

Evapotranspiration models have been used and are planned to be used for irrigation decisions in soybean, corn and cotton in the mid-South, including the Penman-Monteith/FAO56 and Hargreaves models studied here (Allen et al., 1998; Hargreaves and Samani, 1985). The current Arkansas irrigation scheduler uses a water balance scheduling method requiring daily air temperatures and effective precipitation (University of Arkansas, 2016). By monitoring rainfall and ET, producers conserve water and capture precipitation while preventing possible water stress. However, implementation and verification of ET models in mid-South rice are limited. Models may have limited utility because of high humidity in mid-South.

The FAO56 equation is universally accepted as the most reliable model because it accounts for all climatic factors that impact reference evapotranspiration (ET_o), specifically wind speed, total radiation, temperature, and relative humidity (Allen et al., 1998; Fisher, 2012). However, given the amount of inputs the FAO56 may not be available at all sites. The Hargreaves model, currently used in irrigation scheduling, determines modeled ET using estimated radiation (from latitude and day of year) and daily maximum and minimum temperatures. The temperature difference estimates cloud cover and evaporation power of the environment (Barnes, 2011; Hargreaves and Samani, 1985; Kebede et al., 2014; University of Arkansas, 2016). The Hargreaves model can make comparable ET estimates to FAO56 despite only requiring two variables. However, the Hargreaves model has reduced sensitivity to climatic inputs because not all factors are included and requires either measured ET values or FAO56 estimated values at least every 1-3 months or during large landscape changes to calculate correction factors. The crop water use (ET_c) can be calculated by multiplying the reference evapotranspiration by a crop coefficient (K_c). The K_c factor can change at different growth stages. (Bezerra et al., 2012).

The goals of this study are to (1) compare ET of two irrigation techniques – continuous flooding (CF) and alternate wetting and drying (AWD) at production sized, zero-grade, hybrid cultivar rice fields in the mid-South United States, (2) validate ET measurements in accordance to Penman-Monteith/FAO56 and Hargreaves models, and (3) use CO_2 flux measurements to illustrate plant transpiration. Previous studies in the mid-South have analyzed AWD focusing on irrigated water onto the field, not water use in comparison to the evapotranspiration (Kebede et al., 2014; Massey et al., 2014)

METHODS

This study uses Eddy Covariance (EC) and heat flux measurements to measure actual crop evapotranspiration to compare to Penman-Monteith/FAO56 and Hargreaves models. The predictive power of the models was compared using the Nash-Sutcliffe model efficiency coefficient and a three day moving average. The coefficient can range from $-\infty$ to 1, where values closer to 1 indicate more accurate models, and a value of 0 indicates the observed mean performs just as well as the model.

Experimental Site

An Eddy Covariance (EC) system was installed in the center of the rice field in 2013 and in the center of the north edge of the rice field in 2015. Two systems were installed on two adjacent zero grade 40 acre fields in Mississippi County near Burdette, Arkansas (35°42'N, 90°4'W). Fields were in a rice/soybean rotation with a predominant South/Southeast wind direction. The soil type was Sharkey Steel complex, characterized by very fine, montmorillonite, neutral soil (pH 5.1-8.4), about 70% Sharkey soil and 30% Steele. Sharkey series soils are characterized by poorly drained clayey alluvium, while Steele soils appear as sandy clayey river deposit in the complex. The soils are mapped together because they intermingle in an intricate pattern that is not practical for soil map scales (McKimmey et al., 2008). Irrigation and fertilizer timings were made according to rice staging outlined in Counce et al., (2000) and cooperating producer management practices.

In 2013 fields were dry seeded with XP 4534 on 10 April. Irrigation started 1 June. Pre-flood treatment of 134 kg N ha^{-1} was ground applied, and mid-flood nitrogen application of 33 kg N ha^{-1} was aerially applied. Fields were drained 8 August and harvested 2 September. In 2015, XL 753 was planted, irrigation started on 30 May, with four applications of urea of 112 kg N ha^{-1} aerially applied on to flooded fields due to excessively wet early season conditions. Both fields were drained 12 August and harvested 27 September.

The thirty-year climate average (1981-2010) used data from Jonesboro, AR (35° 49'N 90°38'W) from the 2015 NOAA National Centers for Environmental Information because of a consistent and complete record. The Jonesboro weather station was located

54.34 km from the experimental site. Due to proximity, conditions at weather station were assumed to represent the climate average. Weather data collected on site including temperature, relative humidity, wind speed, wind direction, and solar radiation were collected on site using weather stations at field site and used for gap filling EC data and ET modeling. Energy balance closure was calculated with latent (LE), sensible (H) heat flux, net radiation (Rnet), heat flux of soil (G), and the rate of change of heat storage (S) following Wilson et al., (2002).

Irrigation Practice

Fields were dry seeded in early spring and flooded at the V4-V5 stage. The continuous flooded (CF) field was flooded with 8-10 cm of water until the field was drained for harvest. Alternate Wetting and Drying (AWD) was applied similarly to Massey et al., (2014). Briefly, weed and disease control including pre-emergence herbicide and broad spectrum herbicide were added after planting. At first tiller (V4-V5) flood was initiated and maintained for at least 10-14 days to stabilize nitrogen and for canopy closure to aid in weed control similar to CF. AWD begins by halting irrigation and allowing the flood to subside naturally through evapotranspiration and percolation to a mud, where floodwaters were then re-established. A flood was re-established at mid-season for nitrogen application in 2013, but not in 2015. A shallow flood was sustained during panicle initiation. The number of wetting and drying cycles achieved depends on weather, soil and field conditions.

Eddy Covariance Measurements

Eddy covariance (EC) measurements were 1 June - 8 September 2013 and 6 June - 24 August 2015. High frequency data (10 Hz) were collected by a three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Logan, UT) with a 10.0 cm vertical path length and 5.8 cm horizontal path length measured fluctuations of wind velocity in three components (u, v, w). Carbon dioxide and water vapor concentrations were measured with a fast response infrared gas analyzer (LI-7500, LI-COR Inc., Lincoln, NE) with a 12.5 cm open path length installed at the same height as the sonic anemometer with a 15 cm separation. All instruments were installed at a height of 2 m above the ground. The gas analyzer stored data at a 10 Hz rate using a 16-bit data logger. The fetch was in the prevailing S-SW direction and extended 400 m. Fast response measurements were averaged over 30 minutes using standard post-processing tools in EddyPro (Version 5.1.1, LI-COR Inc., Lincoln, NE). The footprint analysis followed Kljun et al., (2004). Data were checked and flagged according to a 0-1-2 system (Mauder and Foken, 2006). Density fluctuations compensation were converted to mixing ratios if possible according to Burba et al., (2012). Other instruments included in the tower were batteries and a solar panel to charge the batteries. Negative flux values show sequestration or uptake by the ecosystem while positive flux values show emissions or release into the atmosphere.

Data were filtered by wind direction in 2015 to remove winds not originating from field of interest. Since the system was in center of field in 2013, no similar data removal was needed. About 25% of data were gap filled because data were not collected due to instrument failure or low signal strength, flagged as erroneous, or beyond 5σ from a 5 day moving average. Missing ET values during 0.5-2 hour gaps were filled linearly. While gaps 2-5 hours were filled with measured values that included similar wind speed, wind direction, and temperature in 1-2 hours before and after. ET values beyond the 5-hour gap were not filled and the measured daily value was not computed.

Growth Staging

Rice growth and development was characterized by cumulative leaf numbers in accordance to Counce et al., (2000) for the 2013 season. Growth stages were grouped by morphological developments: vegetative (V4-V15), reproductive (R3-R7) and ripening (R7-R9). One hundred plants were staged over course of season at 2-7 day intervals. Plants were numbered and tagged with plastic markers. Stages were tracked using permanent markers and field notes. Staging began at the V4 stage on 31 May 2013 until harvest. The date at which plants reached certain growth stages were recorded for all 100 plants. However, some plants reached growth stages earlier than others, so an aggregate stage was used to determine divisions in individual stages and morphological developments. Crop development may vary across an agriculture field due to soil variations (composition, aeration, structure, supply of mineral nutrients) and microclimate differences (Leopold and Kriedmann, 1975). In 2015, rice growth and development was determined visually.

RESULTS AND DISCUSSION

Arkansas has a sub-humid climate. Rice production takes place once a year from June to August. Before June, the plants emerge, and they do not require water in delay flood management. Small CO_2 fluxes and ET were predicted and observed. In mid to late August, fields were drained and towers removed for harvest in late August early September. This includes removal of towers from field sites. Ideally, towers would stay in the study fields all year in the same location to capture yearly trends. However, the focus of this study was to look at ET during the production season to inform irrigation decisions.

The summer months of June-August were chosen to represent the production season and averaged 26.4±1.5°C in a 21-32 °C range with 250 mm precipitation in the 30-year climate average. Both 2013 and 2015 had normal temperatures but wetter conditions compared to the average conditions. In 2013, the average temperature was 26.4°C with 282 mm precipitation. While in 2015, temperatures averaged at 25.5°C with 387 mm precipitation (NOAA National Center for Environmental Information, 2015). Higher than normal precipitation prevented more drawdown events to occur in both years. In the future, assuming lower or normal precipitation, investigators anticipate to achieve two or more draw down events similar to previous AWD studies (Linquist et al., 2015; Massey et al., 2014).

No significant difference was observed in the morphological development of rice across the two irrigation managements in 2013. Notable plant developments (leaves/ panicle initiation/ grain development) varied by 1-2 days between CF and AWD fields, the same variation found in individual plants in the same irrigation management. Crop development may vary in the same agriculture field due to soil variations (composition, aeration, structure, supply of mineral nutrients) and microclimate differences (Leopold and Kriedmann, 1975). Delays in morphological development can increase the production season costing more money because of higher irrigation requirements.

In both years, yields were comparable between irrigation managements. In 2013, yields were 9600 kg ha^{-1} (190.5 bu ac^{-1}) and 9300 kg ha^{-1} (184.5 bu ac^{-1}) for CF and AWD, respectively. In 2015, yields were measured at 11000 kg ha^{-1} (214.5 bu ac^{-1}) under CF and 10800 kg ha^{-1} (219 bu ac^{-1}) in AWD.

About 25% of data were gap filled because data were not collected due to instrument failure, low signal strength, flagged as erroneous, or beyond 5σ from a 5 day moving average. This included 13% in AWD and 20% in CF in 2013, and 17% in AWD 20% in CF gaps in 2015. Net CO_2 flux, measured as Net Ecosystem Exchange (NEE), had more gaps in the data, 30% in CF and 13% in AWD in 2013, and 60% in 2015. The majority of the gap data were early in the season. For the purposes of this paper, NEE data were only used anecdotally to explain ET trends.

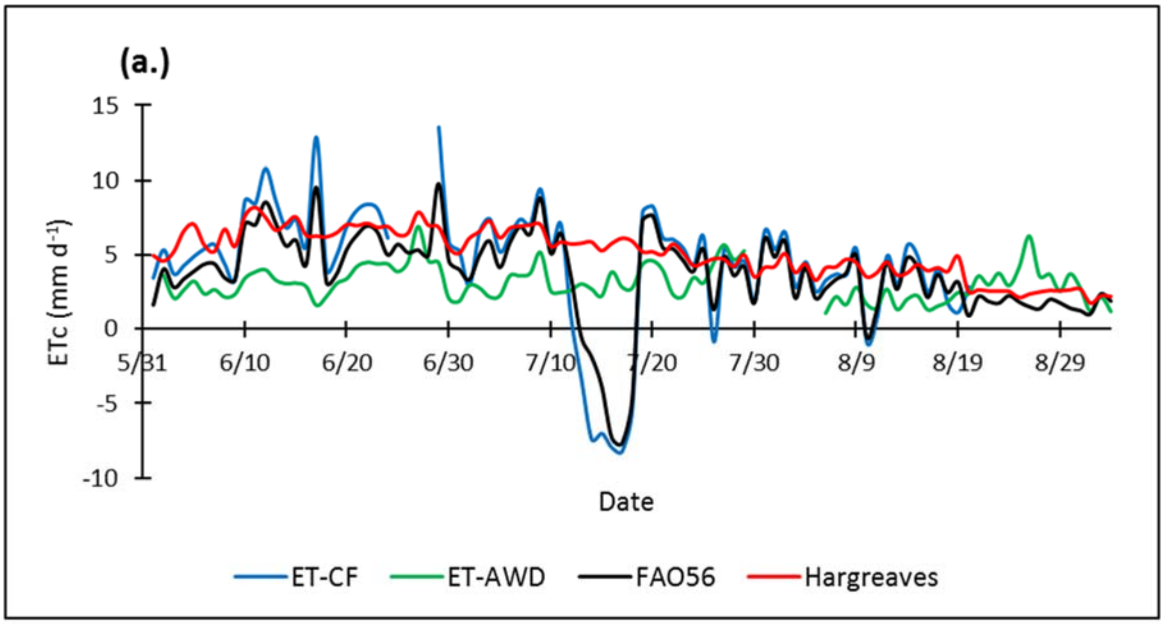
Generally, ET was lowest early and late in the season with the absence of floodwater and lowest plant transpiration demand. ET followed opposite trends to NEE. ET was positive during day and negative at night. Therefore, NEE can be used as an indicator of the transpiration component of ET. The evaporation component was strongly related to solar radiation and temperature, with greater evaporation during higher temperatures and solar radiation. Carbon dioxide flux measurements were not statistically different which suggests similar photosynthesis and evaporation trends in both fields. Therefore, any differences in ET are assumed to be due to changes evaporation, not transpiration. Rice ET demand in both years was significantly lower after removal of flood compared to flooded period which suggests that management practices and climate have greater impact on water use than growth stage as found in previous studies (Li and Cui, 1996; Saito et al., 2005).

Overall ET measured for the season at the CF fields was 343 mm and 655 mm in 2013 and 2015, respectively. In 2013, ET demand averaged 4.36 mm d^{-1} during vegetative and reproductive and 0.86 mm d^{-1} during the ripening compounded with a drained field. In 2015, ET demand was 8.66 mm d^{-1} during vegetative and reproductive growth and 5.51 mm d^{-1} during ripening with a drained field. Similar to 2013, the ET demand during the after draining the field was lower due to absence of floodwater and decrease in evaporation.

In 2013, one drain event occurred on July 10-11. During the non-submerged period, the water depth in field remained at zero. The measured water savings compared to other AWD implementation studies (Alberto et al., 2011; Belder et al., 2004; Massey et al., 2014). The Sharkey Steele complex soil high clay content allows majority of water to stay on field with minimal loss from water percolating into the soil and ultimately the groundwater (McKimmey et al., 2008). However, an extreme drying cycle with water below the surface was not achieved due to continuous cloud cover and precipitation from July 12-18. Differences in measured ET were evident even without an extreme drying event. A negative ET value suggests condensation indicating water added to the system and was observed in the 2013 CF field but not in the AWD field (Figure 1). The lack of negative ET demonstrated the water capture ability of AWD. The AWD field was not submerged before the precipitation, so positive ET values demonstrate how precipitation added enough water to the system for normal evapotranspiration. A reduction of 33% in AWD and CF ET values were measured for the season (considering only values where measurements from both fields were available and of sufficient quality) were 209 mm and 309 mm, respectively.

In 2015, one drawdown event was observed in early July. The AWD field did not have any pumped water from June 25 to July 14 while the CF field had 5.3 cm water applied measured by flowmeters installed at irrigation well. The soil moisture at 7.5 and 15 cm depth was measured near 40% of the saturated soil volumetric water content before flood was reestablished on July 14 (Figure 2). For the season, there was no significant difference in the total amount of water applied. Irrigation management did not change the overall trend of carbon capture in rice plants. In both years, later drawdown events were not achieved due to high precipitation. No significant difference in AWD and CF ET values were measured for the season (considering only values where measurements from both fields were available and of sufficient quality) and were 365 mm and 377 mm, respectively. The similarities between fields in 2015 were most likely due to the shorter duration in 2015 compared to 2013 where field was dried. time where the 2015 AWD field was dried.

All model comparisons were made between the CF field and modeled crop evapotranspiration (ET_c) values. In both years, FAO56 and Hargreaves model were consistent with ET measured with the eddy covariance technique (Figure 1-2) but have bias early in the season and late in the season (standard residual >2) when the environment changes from a non-flooded to flooded, then to non-flooded conditions again. Hargreaves cannot be used to estimate hourly or half-hourly fluxes because the model uses daily temperature maxima and minima to estimate cloud cover and daily evaporating power. Moreover, the Hargreaves method daily estimates may be influenced by large variations in wind speed and cloud cover, and therefore recommended to use in 5-days or longer time steps such as yearly or multi-yearly (Hargreaves and Allen, 2003). The FAO56 model used the typical rice K_c curve (K_c=1.05 (early vegetative), 1.2 (mid vegetative to early reproductive), 0.2 (late reproductive) and shows strong agreement with the actual measurements.



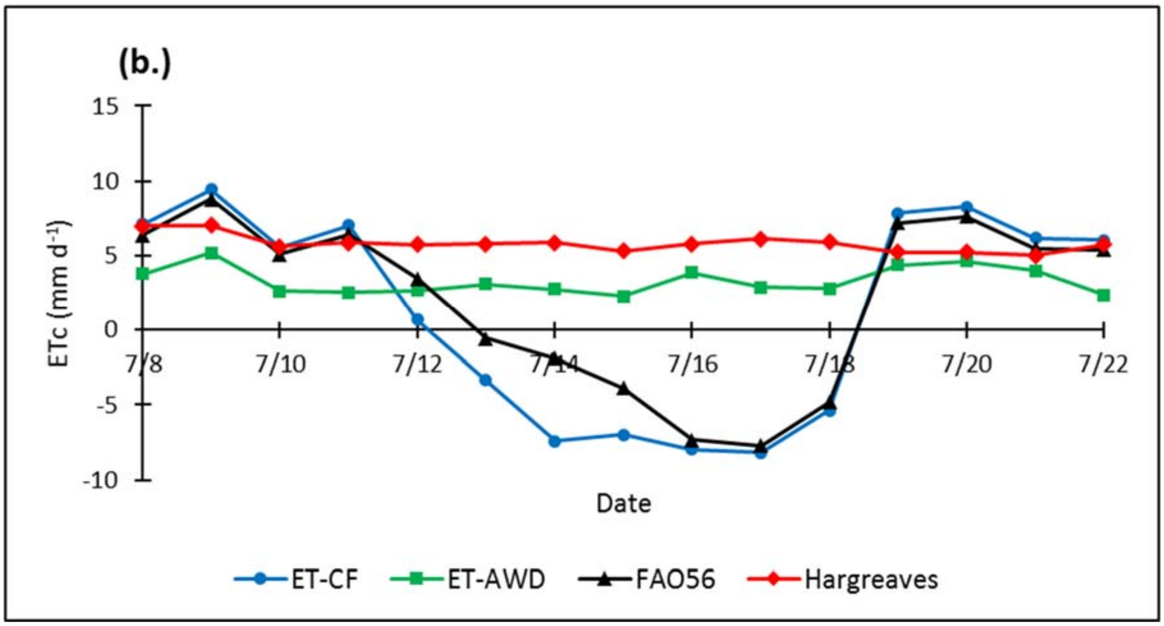


Figure 1. Comparison of crop evapotranspiration (ET_c) measurements in 2013 of rice grown under continuous flood (CF) and alternate wetting and drying (AWD). Measured ET_c is compared to Penman-Monteith/FAO56 model (FAO56) and Hargreaves model (Hargreaves) calculated values for (a.) the entire season and (b.) highlighting the drawdown event on July 13.

The Hargreaves model more closely matched measured ET_c trends after applying a correction factor as instructed in model calculations (Hargreaves and Samani, 1985). Correction factors included crop coefficients (K_c) were adjusted every 1-2 months of measurement or during ecosystem or environmental changes, and calculated by comparing to FAO56 estimates or actual ET measurements with regression analyses. In this study, different correction factors were added for after draining field than during the flooded period. This correction factor was 1.2-early to mid-vegetative, 1-mid vegetative to reproductive, and 0.5 for ripening development and drained field conditions in 2013, and 1.7 for vegetative and reproductive growth, 1 for drained field conditions in 2015. Correction factors were adjusted during large changes in landscape. In 2015, an additional correction factor during reproductive and ripening stages was not added possibly due to abnormally wet year (nearly 100 mm extra precipitation than 30-year average). Season ET demand was calculated by adding daily ET demands (Table 1).

In 2013, the FAO56 model was found to correlate with actual measured ET, while the Hargreaves model overestimated ET. The FAO56 model predicted ET accurately during majority of the season, capturing negative ET during cloud cover and precipitation (Figure 3a), Nash-Sutcliffe coefficient (NSC) at 0.753. The Hargreaves model predicted greater ET_c than measured and did not predict ET_c as accurately FAO56 (NSC=-0.323). The Hargreaves model did not measure negative ET or capture changes in ET due to continuous precipitation and long periods of cloud cover, (red circle in Figure 3b). A negative ET indicates condensation, or water added to the system. However, the short term of this measurement (days) may indicate a numerical consequence of system and/or associated water balance.

Table 1. Season ET demand compared to FAO56 and Hargreaves models in continuously irrigated fields.

Year	Measured ET demand from Continuous Flood (mm season^{-1})	FAO56 (mm season^{-1})	Hargreaves (mm season^{-1})
2013	343	345	485
2015	655	725	659

This deposition was captured in the FAO56 model (Figure 2 and Figure 3a) from July 13-18. In addition, the Hargreaves model can overestimate ET_c up to approximately 40% in calm, humid and clouded areas (Barnes, 2011). However, when the negative ET values were not considered in the comparison, the Hargreaves model modestly improved performance (NSC=0.244). This improvement may be helpful when not all meteorological data are available at a site. However, the Hargreaves model requires comparisons to the FAO56 model at least every 1-3 months or when site conditions change to calculate correction factors for ET_o and ET_c similar to the K_c value.

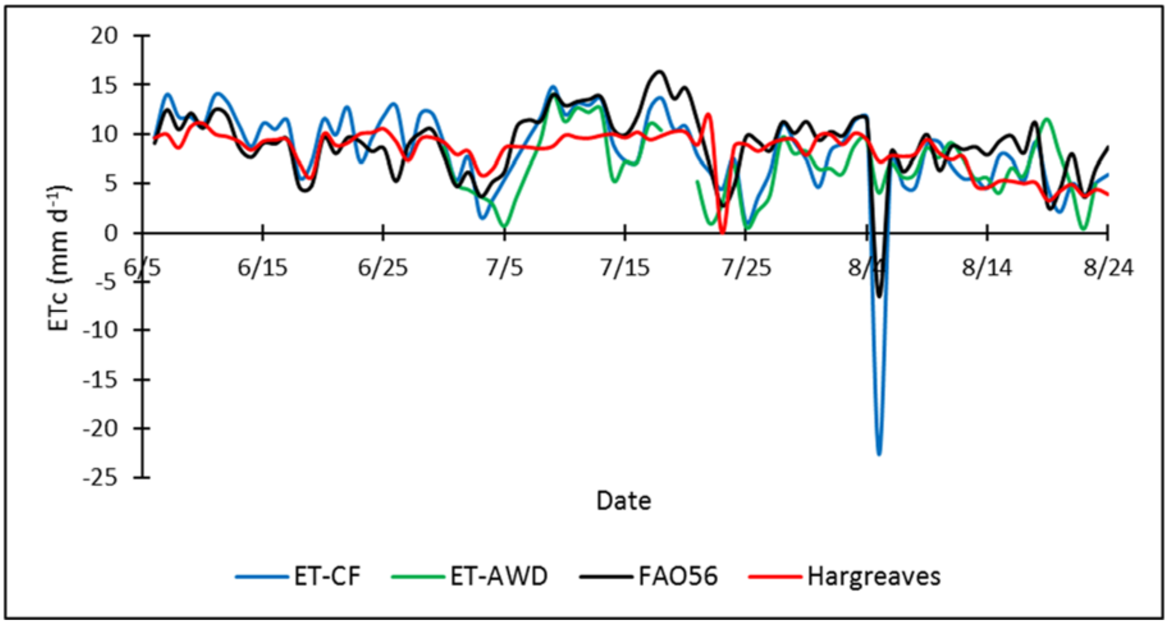


Figure 2. Comparison of crop evapotranspiration (ET_c) measurements in 2015 of rice grown under continuous flood (CF) and alternate wetting and drying (AWD). Measured ET_c is compared to Penman-Monteith/FAO56 model (FAO56) and Hargreaves model (Hargreaves) calculated values.

Higher ET values and model inaccuracies in 2015 compared to 2013 could possibly be due to greater wind speeds, higher average solar radiation, and higher precipitation measured in 2015 (1.82 m s^{-1}, 248 W m^{-2}, and 287 mm, respectively) than in 2013 (1.56 m s^{-1}, 224 W-m^{-2}, and 271 mm, respectively). The FAO56 model did not predict values as similar to measured values in 2015 (NSC = 0.291) but performed better than did Hargreaves model (NSC = -0.322) as shown in Figure 2 and Figure 3.

Usually the FAO56 model may slightly underestimate demand due to small aerodynamic term and lack of local calibration of temperature measurements to model (Allen et al., 1998). On average, FAO56 predicted values were 5% less than measured values in 2013. Alternatively, the difference may be due to issues with energy balance closure. For the growing season of energy balance ratio was 0.774, with the following linear fit: ($y=0.5x+48.19$, $n=983$, $R^2=0.80$). The sensible and latent heat flux (H+LE) were overestimated compared to Net radiation, soil heat flux, and rate of change of heat storage (Rnet-G-S). Consistently measured G was 2-4 factors off predicted G flux computed as (Rnet-H-LE). Compared to net radiation, G is still small. Therefore, a large difference between the measured and predicted soil heat flux did not significantly impact the energy balance closure. Ideal closure is rarely achieved in the Eddy Covariance method because difficulty measuring soil heat flux and differences between heat transfer of water and gases of interests (Wilson et al., 2002).

However, in 2015, the FAO56 model overestimated the ET. This overestimation may be due to the energy balance closure as explained above or atypical large amount of precipitation in the 2015 growing season.

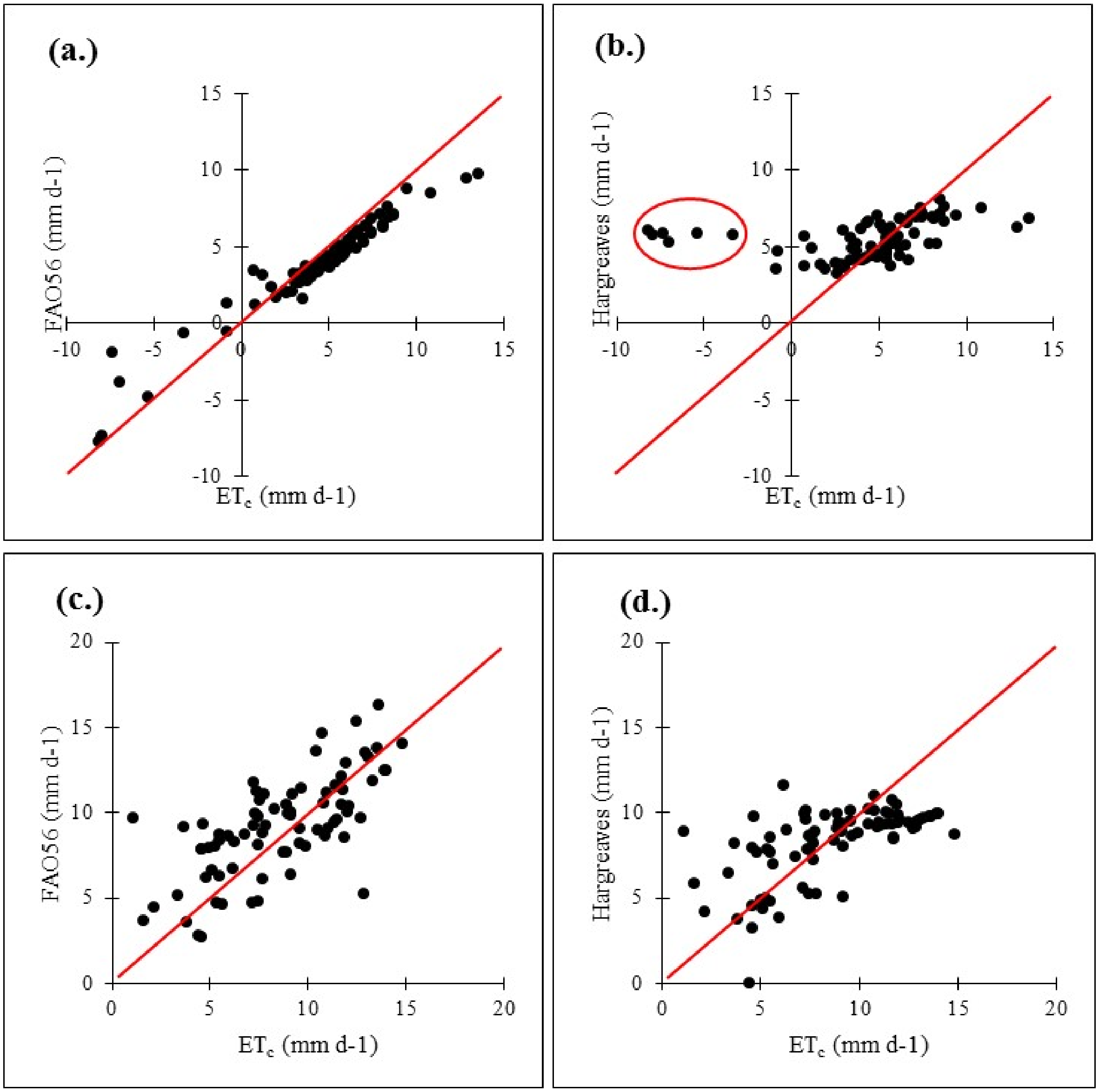


Figure 3. Crop evapotranspiration (ET_c) and model comparisons in 2013 (a.) FAO56 and (b.) Hargreaves and in 2015 (c.) FAO56 and (d.) Hargreaves. In (b.) the Hargreaves model does not account for continuous cloud cover and a severe rain storm in 2013 and cannot accurately predict ET.

CONCLUSION

Application of alternate wetting and drying (AWD) to a production size rice field reduced seasonal ET by 33% when compared to continuous flood (CF) in 2013 and no significant reduction in 2015. The degree of drying impacted the differences in measured ET as did the meteorological conditions. Seasonal ET demand measured was 342 mm in 2013 and 655 mm in 2015 at the CF field and was found to be influenced more by climate and management practices than growth stage. The Penman-Monteith/FAO56 model predicted ET accurately throughout the crop growing season, with a standard K_c curve in 2013. The corresponding Nash-Sutcliffe coefficient was adequate NSC = 0.753 in 2013 and it was preformed moderately better in 2015 (NSC = 0.291). The Hargreaves model overestimated ET demand during continuous cloud cover and precipitation and required calculated correction factors from the FAO56 model (NSC = -0.323 and -0.322). The FAO56 model underestimated fluxes possibly due to and energy gap closure bias from soil heat flux that was 2-4 factors off from predicted flux in 2013, and overestimated flux in 2015 possibly due to energy gap closure or atypical large amount precipitation in 2015. There was no significant impact on harvest yield with AWD and CF in either year studied. This study recommends AWD irrigation on the field scale to address the declining water resources and save irrigation costs. Careful consideration to the 'severity' of the drying events must be considered.

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PREDICTING RIVER EFFICIENCY IN THE RIO GRANDE PROJECT

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ABSTRACT

Surface water losses in the Bureau of Reclamation's Rio Grande Project have become more prevalent within the past few years. Simple regressions were performed in order to find correlations and determine factors that may affect the flows within the Rio Grande Project. Groundwater levels data was taken from a United States Geological Survey well section in the City of Las Cruces, New Mexico. The well section is located in a major losing reach of the Lower Rio Grande River. Groundwater levels and the diversion ratio were found to be highly correlated for certain wells. Groundwater levels have been declining in this section as the diversion ratio has also been declining. A declining diversion ratio points to dropping groundwater levels. The previous year's groundwater levels could potentially be used to get an estimate of the diversion ratio for an upcoming irrigation season. Wells LC-2A and LC-3A had the highest r-squared results for predicting the upcoming irrigation season's diversion ratio using the previous year's groundwater levels. The best prediction of the diversion ratio was with LC-2A USGS approved data with an r-squared value of 0.85, and the correlation was: Diversion Ratio = 1.542 – 0.024 (Previous Year's LC-2A depth in feet). Increased Caballo Reservoir release amounts from high storage and/or snowmelt runoff could potentially increase groundwater basin storage and increase the diversion ratio for the Rio Grande Project.

INTRODUCTION

The Rio Grande River begins at the headwaters in the San Juan Mountains of southern Colorado and flows down to its mouth in the Gulf of Mexico near Brownsville, Texas (TX). The flow of the river from the headwaters in Colorado to El Paso County, TX is mostly supplied by winter precipitation that falls in the San Juan Mountains of Colorado, and to a lesser extent in the mountains of northern New Mexico (NM). A series of dams were built along the river in order to collect the spring snowmelt hydrograph and store it for agricultural use later on in the season. Irrigation water is typically released throughout the spring, summer, and fall months in order to provide water for farms and for municipal uses as well.

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This study focuses on a part of the river sometimes referred to as the “Lower Rio Grande” but is also known as the Bureau of Reclamation’s “Rio Grande Project” (RGP). The Rio Grande Project begins with Elephant Butte and Caballo Reservoirs located in Central New Mexico and ends at the Fort (Ft.) Quitman gaging station in Ft. Quitman, TX. The river water in this section is reserved mainly for irrigation in southern New Mexico and El Paso County, TX, but is also used directly for municipal purposes by the City of El Paso, TX, and indirect municipal uses by El Paso TX, Las Cruces, NM, and other municipalities in or near the valley, as well as industrial uses. Indirect use is when groundwater that is extracted leads to lower return flows into the river and causes greater canal and river losses as well. Most of the Project water released in this area gets used before it reaches the Ft. Quitman gaging station. A series of negotiated agreements allow for water to be allocated to different sections of lands and water rights owners within this river segment. Three major entities split the river water in this section. One of these entities is in Southern New Mexico and is named the Elephant Butte Irrigation District (EBID). Another entity is part of El Paso County in Texas and is known as the El Paso County Water Improvement District #1 (EP#1). The last entity is the country of Mexico. The two irrigation districts and the Bureau of Reclamation are bound by an “Operating Agreement” (USBR, 2015) which allocates a certain amount of water to each district and Mexico according to irrigable acreage, current and forecasted supply, and treaties and laws.

The water supply from the Rio Grande is vital for the livelihood of farmers and for the city of El Paso. The river diminishes the necessity to pump groundwater in order to supplement the city’s drinking water supply. In the desert southwest, the river is critical for meeting all water needs.

The deliverable water amount in the Rio Grande Project depends on the snowmelt runoff forecast and measured inflow at the Rio Grande at San Marcial, NM gaging station, as well as current credits or debits as per the Rio Grande Compact. Treaties, compacts, and other agreements allow for the allocation of water to separate entities in Colorado, New Mexico, Texas, and the country of Mexico. Federal, state, and local agencies all take part in accounting for the water that gets delivered and transferred.

One parameter of importance to the Operating agreement and the water accounting for the Project is the “diversion ratio.” The diversion ratio is the total diversion volume divided by the total volume of water released from Project storage from Elephant Butte Reservoir (1918 to 1938) and Caballo Reservoir (1938 to present). This is called the “raw” diversion ratio and is shown in Equation 1. Since the inception of the 2008 Operating Agreement (USBR, 2015), the calculation of the official diversion ratio changed (Equation 2), which will be explained later, but it has not been different from the “raw” diversion ratio in recent years (personal communication with Filiberto Cortez of Reclamation and member of the RGP allocation committee, 2015). The diversion ratio is an indicator of the losses or gains in the river.

Diversion Ratio (Pre Operating Agreement) = Total Diversions / Total Project Release (1)

Diversion Ratio (Post Operating Agreement) = Total Charges to Mexico, EBID, and EP#1 / Total Project Releases (2)

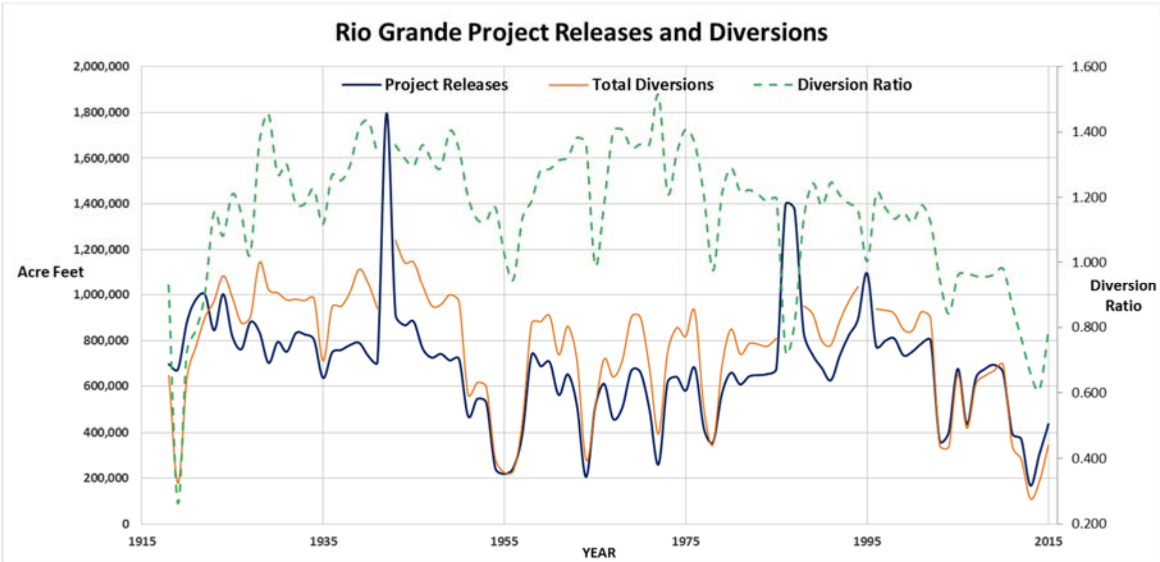

Figure 1. Rio Grande Project Annual Releases and Diversions, 1918 to 2015 (USBR, internal) Source: internal data from U.S. Bureau of Reclamation – El Paso (unpublished)

The diversion ratio has typically had a value greater than 1.0 since the Rio Grande Project began delivering water, with an average diversion ratio of 1.18 from 1919 to 2010 (Figure 1). This means that the performance of the river has been above 100% for the majority of the Project history, and that more water was diverted downstream at the delivery points than the volume released from Project storage. Some exceptions were the early years of the project from 1918 to 1922, 1956, 1978, and the wet years of 1986 and 1987. The accretions were due to return flows from drains that were supplementing the river flow. One of the purposes of the drains is to collect excess salts so that agricultural crops are not harmed by water logging or excess salinity (Weeden and Maddock, 1999). This system of drains allows for the return of irrigation water from irrigated fields and canal seepage, as well as groundwater seepage to reenter the river system once again during periods where groundwater levels are higher.

Since 2010, the diversion ratio has been consistently falling below 1.0, even falling as low as 0.61 in 2014, the lowest diversion ratio since 1922. Even during the severe drought of the 1950's, the lowest recorded diversion ratio during this period was 0.95 in 1956. The only other time this happened was during the 1918 to 1922 period, which also saw an unusual period of low diversion ratios, one as low as 0.27 in 1919. After this period, the diversion ratio has been above 0.94 up to the year 2004 when it dropped to 0.84, then back up to 0.95 and above for the next six years to 2010, before falling consecutively during the drought years of 2011 to 2014.

The reasons for this points to groundwater levels, and/or increases in groundwater pumping. According to Nickerson and Myers, 1993, “groundwater pumping for irrigation of crops accounts for much of the annual groundwater withdrawal in the Mesilla Valley” and “the significant increase in population within the Mesilla groundwater basin and adjacent areas has resulted in competition for existing groundwater resources” (Nickerson and Myers, 1993). Also, the operating agreement, which was enacted in 2008, adjusts allocations of surface water to account for increased groundwater pumping by New Mexico farmers at the expense of less surface water deliveries. As groundwater pumping across the region rises during drought years in order to alleviate the reduced surface water allocations, the groundwater levels drop and more surface water losses occur in the river. The New Mexico farmers are then forced to turn to use groundwater to make up the decrease in Project surface water (Bushnell, 2013). Pumping induces even more surface water losses resulting in a downward spiral of surface water losses for Southern New Mexico farmers during drought years

These losses are calculated after the season, and can be troublesome for water managers who forecast a certain amount of water to be released, but less water is able to be diverted to the farmers and municipalities later on in the year. Currently, the previous year’s diversion ratio is used to forecast the present year’s diversion ratio, or estimated losses or accretions.

The purpose of this study was to find factors and possibly predictors for the losses in the river system in the Rincon and Mesilla Valleys. These factors and predictors could aid water managers in making decisions that could improve the efficiency in the Rio Grande Project and help stakeholders in the region who depend on the river. A predictor for the diversion ratio in the river would be a good management tool for water managers to use for an upcoming season so that farmers and stakeholders can better plan crop cycles and choices, and water usage.

METHODOLOGY

For this study, Microsoft Excel was used for the regression analysis of many comparisons. Aquarius Time-Series software by Aquatic Informatics was also used for compiling data into annual averages.

The groundwater levels used for this study were the LC-2 and LC-3 sections of groundwater wells A-A’ (Figure 2) managed by the USGS within the city of Las Cruces, NM.

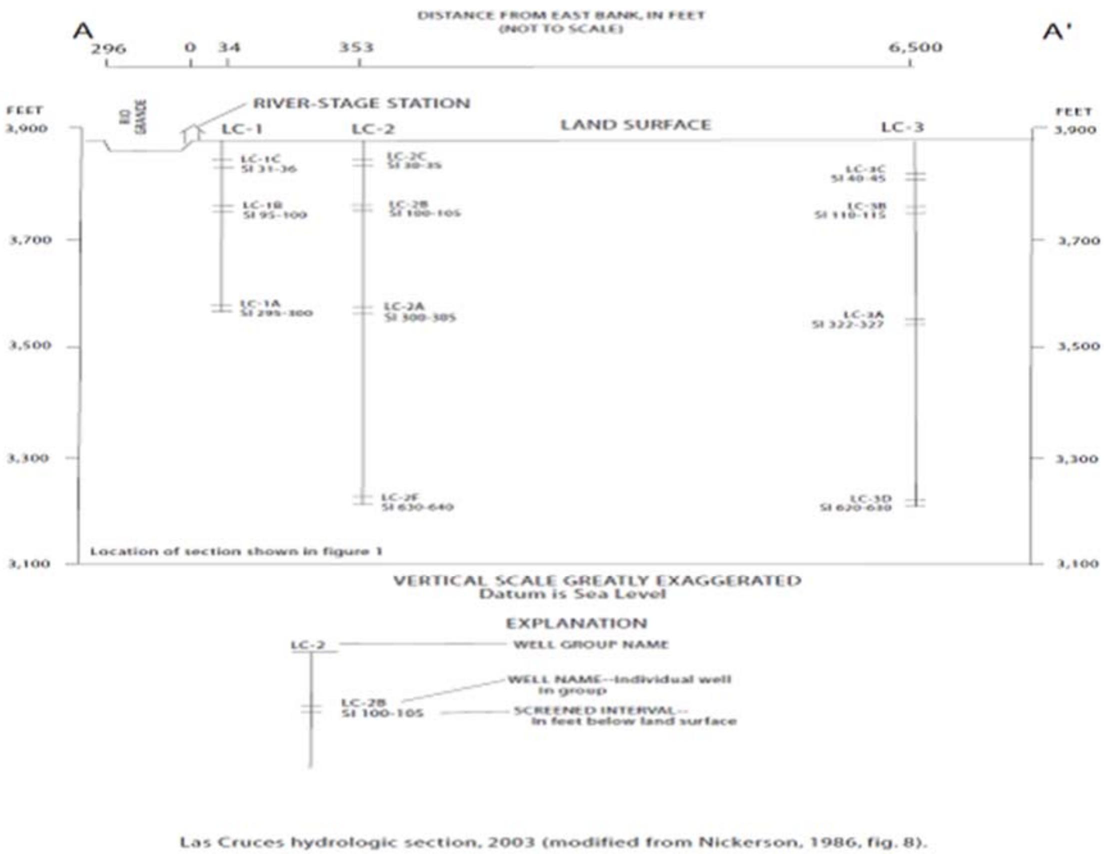

Figure 2. USGS Las Cruces Well Field (USGS, 2015)

Before the enactment of the Operating Agreement of 2008, the diversion ratios were calculated by summing the annual diversions measured at the main diversion points. This included return flows from drainage canals throughout the entire year. The main diversions were the diversion to Mexico, Leasburg Canal, Westside Canal, Eastside Canal, Del Rio Lateral, Riverside Canal, and Franklin Canal. When the Operating Agreement was enacted in 2008, the calculation of the diversion ratio was changed to Equation 2. The total charges/diversions were only for the irrigation release season, and not the entire year as before, which would not include any diverted return flows during the irrigation offseason. As mentioned earlier, the diversion ratio in the Operating Agreement has not been much different from the “raw” diversion ratio in recent years (personal communication with Filiberto Cortez of Reclamation and member of the RGP allocation committee, 2015) most likely because offseason return flows were not considered substantial during these years. In this study, the raw diversion ratios were calculated using Equation 1 for years 1918 to 2010. In years 2011 to 2015, the diversion ratios in Equation 2 were used and were also confirmed with Filiberto Cortez of Reclamation. The charges in Equation 2 are the gross charges/diversions and did not include adjustments and credits, for this study.

The Mesilla groundwater basin observation well network was established in 1983 to monitor groundwater levels. The Las Cruces observation well section is at the western edge of the City of Las Cruces, NM. Observation well groups at the Las Cruces hydrologic section are completed in the Rio Grande flood-plain alluvium/Santa Fe Group aquifer system at depths ranging from 30 to 327 feet below land surface. The shallow floodplain alluvium LC-C wells are at depths ranging from 30 to 45 feet below land surface. The LC-B wells are completed in the Santa Fe Group at depths ranging from 95 to 115 feet below land surface. The LC-A wells are also completed in the Santa Fe Group at depths ranging from 295 to 327 feet below land surface (Figure 2). Water levels in the LC-B and LC-A wells represent the potentiometric head at depth within the upper Santa Fe Group (Nickerson and Myers, 1993). Estimated aquifer thickness at the Las Cruces hydrologic section is about 3,800 feet (Hawley, 1984, pi. 6). Wells LC-2F and LC-3D are about 700 feet deep and are in a section from 400 feet to 1400 feet below the water table where sand and gravel are most common, followed by silt and clay sediments (Wilkins, 1998; Myers & Orr, 1985).

These wells were chosen because the data collected from these wells is continuous and instantaneous, and in some cases, goes back to 1985. Also, this data goes through a thorough review process. Only these sections from the USGS Mesilla Groundwater Monitoring network contained real-time continuous data up to 2015. Other sections contained groundwater level measurements, but were sporadic and not continuous. The LC-1 well section had instantaneous data only up to 2010. Therefore, the data from the other sections would not represent a fair average of the changing groundwater levels throughout a given year, or take into account the lower diversion ratios in recent years. At the time of this analysis, the groundwater data from 1985 to 2015 had been reviewed and approved by the USGS. Thus, more data was available from these sections in order to study this correlation.

The diversion ratio was compared with the annual average groundwater depths of all LC-2 and LC-3 wells. Some wells such as LC-2B, LC-2F, and LC-3D had missing data for a number of years, and/or had missing data during some of the year making the averages unrepresentative of an actual annual average. Therefore, these wells were not considered to be accurate for analyzing the connection between the diversion ratio and groundwater levels at this time. The diversion ratios for years 1986, 1987, and 1995 were not used in this analysis due to the unusually high release volumes during these years, which would have decreased the diversion ratio because of the higher waste of water during these years, and would not be representative of a "normal" year of a full allocation of around 700,000 acre feet where water would be used more efficiently (Figure 1). During these high release years, release volumes would have surpassed demand, as opposed to average years, where water is released only to meet demand. Incomplete annual groundwater level averages were not included in these evaluations. Averages were considered to be incomplete if there were a few months of data gaps for a given year.

RESULTS

A correlation was discovered between the diversion ratio and groundwater levels in the Mesilla Valley Region of Southern New Mexico. The correlation is a strong indicator hat groundwater levels play a key role in river losses. Better collection of well data will need to be ensured, and further future analysis of this correlation will need to be performed if this correlation is used for predicting future diversion ratios in this river system.

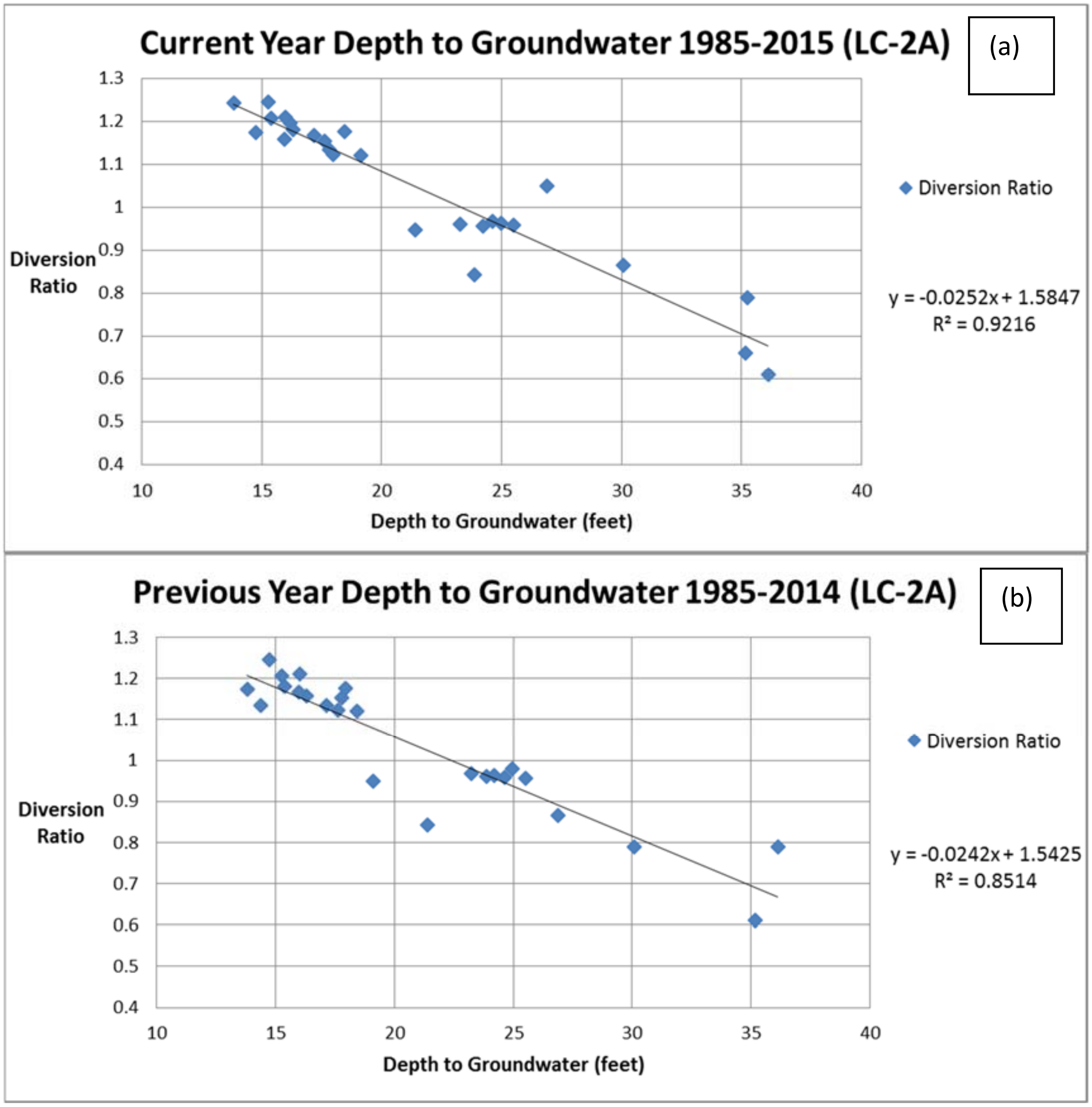

Figure 3.Well LC-2A; Diversion Ratio (USBR, unpublished) & (a) Current Year Depth to Groundwater (USGS, 2015)), 1985 to 2015. Diversion Ratio (USBR, unpublished) & (b) Previous Year Depth to Groundwater (USGS, 2015), 1985 to 2014

From these results, the best fit current year models occur for wells LC-2A (Figure 3a), followed by wells LC-3A ($R^2 = 0.89$) and LC-3C ($R^2 = 0.86$). Wells LC-2A, LC-3A, and LC-3C are well represented by a linear fit model, as opposed to LC-2C which is best represented by a power fit trend. Well LC-2B had high r-squared results ($R^2 = 0.93$) with a power fit trend, but there were not enough data points to conclude that it is an accurate predictor for diversion ratios. Well LC-3C had high r-squared results, but years 2013 and 2014 were considered to be incomplete averages. Wells LC-2B, LC-2F, and LC-3D had many years of missing data, and therefore an accurate analysis for these wells could not be currently performed. The r-squared values for wells LC-2F and LC-3D are not high and should be ignored at this time. Again, the diversion ratios for years 1986, 1987, and 1995 were not used due to higher than average releases which would have led to greater wastes in the river system and lower diversion ratios.

To summarize, LC-2A (Figures 3a and 3b) had the highest r-squared values for correlating the diversion ratio from current year and previous year groundwater depths. The best prediction of the diversion ratio was with LC-2A with USGS approved data that has an r-squared value of 0.85 (Figure 3b), and the correlation is shown in Equation 3:

$$\text{Diversion Ratio} = 1.542 - 0.024\ (\text{Previous Year's LC-2A depth to groundwater}) \quad (3)$$

Well LC-3A had the next best results with current and previous year groundwater depths and diversion ratio correlations 0.89 and 0.84 respectively. Well LC-3C also had high results at 0.86 and 0.85 for both current and previous year's groundwater levels, respectively, but data for years 2013 and 2014 could not be included because of incomplete averages for these years. It would be interesting to compare groundwater levels and diversion ratios in the future for well LC-3C if more complete data is available. This is also the case for LC-2B, LC-2F, and LC-3D. Well LC-2C had high power fit correlations for current year groundwater levels and diversion ratios at 0.86, but the previous year's correlation was at 0.69.

DISCUSSION

<u>Diversion Ratio Synopsis</u>

This study indicates that the diversion ratio is best predicted by the groundwater levels in the LC-2 and LC-3 well sections of the northern Mesilla Valley. The LC well segment is also where the greatest losses occur in the whole river section as discussed below. Wells LC-2A and LC-3A had the highest r-squared values for predicting the diversion ratio using the previous year's average groundwater depth. The r-squared values for current years in Wells LC-2A, LC-2C, LC-3A, and LC-3C were all above 0.80, with LC-2A having the highest r-squared value at 0.92. This means that the groundwater levels in this reach have a correlation with the final annual diversion ratio.

Well LC-2B should not be regarded for predicting current diversion ratios due to the absence of good data even though the r-squared values were considered high. Further evaluation of Well LC-2B will have to be done when enough complete current data is gathered in order to confirm whether or not this well is an accurate indicator of predicting diversion ratios. This is also the case for all of the wells.

The correlation between river losses and groundwater levels could be explained by Darcy's Law ($Q = KA\ (\Delta H)/L$) which states that the larger the difference between two different water levels, the greater the flow. This is the case for different groundwater levels between aquifer depths, and for horizontal flow for groundwater levels for wells of the same depth at distances away from the river as discussed below. The recharge flow will also depend on the transmissivity of the aquifers. In all, this means that the losses from the river will increase as groundwater levels decrease.

When water is applied to the fields, a portion of this water seeps into the shallow groundwater and is returned to the system by the irrigation drains. The drain return flow allows water reuse that increases the efficiency of the river system above 100%. However, when groundwater levels decline, drains no longer flow or flow more slowly and less water returns to the river. Likewise when farmers, municipalities, and industries pump from the aquifer, the major effect is lowered drain flows with increased seepage to the aquifers from the river and canals to a smaller extent.

Rincon and Mesilla Valley Aquifer Systems

The two main groundwater basins along the Rio Grande in this reach are the Palomas/Rincon and Mesilla basins (Wilkins, 1998). The Jornada del Muerto basin, east of the Palomas/Rincon basin, is separated from the Mesilla basin by the Jornada fault zone (Seager and others, 1987), but there may be some water passing through the fault zone (Nickerson and Myers, 1993). Little underflow enters the Mesilla Valley through the alluvium from Selden Canyon in the Rincon Valley (Frenzel, 1992). It is estimated that there are 50 million acre feet of groundwater storage in the top 100 feet of saturated basinfill in the Mesilla, Jornada, and Palomas/Rincon groundwater basins (Cook and Balleau, 1998). One study describes the Rincon and Mesilla Valleys to be gaining reaches using a trend-outflow method, but concluded that more studies are needed for this method (Liu and Sheng, 2011). Weeden and Maddock state that the Rio Grande is predominantly a gaining stream until roughly five miles north of Mesilla Dam due to the geology of the area at which point it changes to a predominantly losing stream (Weeden and Maddock, 1999). Municipal and industrial pumping is negligible in the Rincon Valley area, while it is a significant portion of groundwater withdrawals in the Mesilla Basin (Wilson and others, 1981). Information on groundwater resources of the Mesilla Basin is abundant; however, data for the Rincon Valley area and Selden Canyon are incomplete (Weeden and Maddock, 1999). In their models, Weedon and Maddock found that municipal and industrial pumping appears to decrease Rio Grande flow, especially towards the lower end of the Mesilla Valley, possibly due to Canutillo Wellfield pumping (Weeden and Maddock, 1999).

Rincon Valley. The Rincon Valley where the Palomas basin sits (Wilkins, 1998) is made of flood-plain alluvium which forms a long, narrow, and continuous aquifer two miles wide and about 60 to 80 feet deep. Wilson and others describe that the Santa Fe group in this section is mostly made of a thick sequence of clay that underlies the floodplain alluvium. Recharge to the flood-plain alluvium is from irrigation, seepage from the Rio Grande and canals, precipitation, and surface and subsurface inflows from tributary arroyos. Over many years, the balance between recharge and discharge from this aquifer is about equal. The Rincon Valley groundwater levels may decline as much as 10 feet during years of very little surface water delivery and much groundwater pumping. However, hydrographs show rapid recovery of the water table in those years when large surface water allotments are available. Approximately 540,000 acre feet of fresh and slightly saline water are in storage in the flood plain alluvium aquifer of the Rincon

(Wilson and others, 1981). A seepage study done in 1974 and 1975 in the Rincon Valley shows that the Rio Grande is a gaining reach from Caballo Reservoir to Hatch, NM, and slightly gaining in 1974 and slightly losing in 1975 from Hatch, NM to the southern end of the Rincon Valley (Wilson and others, 1981).

Terracon and others describe some of the hydrologic behavior of the Rincon Valley. "Average water levels within the valley do not appear to be decreasing over time, though a significant amount of seasonal fluctuation may occur. Water is replaced fairly quickly in the alluvial aquifer, due to its high transmissivity and proximity to the Rio Grande. Removing water from the floodplain aquifer probably has a larger effect on surface water levels than groundwater levels. Overall, water levels in the shallow aquifer in the valley have fluctuated 2 to 3 feet, but remain essentially constant. Hydrographs of wells, which have water levels exceeding 100 feet, indicate an overall decrease in water levels. Wells with water levels exceeding 100 feet, which have been monitored for more than 20 years, have experienced declines ranging from 1.9 to 3.3 feet per year, with total drawdown ranging from 33 to 94 feet." (Terracon and others, 2004). Thus, it can be determined that the Rincon Valley aquifer system is much smaller in scale in comparison to the Mesilla Valley, and that for the most part, it is not considered a significantly losing section of the Rio Grande.

<u>Mesilla Valley</u>. The Mesilla Valley is more than 50 miles long and as much as 5 miles wide (Wilson and others, 1981). The Rio Grande floodplain alluvium primarily consists of poorly sorted gravel and coarse to medium grained sand with thin interbedded clay lenses. From 100 to 327 feet below the land surface, the Santa Fe Group primarily consists of alternating layers of coarse to fine grained sand and silty clay with numerous gravel lenses (Nickerson and Myers, 1993). One test hole in the Mesquite area unraveled fluvial deposits in the Santa Fe group about 2,000 feet deep (Wilson and others, 1981). Water in the Rio Grande flood-plain alluvium/Santa Fe Group aquifer system occurs under unconfined and semiconfined (leaky-confined) conditions. Gravel and coarse grained sand within the upper 150 feet of the aquifer have a much greater permeability than deeper sediments of predominantly finer grain size. Horizontal permeability in the aquifer system usually exceeds vertical permeability by several orders of magnitude. The permeability of the aquifer system generally decreases with depth. (Nickerson and Myers, 1993).

Nickerson and Myers state that the "Rio Grande streamflow is a major source of recharge to the aquifer system of the Mesilla Valley. Most recharge to the aquifer system is from Rio Grande seepage in losing reaches of the stream, seepage from irrigation canals, and infiltration of applied irrigation water" (Nickerson and Myers 1993). Surface water losses in the canals that reach the groundwater table is probably 40 to 60 percent of total conveyance losses (Richardson and others, 1972, p. 61). Conveyance losses from irrigation canals in the Mesilla Valley normally range from 35 to 50 percent of the total diversion of irrigation water from the Rio Grande (Peterson and others, 1984, p. 28). Seepage rates of losing reaches of the Rio Grande may fluctuate with annual and seasonal variations in streamflow (Nickerson and Myers, 1993).

In their study, Nickerson and Myers observed that "groundwater levels in nearby observation wells in the Mesilla Valley correspond to changes in river stages and indicate significant recharge to the aquifer at the river. The rapid response of groundwater levels to the abrupt rise in river stage indicates a significant hydraulic connection between the river and the shallow flood-plain alluvium. The water table in the aquifer system decreases with distance from the river at the hydrologic sections, which indicates horizontal groundwater flow away from the Rio Grande. The potentiometric head also decreases with depth below land surface, which indicates a downward, vertical direction of groundwater flow within the aquifer system. Downward vertical hydraulic gradients were recorded in all well groups at the Mesilla Valley hydrologic sections" (Nickerson and Myers, 1993).

In 1985 and 1986, "the Rio Grande was in hydraulic connection with the aquifer system and lost or gained water by seepage through the riverbed in the direction of decreasing hydraulic head. Recorded hydraulic gradients from the river to the aquifer identify the Rio Grande as a losing river at the Las Cruces hydrologic section, Mesquite hydrologic section, and Canutillo well-field hydrologic section" (Nickerson and Myers, 1993).

Nickerson and Myers state that from previous seepage investigations conducted during steady low flow conditions, the Rio Grande is usually a losing stream along most of the 62 mile reach in the Mesilla Valley (Nickerson and Myers 1993). In a June 2012 seepage study from the Caballo gaging station to the El Paso gaging station (Gunn and Roark, 2014), it was observed that the most significant losses occurred in Reach 2, from the Haynor Bridge (Rincon Valley) gaging station to Mesilla Dam (Mesilla Valley) reach. This was one of four reaches in the study. Reach number 2 had the highest calculated loss at 234 cfs, which according to the study, was considered "substantial." The LC well fields are located in this reach. In comparison, Reaches 1, 3, and 4 had losses of 66.8 cfs, 33.0 cfs, and 50.7 cfs, respectively. Gastelum and others, 2012, point to two areas in the Mesilla Valley where the contour levels suggest high groundwater pumping areas; the city of Las Cruces, and the Canutillo Well Field area. The contour levels along the Rio Grande for years 1998 and 2007 show that the reach near the LC (USGS A-A') well section is a losing reach. From studying these contours along the river, the losing reach appears to run from where the Rio Grande enters the Mesilla Valley to a few miles below the USGS B-B' well section near Mesquite, NM. River mile reach 1289 to 1299 where the LC well section is located is identified to be where most of the river losses occur in the Mesilla Valley. The Mesilla Valley in general is dominated by losses rather than gains (Gastelum and others, 2012). Slight river gains have been reported in the short upstream reach from Leasburg Dam to about 6 miles north of Las Cruces (Wilson and others, 1981, p. 66) and immediately upstream from the El Paso Narrows in the extreme southern end of the Mesilla Valley (Peterson and others, 1984, p. 29).

Peterson and others say that "during wet years with relatively high streamflow, the groundwater table may rise above the riverbed. Under these conditions, the Rio Grande is considered hydraulically connected to the aquifer; seepage rates are proportional to the hydraulic conductivity of the aquifer and the hydraulic gradient between the river and the groundwater table. During dry years with relatively low streamflow and increased groundwater withdrawals, groundwater levels may drop as much as 10 feet below the riverbed" (Peterson and others, 1984, p. 32). Recently, groundwater levels in well LC-2A have dropped about 22 feet, and 30, 31, and 24 feet in wells LC-3A, LC-3C, and LC-3D, respectively over some years. There is no doubt that the recent drought has contributed to these significant groundwater level declines.

A higher than average release season could potentially raise groundwater levels significantly which would reduce flows from the river to the groundwater over time based on decreasing groundwater level differences, and thus reduce river losses and increase the diversion ratio. This should be taken into consideration when planning an irrigation season at a time when there is ample storage in the reservoirs and/or there is a forecasted high snowmelt runoff from the Rio Grande basin mountain ranges. If this is the case, the diversion ratio may potentially increase significantly from one year to another.

CONCLUSIONS

An efficiency prediction tool may benefit water managers so that they can make accurate decisions about how to improve water use in this dry region. Strong correlations were found between the diversion ratio and groundwater levels in the USGS LC-2 and LC-3 well sections of Las Cruces, NM. The best prediction of the diversion ratio was with LC-2A with USGS approved data with an r-squared value of 0.85 (Figure 3b), and the correlation is shown in Equation 3:

Diversion Ratio = 1.542 – 0.024 (Previous Year's LC-2A depth to groundwater)

This correlation affirms that declining groundwater levels are the driving force behind increasing losses in the river system, and are reducing drainage flows that return to the river, all of which lower the diversion ratio. Due to this, seepage from the river and irrigation systems that normally returns to the river via drains is instead replenishing the aquifers.

The previous year's groundwater levels could potentially help water managers estimate what the diversion ratio will be for an upcoming irrigation season so that farmers and other stakeholders in the region may use water more efficiently and could further help prevent financial losses from unexpected water shortages. Wells LC-2A and LC-3A had the highest r-squared results for predicting the upcoming irrigation season's diversion ratio. More data collection of water data in this region is needed so that further studies can be done to more accurately assess the water balance in the river.

The correlation between the diversion ratio and groundwater levels at the LC well section in Las Cruces, NM may be due to the fact that groundwater levels were used from a major losing reach in a section of the Rio Grande. These correlations may change if another reach of the river is deemed to be a major losing reach, or if other reaches begin to have a larger impact in groundwater recharge. Monitoring of water data in this region is crucial for better understanding the dynamics of the river and aquifer system. Other well sections may provide better correlations in the future if there are more well data collection efforts. Considering that recharge to the aquifer is from the Rio Grande and irrigation, return flows from drainage canals will increase return flows into the Rio Grande and thus will increase the diversion ratio. Since groundwater levels and drainage return flows are linked, studying the relation between the return flows and efficiency should also be considered. Crop report data was not studied for this paper. If a trend of planting water-intensive crops such as pecans has increased in recent years, this could also have an effect on return flows.

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WEB-BASED DECISION SUPPORT FOR SUSTAINABLE SALINITY MANAGEMENT IN THE SAN JOAQUIN RIVER BASIN

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ABSTRACT

The concept of real-time salinity management was incentivized by the California Regional Water Quality Control Board by promoting it in the Water Quality Control Plan as an alternative to Waste Discharge Requirements specified in the 2004 salinity TMDL for the San Joaquin Basin. Adherence to the principles of real-time salinity management have been shown to increase annual average salt export from the San Joaquin Basin and avoid potential fines associated with exceedences of monthly and annual salt load allocations which could exceed $1 million per year for the entire Basin based on average year hydrology and TMDL-based export limits. Over the last decade the essential components of this program have evolved that include the establishment of telemetered sensor networks, the establishment of a web-based information system for sharing data, the development of a GIS-based, basin-scale flow and salinity forecasting model and institutional entities tasked with performing weekly forecasts of San Joaquin River salt assimilative capacity and coordinating west-side drainage return flows. This paper provides an overview of progress made to date and describes an alarming finding of diminishing ungauged River accretions that threaten sustainability of the River resource made possible by the advances in modeling resolution resulting from this Program.

INTRODUCTION AND BACKGROUND

Salinity Management in the San Joaquin Basin

Salt export from agricultural, wetland and municipalities in the San Joaquin River Basin (SJRB) is regulated as part of a comprehensive Total Maximum Daily Load (TMDL) (CEPA, 2002; CRWQCB, 2004a, 2004b). The TMDL is intended to identify, quantify and help control sources of pollution that affect attainment of water quality objectives and full protection of identified beneficial uses of water. The TMDL includes both point and non-point sources of salt load. Non-point sources of salinity (LA) are not amenable to the establishment of fixed monthly or seasonal salt load allocations because of the

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diffuse nature of these non-point source loads in the watershed which makes it difficult to assign responsibility.

There are technical challenges to monitoring flow and EC at individual discharge points compounded by the high seasonal variation in export flows and salt loads. Base salt load allocations (LC) are made to account for the variable assimilative capacity of salt within the San Joaquin River (SJR) – these are calculated based on the lowest anticipated flow condition in the River and the SJR's assimilative (load) capacity (LC) for salt during these episodes. Point source (WLA's), background salt loading, including salt loads contained in groundwater return flows to the SJR, are subtracted from the total River assimilative capacity to determine the salt load allocation to all non-point sources. (Holm, 2010).

$$TMDL = LC = \Sigma WLA + \Sigma LA + MOS \quad \ldots\ldots\ldots \qquad \text{(CRWCB, 2004b)} \qquad (1)$$

Where : LC = salt assimilative load capacity (tons of salt)
WLA = point source salt load allocation (tons of salt)
LA = non-point source salt load allocation (tons of salt)
MOS = margin of safety (%)

Much of the irrigation water supplied to the west-side of the SJRB is pumped from the Sacramento-San Joaquin Delta through the Delta Mendota Canal and contains low levels of salinity (usually between 300 and 450 ppm) – allowances have been made for the salt load contained in imported water supply and for the evapoconcentration of this water when consumptively used by crops or seasonally managed wetlands. The TMDL (CRWQCB, 2004a, 2004b) applies a water supply salt load credit for the salinity of water imported from the Delta and a consumptive use allocation credit for agricultural and wetland use of the water (an incentive for these entities to discharge return flows that have not been degraded).

The success of the TMDL concept as a regulatory tool is testimony to the consistency of the methodology and its ability to provide quantitative measures of application outcome. The conceptual TMDL model breaks down in regions such as the western United States where hydrology is often extreme with wet hydrologic years, capable of causing severe flooding, interspersed with periods of severe drought – making attainment of load objectives very challenging, even with wet and dry year allowances. Another limitation of the TMDL approach is the inflexibility of the methodology to account for watershed undergoing adaptive change – where average conditions cannot be established and baseline salt loads are not applicable. In the SJRB TMDLs developed for salinity and dissolved oxygen problems in the San Joaquin River Deep Water Ship Channel can be in conflict – whereas the salinity TMDL limits can best be attained by reducing salt loading to the River, the loss of flow associated with a reduction in salt loading can exacerbate dissolved oxygen sag and creates an environmental barrier to fish passage.

Basin-scale real-time salinity Management

A unique provision in the published salinity TMDL for the SJRB was the addition of a "real-time" load allocation that can supersede the conservative base flow non-point source load allocation (LA) if the elements of a real-time salinity management program (RTSMP) are implemented in the SJRB. This has been elaborated in the current SJRB Water Quality Control Plan. The core requirements of this program include: the development of a basin-scale, sensor network to collect real-time monitoring of flow and salinity data; an information dissemination system for effective sharing of data among basin stakeholders; a calibrated simulation model of hydrology and salinity in the SJR and its contributing watersheds to allow forecasting and daily assessment of River assimilative capacity (Figure 1); and finally the sanction of the Central Valley Regional Water Quality Control Board. The impact of the additional real-time salt load allocation would be to permit greater export of salt load from the watershed during most years (Quinn and Karkoski, 1998; Quinn and Hanna, 2003; Quinn et al., 2005; Quinn, 2009; Quinn et al., 2011) and help to overcome salt accumulation within the shallow groundwater system which would ultimately degrade the groundwater resource within the SJRB.

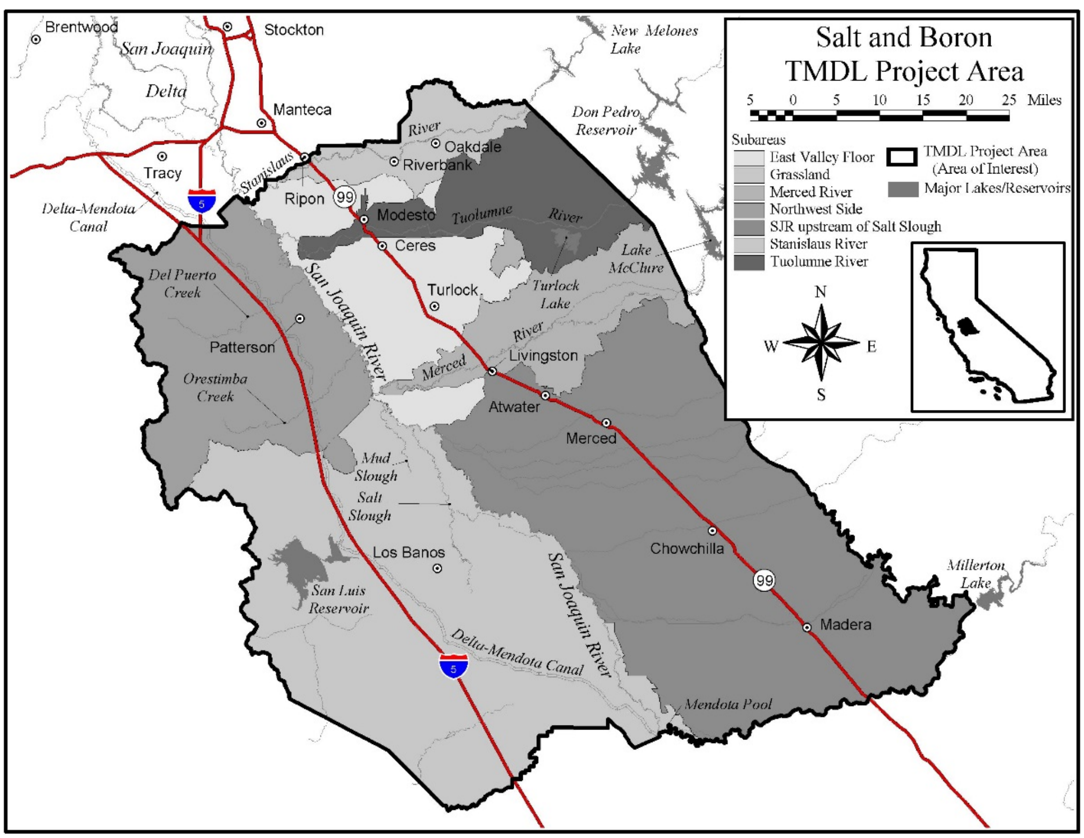


Figure 1. Subareas within the San Joaquin Basin draining to the San Joaquin River defined in the salinity TMDL (CRWQCB, 2002).

Real-time salinity management (RTSM) relies on the provision of continuous flow and EC data from willing stakeholders to allow forecasting of SJR assimilative capacity so as to match those that supply assimilative capacity and those that consume it. East-side reservoir releases of high quality Sierran water provide dilution to the SJR that drains west-side salt-laden soils.. West and east-side agricultural return flows are highest during the summer irrigation season. Return flows from seasonally managed wetlands are highest during the months of March and April when the majority of the seasonal wetland ponds are drained to promote establishment of moist soil plants and habitat for migratory waterfowl. RTSM should provide timely decision support to agricultural water districts, seasonal wetland managers and municipal dischargers - allowing them to improve the coordination of salt load export with the available assimilative capacity of the San Joaquin River (Quinn and Karkoski, 1998; Quinn and Hanna, 2003).

MONITORING NETWORKS – DATA MEASUREMENT AND TELEMETRY

The monitoring of flow and electrical conductivity (EC) at purpose-built monitoring stations is undertaken mostly by water agencies such as the California Department of Water Resources (CDWR) and the US Geological Survey (USGS) along the SJR and its major east-side and west-side tributaries (Figure 2). Water districts and local agencies are responsible for the majority of the flow and salinity monitoring within the watersheds that discharge to the River. Critical data on SJR diversions is currently only collected by the major SJR diverters. Recent California legislation requires estimation and reporting of SJR diversions by all riparians with an established right to SJR water supply.

Most agency flow monitoring is still performed using continuously recording pressure sensors and stage-flow ratings that are updated monthly during routine monitoring site maintenance. Over the past decade orifice bubbler technologies using compressed air produced on-site, manufactured by companies such as Design Analysis ™ have replaced more complicated nitrogen-based systems and solid state pressure transducers for most agency monitoring of the SJR and its major tributaries. However, real-time salinity management requires that water quality simulation and forecasting models have reliable data, leading to stakeholder pressure to introduce acoustic Doppler current profiler technologies using instruments such as the SONTEK/YSI Argonaut ™ and TELEDYNE TRDI ™ (Simpson, M.R., 2002; Teledyne RD Instruments, 2008; SonTek/YSI, 2000) to produce more accurate flow measurements that are accurate even under backwater flow conditions in the SJR.

During winter and spring high rates of discharge from east and west-side tributaries can create backwater conditions and retard flow at the SJR confluences that produce elevated stage at upstream monitoring stations unrelated to the actual flow. Since Acoustic sensors measure current directly they are not subject to the same errors. Acoustic sensors typically can be equipped with both acoustic and pressure sensors to measure stage – providing a measure of redundancy that can improve data quality assurance. Additional benefits will accrue in the reduction in field personnel staff time – field crews are typically mobilized to re-rate flow monitoring sites during backwater events – and in improvements in the quality of the data record. Water districts and local agencies have been more ubiquitous in their use of Doppler technologies for flow measurement in the past decade as the size of transducers has decreased, reliability has improved and cost reductions have occurred. Upward and side-looking acoustic Doppler transducers that have embedded pressure sensors such as those manufactured by MACE ™ and SONTEK/YSI ™ can be installed in both open delivery and drainage channels as well as closed pipes and culverts. The cross-section of these conveyances can be entered into each of these units allowing the discharge to be estimated by the product of mean water velocity and the calculated flow cross-section. Placement of these transducers depends on the turbidity of the water and the risk of sedimentation - deployment on the sides of pipes or channels is appropriate where the unit could be buried by a layer of sediment.

Telemetry costs and options have also improved over the past decade with cellular data plans making it affordable to have individual accounts associated with each monitoring site. In the recent past integration technologies such as YSI-ECONET ™ found a niche primarily by allowing more costly cellular CDMA telemetry to interface with local RF-based systems. YSI-ECONET ™ enables a sensor network of RF-enabled “data nodes” that collect flow and water quality data from individual monitoring sites to deliver these data to a smaller number of CDMA-enabled” access nodes”. Access nodes transmit

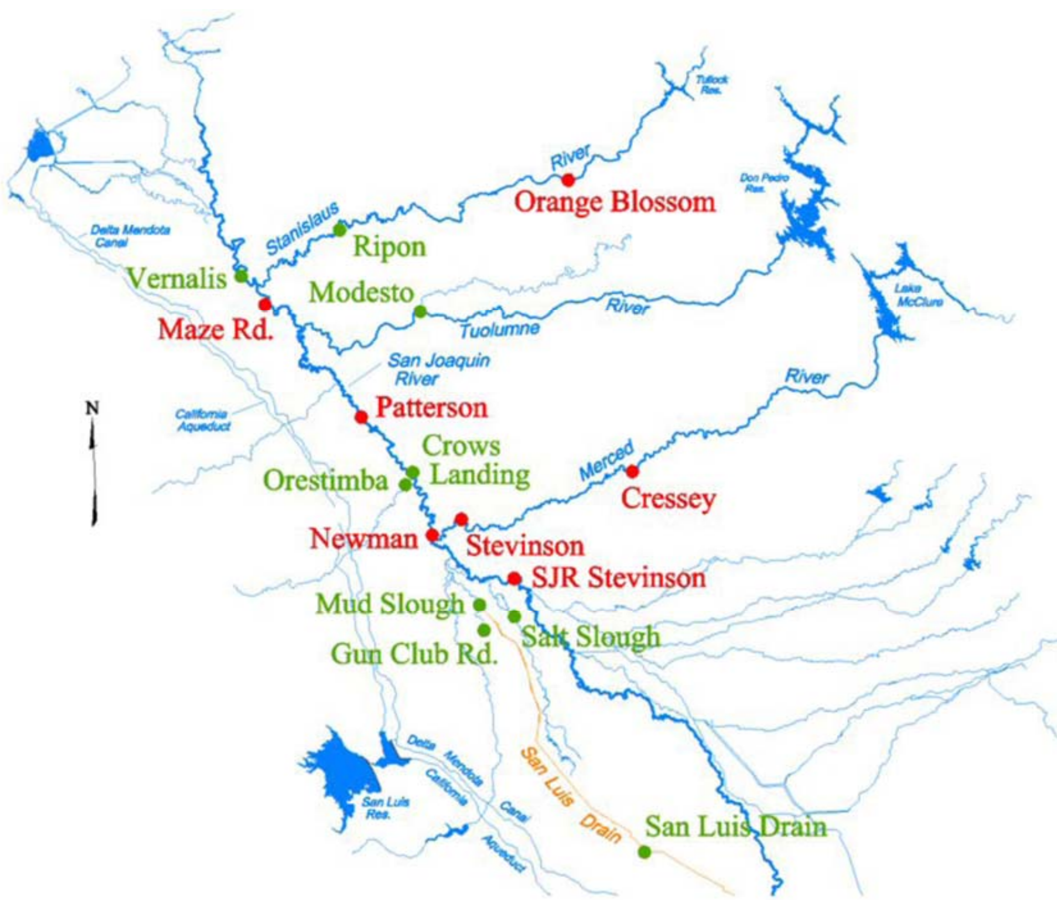


Figure 2. San Joaquin River Basin showing major primary real-time monitoring stations (source: California Department of Water Resources).

logged data to a remote Data Center from which the stored data is made accessible through the Internet. These Data Centers perform enterprise-level database access and web-based data visualization. The YSI-ECONET wireless mesh “multi-hop” network topology has allowed "point-to-point" or "peer-to-peer" connectivity and is self-organizing and self-healing – hence loss of one or more nodes does not necessarily affect its operation. This has helped to increase the overall reliability of the system by allowing a fast local response to critical events in the event of communication problems.

YSI-ECONET deployment (Figure 3) in 2005 within the Grassland Water District (GWD), a water purveyor responsible for the delivery of seasonal wetland water supply to 160 duck clubs and cattle operations on the west-side of the San Joaquin Basin, has allowed wetland managers more time to perform bi-weekly sensor data quality assurance checks including cleaning of sensors and checking the accuracy of staff gauge data (used in the computation of flow). YSI-ECONET is “middleware” technology that has provided a relatively inexpensive pilot sensor network solution that has proved to the District and adjacent state and federal wildlife refuges the benefits of real-time flow data for water conservation and local reuse.

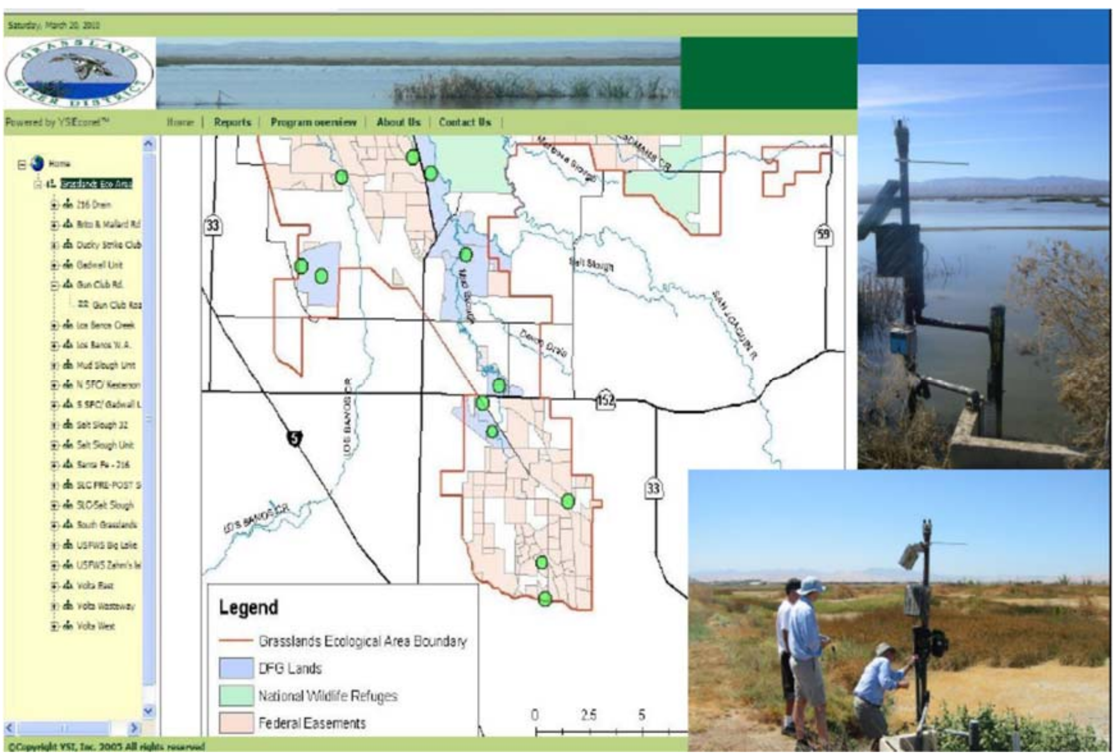


Figure 3. Map-based graphical user interface to current YSI-ECONET web-based real-time data acquisition and reporting system installed in the Grassland Water District. Auxiliary sites are installed at pond outlets and in channels within the State and Federal Refuges. Flow and EC sensor data is reported to the website every 15 minutes from Access nodes (shown in green on the map). Multiple “data” nodes report to each “access” node.

Low cost cellular and satellite data plans with greater accessible data bandwidth, available since 2005, have created new opportunities in the past five years making it cost effective to bypass this “middleware” technology and have hydrologic data management systems (HDMS) housed in agencies and local water districts pull data directly from flow and EC monitoring stations. The WISKI (https://www.kisters.net/NA/products/wiski/) HDMS technology uses a data acquisition software module SODA that contains a suite of custom data transfer protocols that allows communication with a large array of commercial dataloggers and data modems. Data transfer technologies include IP-telemetry, remote call, file transfer, web services and e-mail and accommodate push, pull, D-channel, remote call data transfer directions using telephone, GSM, UMTS, GPRS, internet, radio and satellite data transfer pathways. Having the environmental sensor network, data storage and data processing tightly integrated helps to minimize monitoring network downtime, provides greater data integrity, lowers overall system operational costs and lends itself to the introduction of real-time data quality assurance practices. GWD is currently making the transition from YSI-ECONET to a turnkey WISKI-based real-time data acquisition and monitoring system prompted, in part, to the phase-out of YSI-ECONET by XYLEM Inc., the new corporate owner of the YSI/SONTEK product.

Data Quality Control and Assurance

A limitation of many environmental decision support projects that rely on the telemetry of monitored data to a stakeholder community is data quality assurance. Data quality assurance protocols for discrete environmental sampling are well established and data quality control plans are integral components of most environmental monitoring projects. For continuously recorded and reported data, however, the logistics of monitoring site visitation and procedures, data management, processing and error correction are not coherent throughout the Basin. Established software tools used by local water districts (WISKI) the California Department of Water Resources (HYDSTRA) and the US Geological Survey (AQUARIUS) facilitate and guide these tasks that use QA data to error-correct and apply averaging techniques to continuous records (Figure 4). This produces a reliable data record that can be publicly shared and readily utilized in flow and salinity forecasting models. Inaccurate or absurd data posted to a project website can cause irreparable harm to a project and can quickly lead to a loss of confidence within the stakeholder community.

These software tools can be used for data management and quality assurance for open and closed sensor networks. Open sensor networks such as the system developed by GWD have the capability of incorporating data from monitoring stations accessible by SODA but outside the District’s portfolio of stations. Examples of closed sensor networks are those provided by SCADA which provide control capabilities not offered by typical dedicated monitoring sensor networks. However SCADA systems require technical skills that are beyond the staff resources of most smaller water districts. Post processing data quality assurance tools such as WISKI can be configured to work with both open and closed sensor networks. The WISKI HDMS, like the other software products, provides a user interface that lists site names associated with a number of parameter subcategories that are being logged together with the deployed sensors.

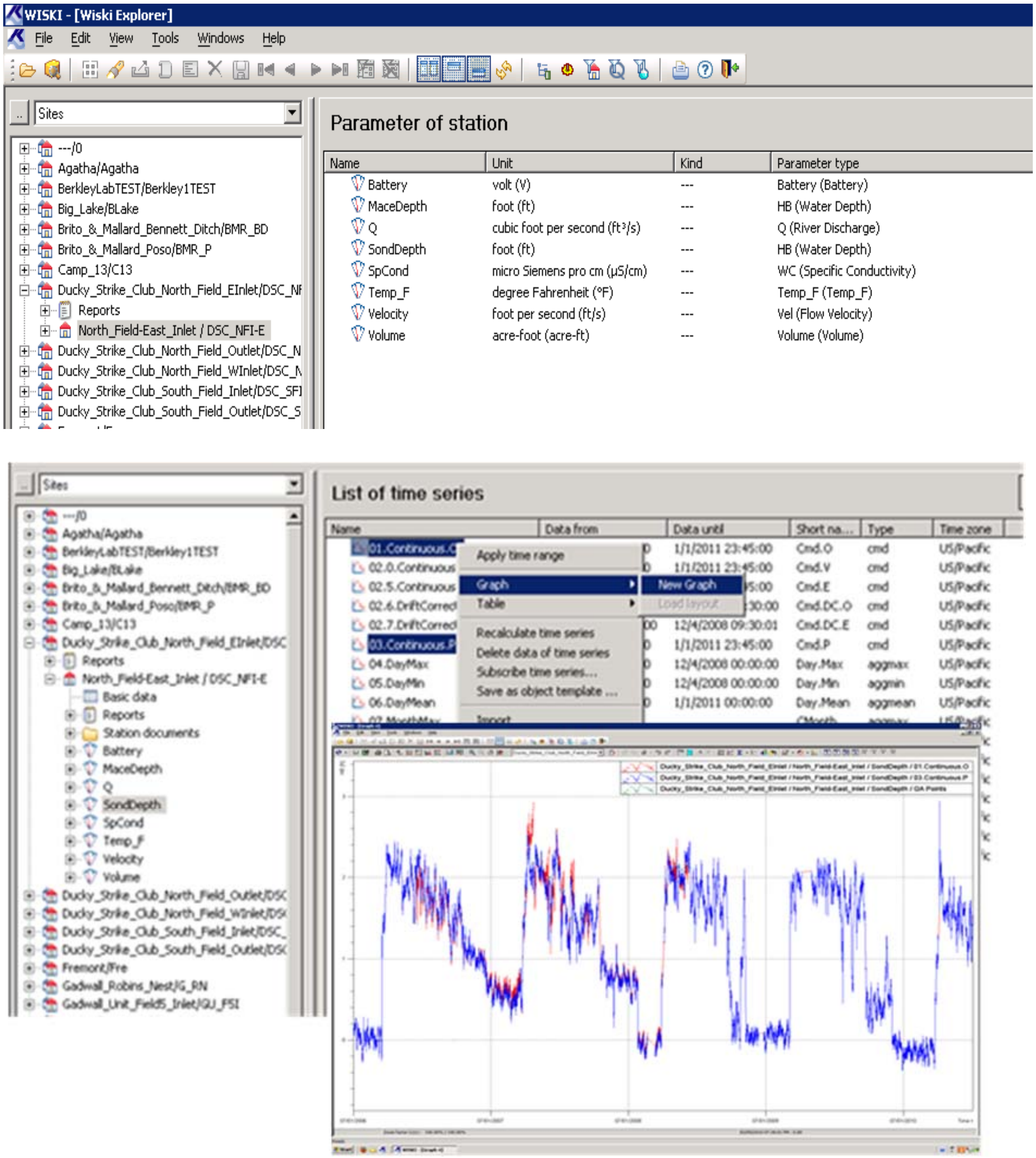


Figure 4. WISKI hydrologic data management software showing station parameters and time series associated with each parameter. WISKI can be used to automate processing of preliminary data and to fit a new time series to an imported set of quality assurance data points for stage, flow and electrical conductivity.

Each of the times series entries contains the original data (labeled “01. Continuous.O”, etc.), while each subsequent time series entry is modified as a result of quality control operations performed on the data. The second time series (“Continuous.V”) is an exact copy of the original data, but can be edited and modified (Figure 4). The next time series (“Continuous.P”) is the product time series, which displays the final data after all data quality assurance (QA) adjustments, drift corrections, missing value interpolations etc. have been completed. The next time series plots contain average, maximum and minimum values for the data over certain time periods (daily, monthly, yearly). For sites for which data QA has been performed through the WISKI data management system, an additional time series entry will be present. The time series "QA Points" represent the manual measurements taken in the field at the site while the "Drift Correction" time series shows the results of calculations performed to adjust the final data. The final data field is still displayed within the "Continuous.P" time series plot.

Real-Time Operations, Alerts and Alarms

The WISKI software suite includes several advanced productivity tools such as KiDAT (data acquisition tool) and KiDSM – automated scheduler and data importer and the KISTERS Alarm Manager which sets alarms and set responses to pre-set conditions. This last development has significant advantages for real-time data management in that full SCADA was previously needed for a data collection platform or PLC to react to a field condition informed by a sensor or number of sensors working together. Alarm manager software allows the system to respond to data or combined data contained in the user database. For example having a sensor value rise above a set condition could trigger an alarm (such monthly target salt loading at an outlet). Similarly - the sensor value can be compared to any parameter value in the database or even a model calculation (such as computed salt load at Vernalis) or to San Joaquin River calculated salt assimilative capacity. KiDAT software is able to automatically download real-time data from various agency websites including: the USGS National Water Information System (NWIS); the California Data Exchange (CDEC) and Environmental Protection Agency (STORET). The software can "data scrape" any website once a template for that sites has been established.

This software feature has narrowed the technical capability advantage that SCADA systems have had over monitoring network systems helping to drive down the cost of deployment and making these HDMSs more accessible to smaller water districts. It also allows the enhancement of sensor networks for decision support in those instances where web access to the public and data downloads in real-time are possible. Basin-wide real-time salinity management (RTSM) will require the both the development of new stakeholder initiated sensor networks and the synthesis of these networks into a basin-scale application where they are combined and made available for a computer-aided model simulation and forecasting tool capable of estimating future salt assimilative capacity conditions in the SJR. Real-time data quality assurance tools will play a significant role in encouraging the free sharing of data necessary for developing timely and realistic forecast of river flow, EC and salt assimilative capacity.

DATA VISUALIZATION AND DECISION SUPPORT SYSTEM DEVELOPMENT

The web-based data synthesis tool under development that also has the capability of sharing forecasting model outputs is known as WARMF-Online (Figure 5). The Watershed Analysis Risk Management Framework application for the San Joaquin River (WARMF-SJR) provides the analytical backbone for the web-based data visualization system implemented within OpenNRM – open-source software developed by 34 North Inc. OpenNRM addresses the need for a collaborative software workspace for supporting, organizing, managing, analyzing, visualizing, archiving and reporting project and operations information. The software provides a number of features including: (a) compilations of existing data sets for regularly assessing, comparing and reporting on these datasets (b) simplification of data management and access by centralizing key datasets and management tools; (c) the creation of a collaborative workspace will facilitate analysis, synthesis, assessment and communication; (d) creation of a web based workspace for developing a credible process, in which stakeholders can participate, to ensure that data are appropriately assessed, interpreted, and reported; (e) visualization tools so that modeling and visualization runs can be easily modified, enhanced and repurposed for additional studies; and (f) analytics - status and trend monitoring is simplified by automation of many of these core activities (Figure 5).

When fully implemented within the OpenNRM system - WARMF- Online will supply real-time flow and salinity data from public water agency websites, cooperating water districts and other stakeholders in an input format to enable reliable daily simulation and forecasts of River assimilative capacity the San Joaquin River to be made. Although at present, these model runs and assimilative capacity forecast are made within both the California Department of Water Resources and US Bureau of Reclamation future forecasts will utilize a single web-based version of the model application which is kept up to date, continuously calibrated and upgraded with new algorithms and bug fixes. Future WARMF-SJR model forecast runs will be made by a small core group of stakeholder and/or agency personnel with write access privileges to the model. Model outputs and post-processed visualizations will continue to be made available to the public through WARMF-Online.

Visualization of Wetland Flow, EC and Salt Load Data for Decision Support

The WARMF-Online web portal is designed to serve all stakeholders in the SJRB that discharge to the SJR. Estimates of SJR assimilative capacity, determined using the WARMF-SJR forecasting model and exported to WARMF-Online are accessible to customized decision support tools developed at the water district-level. An example of this is the real-time data visualization tool developed for the GWD (Figures 6 and7). This real-time data acquisition, data quality assurance and visualization system is built upon the YSI-ECONET data acquisition system and WISKI data quality assurance toolbox. YSI-EcoNET data supplied to the District's WISKI database is error-checked and exported to an external ftp server where it can be accessed by a customized GIS-based visualization tool provided by the US Bureau of Reclamation and housed at GWD. The tool provides updates of flow, EC (and calculated salt load) in GWD water supply and drainage conveyance channels as well as at crucial internal measurement and compliance points (Figure 7). A data file of 30 days duration containing hourly flow, EC and salt load data is continuously available to District personnel to support real-time decision making. The District will need, in the future, to monitor and control daily salt export so as not to exceed daily salt load targets either developed internally within GWD or in partnership with other wetland entities draining to Mud and Salt Sloughs.

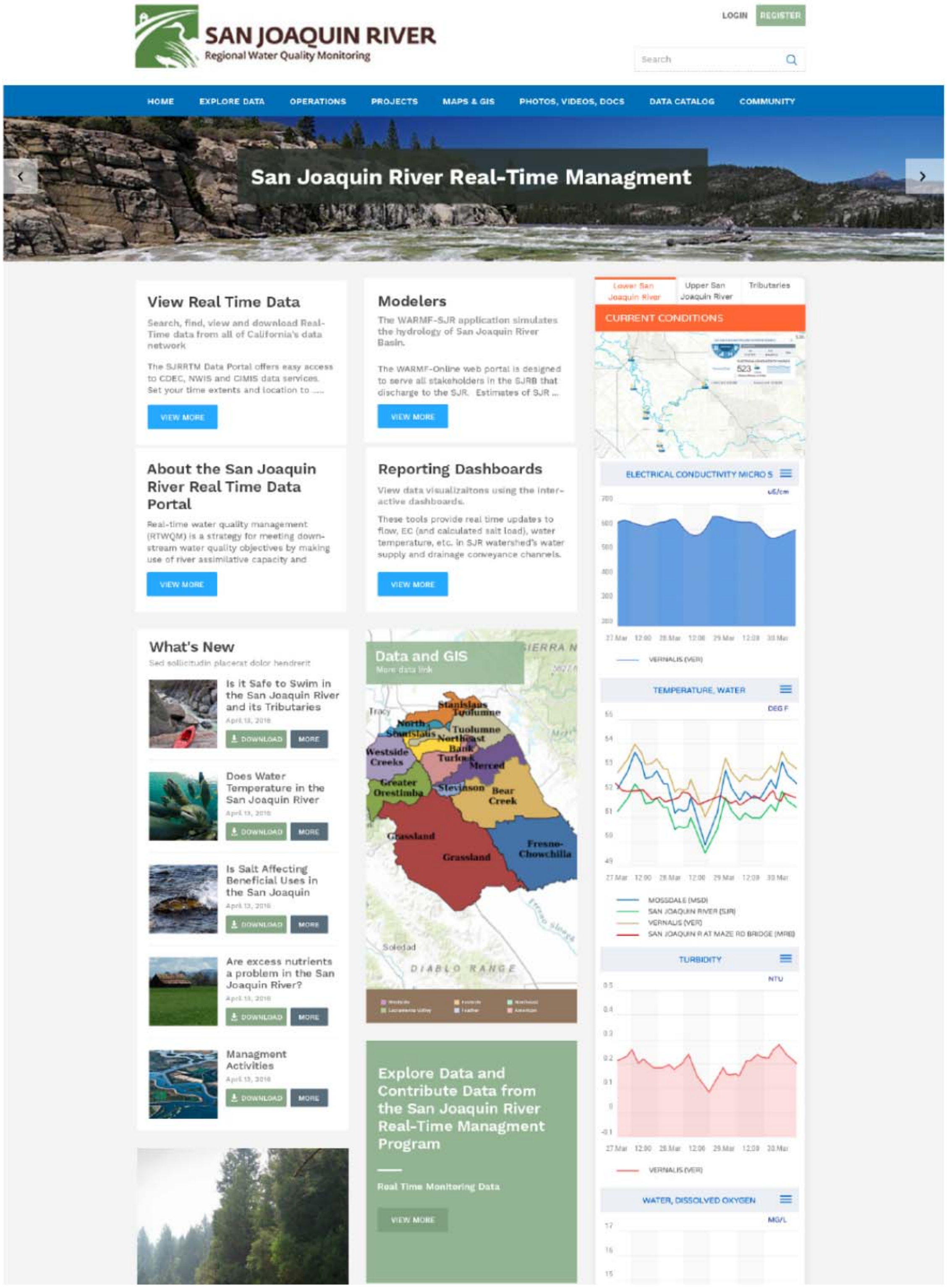


Figure 5. WARMF-Online web portal (homepage) using the 34-North Open NRM visualization toolbox. The web portal provides data access, visualization of WARMF-SJR model output, weekly salt assimilative capacity forecasts and GIS-based data analysis.

FLOW/WATER QUALITY MODELING, SIMULATION AND FORECASTING

The Watershed Management Framework (WARMF) model (Herr et al., 2001; Chen et al., 2001, Herr and Chen, 2006) is comprehensive decision support tool specifically designed to facilitate TMDL development at the watershed-level. The WARMF-SJR application simulates the hydrology of San Joaquin River Basin and performs mass balances for a broad suite of potential contaminants including total dissolved solids. The model (Figure 8) simulates tributary inflows from the major east-side rivers, agricultural and wetland drainage return flows, accretions from shallow groundwater, riparian and appropriative diversions and uses hydrologic routing to calculate flow and water quality at approximately 1.6 km intervals along the main stem of the SJR. Wetland drainage from the Grassland Ecological Area was partitioned into component State, Federal and private wetland contributors to SJR salt load.

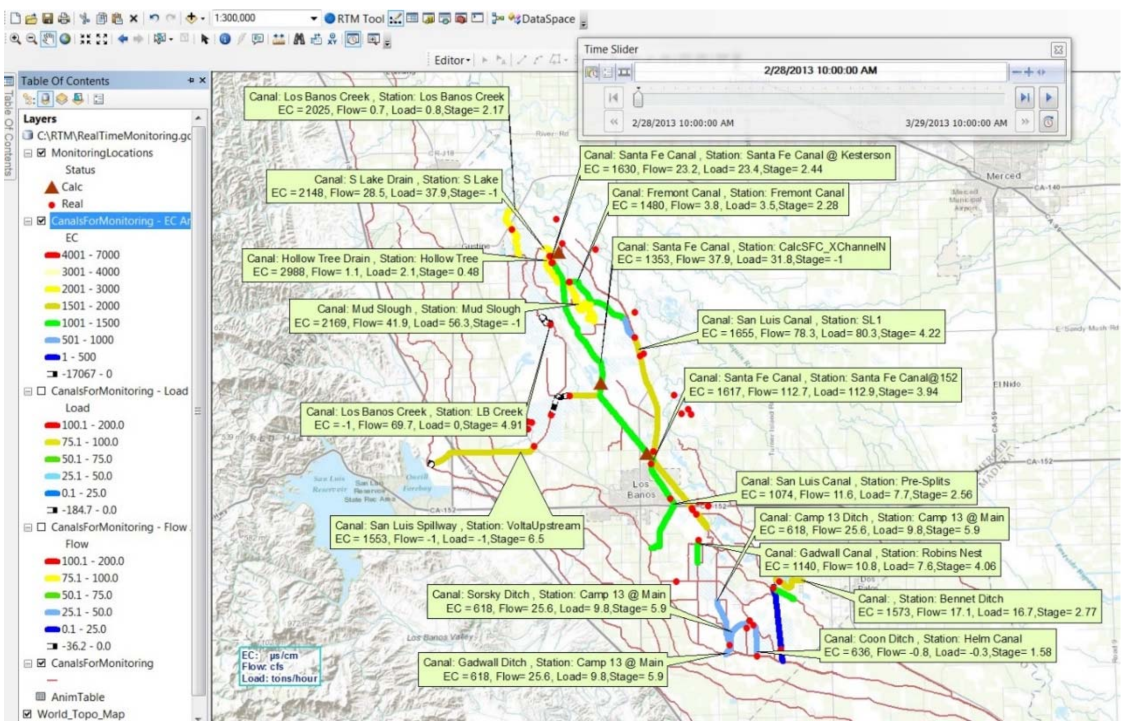


Figure 6. A data visualization and decision support tool was developed for Grassland Water District as an exemplar of the type of information the water master suggested would be most useful to assist with salt load management. Colorized line segments rendered using the ArcGIS MapObject toolbox represent the length of canal associated with each monitoring station in the canal network. This rendering can be toggled to display flow, EC or calculated salt load. Current hourly values are shown in the tagged label associated with each monitoring station.

A GIS-based graphical user interface (GUI) facilitates the visualization of model input flow and water quality data. Data templates expedite automated data retrieval from State and Federal agency hydrology and water quality databases and the automated updating of model input files. Water managers can enter daily schedules of diversions and discharges using the spreadsheet formatted model data interface. Standardized model output graphics aid the dissemination of flow and water quality forecasts (Figure 9).

A wetland water quality module for the WARMF-SJR model has been formulated that simulates water and salinity balances for individual ponded areas and that aggregates wetland discharge and salt loading at the watershed level enabling comparison with future salt load discharge schedules that will be developed by private, state and federal entities within the Grasslands Ecological Area. These wetlands are flooded in the fall and drained in the spring - ponded depth and outflow are a function of the cumulative inflow to the wetland (i.e., precipitation plus applied water). Water levels of wetland ponds and wetland return flows are managed by means of controlled releases through pond outlets. The WARMF-SJR model includes the option to calculate surface water outflow based on inputs of average prescribed pond depth. This approach closely represents real management operations of retaining or releasing water to maintain desired pond depth in wetlands. This wetland simulation approach was tested using time series of pond depths from nine wetland impoundments that have been monitored since 2005. Salt load scheduling using weekly or monthly, seasonally adjusted loading targets is a salinity

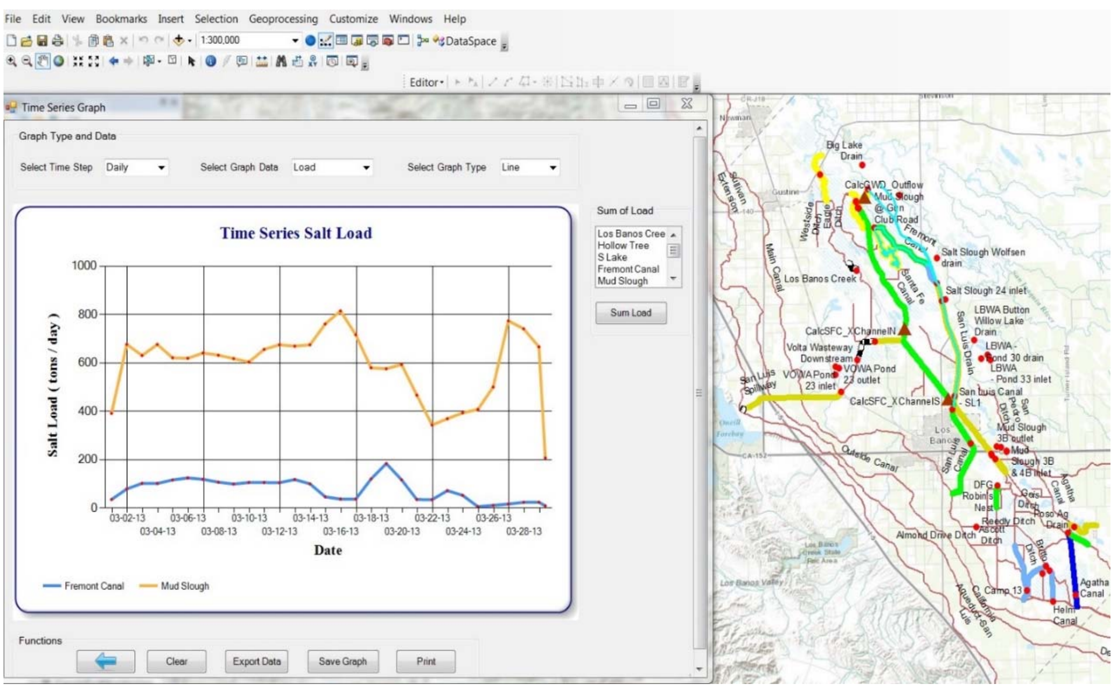


Figure 7. Hourly values of flow, EC or salt load can be displayed over the period of a month using a slider to advance date and time forward or backward. The time series of flow, EC and salt load can also be visualized for each of the 50+ monitoring stations over the same period.

management strategy that could be implemented to help coordinate wetland drawdown and salt load export to the River from private, state and federal wetland entities. Where real-time telemetered data from both agricultural, wetland and municipal entities that discharge to the River is available, these data will automatically overwrite model-estimated values in the WARMF-SJR model. Engaging water district managers and water district staff to pay attention to web-posted information is made easier when their own data is made available and accessible on the web portal. We have demonstrated this during a decade of wetland monitoring on the State Refuge and in Grassland Water District. Having stakeholders pay attention and develop an appreciation for drainage return flows, discharge salinity and salt load export is the first step in participatory real-time salinity management.

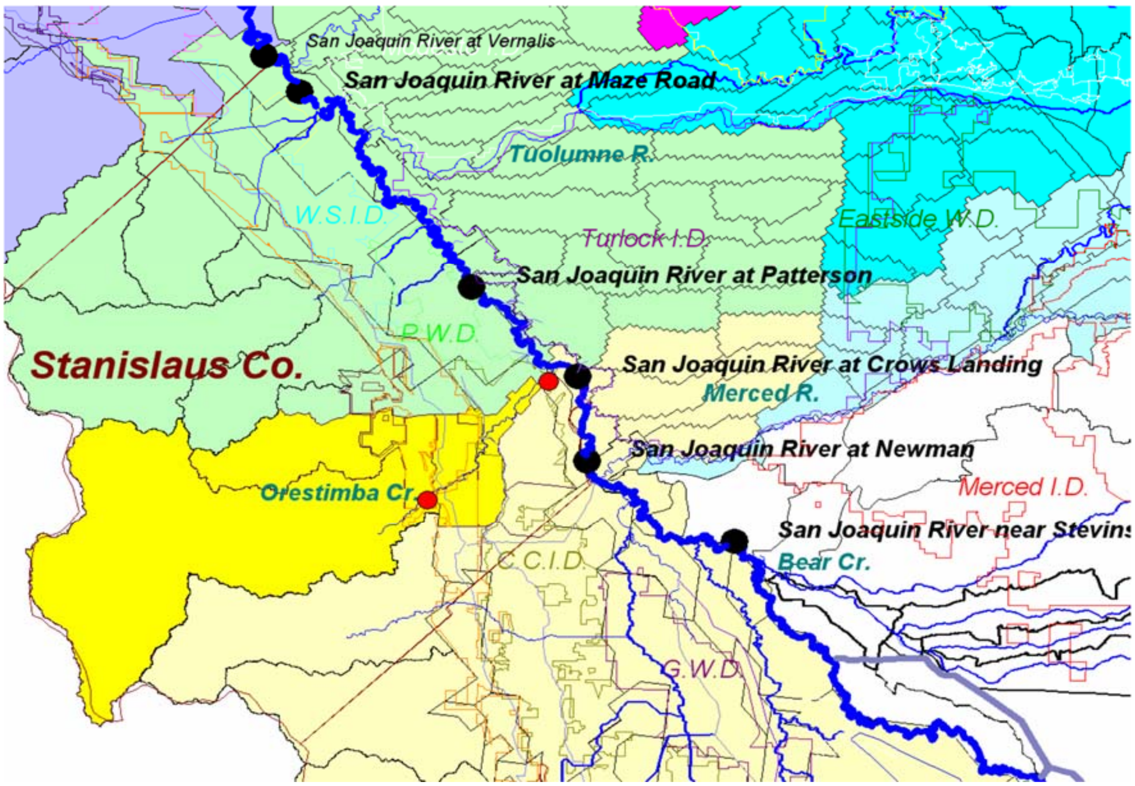


Figure 8. WARMF-SJR model showing the disaggregation of watersheds contributing flow and salt load to the San Joaquin River into component drainages. The hydrology of the San Joaquin Basin is such that the political boundaries of individual agricultural water districts are the most appropriate primary unit (sub-watershed) for monitoring, management and control of salt loading to the San Joaquin River from the west-side. Sub-watersheds on the east-side of the San Joaquin River are determined by the irrigation supply and surface drainage network.

DATA MANAGEMENT COORDINATION

In early 2016 the San Joaquin Valley Drainage Authority (SJVDA) initiated informational quarterly stakeholder meetings on behalf of the Westside San Joaquin River Watershed Coalition (WSJRWC) on the topic of data management, data coordination and mechanisms for data sharing - a core requirement for RTSM. The WSJRWC (www.sjvdc.org) represents water districts and other agricultural and wetland stakeholders located within the Grassland and north-west-side subregions (Figure 1) and manages data collection and submits data reports to the CVRWQCB for a large number of regulatory (Irrigated Lands Program) monitoring sites. The WSJRWC has no mandate for and have little experience with the processing of real-time flow and salinity data however it is the logical administrative entity for real-time salinity management on the west-side of the SJRB. Similarly on the east-side of the Basin the East San Joaquin Water Quality Coalition (ESJWQC) (www.esjcoalition.org) files required monitoring reports with the CVRWQCB on behalf of its 1000+ farmers and stakeholder entities, provides

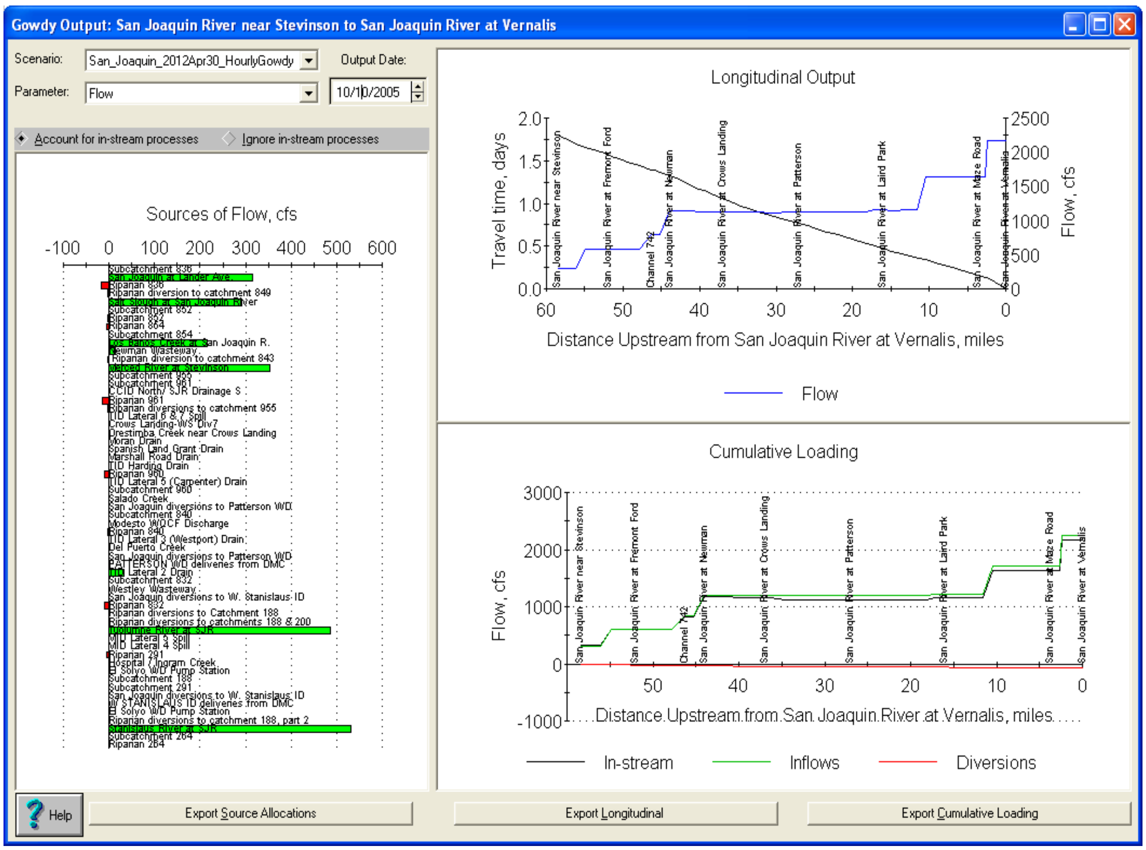


Figure 9. The GOWDY Output is a unique post-processor for the WARMF-SJR model that toggles between views of flow, EC and salt load for the entire San Joaquin River between Lander Avenue and Vernalis (a 96 km reach) for a single day in the year. On the left panel flows into the River show as green horizontal columns superimposed over the input source whereas diversions from the River show up as red horizontal columns to the left of zero. In the top and bottom panels to the right of the screen are shown travel time showing an initial value of 1.8 days diminsihing to zero days at the Vernalis compliance monitoring station. Flow is shown increasing from left to right as the east-side tributaries discharge into the River. The lower right-hand panel shows the same cumulative flow relative to cumulative River diversions.

conditional waiver coverage for members of the coalition, develops and implements the real-time water quality monitoring program and communicates to landowners where water monitoring indicates problems exist and helps in the development of equitable solutions. Ultimately the WSJRWC and the ESJWQC will need to develop a Memorandum of Understanding for joint implementation of the real-time management program recognizing the use of the WARMF-SJR model as a decision-making tool to forecast availability of River assimilative capacity through better coordination with eastside irrigation districts and upstream reservoir operators and through sharing this information with westside salt load dischargers to allow them to improve coordination and scheduling of drainage return flows and westside riparian diverters to manage their diversions to help meet and maintain River salinity objectives. Realization of the potential of RTSM may require the formation of a basin-scale salinity management entity built upon the WSJRWC and the ESJWQC with the authority to encourage compliance with sub-basin salt load targets through incentives or penalties to ensure compliance with internally sanctioned salt load limits and mutually agreed-upon salinity compliance monitoring locations.

The CVRWQCB has recently completed a series of studies supporting a Basin Water Quality Plan amendment to introduce an upstream salinity concentration objective at Crows Landing on the SJR. This entity would have program oversight that would involve maintenance of monitoring stations, discrete sample collection and analysis and monitoring data record keeping, coordination of both drainage return flows and reservoir releases from east-side tributaries, synthesis of real-time data and dissemination of daily salt assimilative capacity forecasts for the San Joaquin River. The monitoring systems and data management systems used for real time management must be robust, reliable, and well maintained to function properly and provide accurate information. The WISKI data management system that is in common use by the Merced, Modesto and Turlock Irrigation Districts on the eastside and the Grassland Water District on the westside and the compatible HYDSTRA data management system (also a KISTERS Inc. product) used by the California Department of Water Resources should be used as the IT backbone for the joint system. Development of an integrated data management system capable of combining all relevant east and west-side flow and EC data is made easier through the use of common IT ontologies and data sharing protocols.

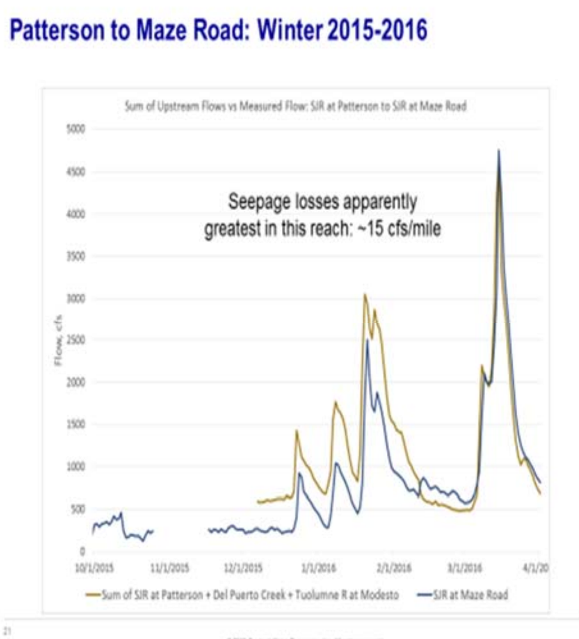
Potential Coordination and Integration with Ongoing Activities

The development of a real-time water quality management system for the Basin is a multi-million dollar endeavor requiring close coordination and cooperation with other water agencies such as DWR and the CVRWQCB as well as landowners and the water districts that represent them - on both east and west sides of the SJRB. Given the potential expense of this undertaking – one cost-saving initiative that can be undertaken is the integration of the current real-time initiative with the significant information technology investment being underwritten by the congressionally-funded San Joaquin River Restoration Program (SJRRP). An important component of the $800 million SJRRP program is the Seepage Management Plan – a highly interactive, real-time monitoring and response program designed to maximize water flow along the critical San Joaquin River reaches newly re-watered, while protecting riparian agriculture from seepage inundation impacts. The real-time monitoring program is centered around a network of sentinel wells which rise during high river stage and provide an indicator of waterlogging in adjacent fields and , in some cases, on property as much as a few miles from the River. The SJRRP has acquired an external data server to allow easier uploading of field data and easier access to the server from cooperating agencies and water districts. The SJRRP data server might offer a number of advantages for the RTSM Program: (a) The current SJRRP monitoring network contains river flow and salinity monitoring stations which will eventually be needed by the real-time salinity monitoring program – since a large component of the River salt assimilative capacity will be generated in the river reach above the Merced River tributary confluence and in the domain of the SJRRP; (b) The real-time salinity management program has developed a data QA solution using WISKI license which does not currently exist in the SJRRP Program.

A single WISKI license could reside on the server and provide benefit to both programs; (c) Integration of monitoring activities makes sense since programmatic releases by the SJRRP will affect river assimilative capacity for salt. Likewise flow forecasts made by the SJRRP to minimize landowner impacts will be useful for improving model forecasting capability for the salinity management program; (d) Overall cost-savings. This is perhaps the only way for the real-time salinity management program to make the sort of progress needed to meet the CVRWQCB expectations for a Basin-wide program that is on track to maintain salinity objectives at Vernalis.

TREND ANALYSIS BASED ON WARMF-SJR MODEL FORECASTS

Both the RTSM and the SJRRP programs are concerned with improved management of flow and water quality in the SJR to meet State-imposed River water quality objectives and to restore the River's Chinook salmon fishery. During winter of 2015-2016,



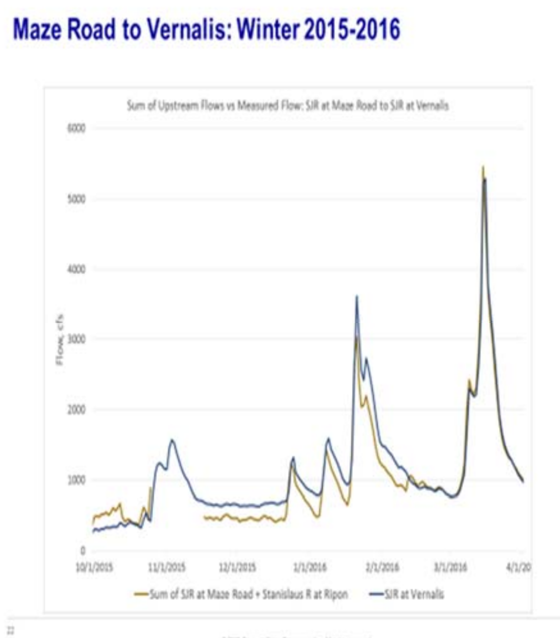


Figure 10. SJR accretion reductions shown for two reaches during 2015/2016.

measured inflow to the lower SJR from its major tributaries was uncharacteristically greater than the measured Vernalis outflow suggesting a higher rate of River depletion along the lower reach of the River. An analysis of measured flow data was performed to ascertain if there might be a longer-term decline of accretions to the lower SJR from groundwater or if the apparent losses were an artifact of prolonged drought conditions. Groundwater accretions were calculated as the difference between the sum of measured tributary inflows to the San Joaquin River and the measured outflow from the San Joaquin River at Vernalis. Daily flow data was collected from 1985-2016 for the gages on the San Joaquin River near Stevinson, Salt Slough, Mud Slough, Orestimba Creek, Del Puerto Creek, Merced River, Tuolumne River, and Stanislaus River and added together to get total daily inflow (Figure 10). In the late 1990's groundwater accretions provided over 600 cfs of flow to the San Joaquin River, but since then there has been a persistent downward trend leading to approximately zero net groundwater accretions in 2015 and net seepage loss from the river in 2016 (Figure 11). This trend is similar between the irrigation season, when there are substantial diversions from the river, and non-irrigation season (Herr 2016).

Water Year:	2012	2013	2014	2015	2016
Ungaged Inflow	364 cfs	289 cfs	51 cfs	16 cfs	-90 cfs

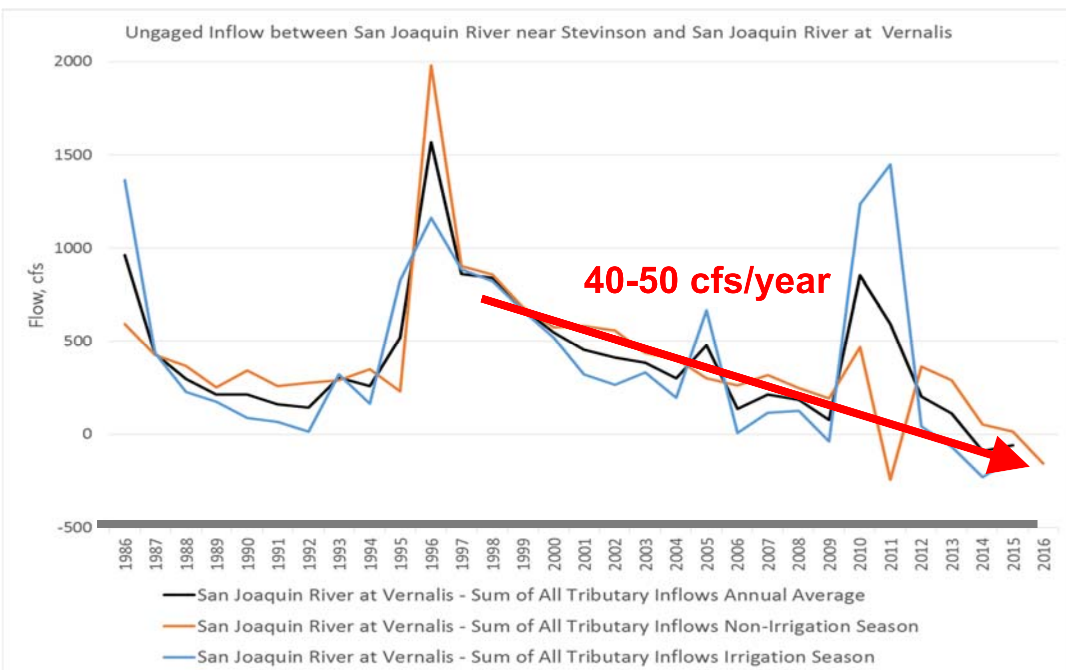


Figure 11. Trend in calculated SJR ungauged inflows over past decade.

A continuation of this trend could result in sections of the river running dry with increasing frequency within 5-10 years. This would have profound impacts on regional water users, the ability to successfully implement a real-time salinity management plan and the effort to restore Chinook salmon to the San Joaquin River.

SUMMARY

Technical advances in data acquisition and information dissemination technologies have made possible the initial stages of implementation of a real-time salinity management program in California's San Joaquin Basin. Experience to date with respect to implementation of RTSM in the San Joaquin Basin suggests the following principles moving forward, that have been discussed in the paper: (a) necessary stakeholder participation in the design and operation of existing and planned flow and water quality monitoring stations and web-based IT solutions that provide easy access to the real-time data being collected; (b) decision support system design should utilize technical expertise within the WSJRWC and ESJWQC at the earliest stage possible to work toward the design of a common system; (c) the WARMF-SJR simulation model that forms the core of River salt assimilative capacity decision support systems should be significantly enhanced with full GIS capabilities and made more robust in its ability retrieve real-time data through the current WARMF-Online web browsing tool and visualization engine to invite greater stakeholder understanding of the process and boost engagement; (d) provide more widespread support for data quality assurance technologies such as WISKI and HYDSTRA to improve accuracy of the real-time data being utilized by the WARMF-SJR forecasting model and reduce the fear of posting erroneous data . The process of implementing RTSM in the SJRB will further encourage innovation – successful implementation will have significant transfer value to other highly regulated river basins where water quality is a concern.

ACKNOWLEDGEMENTS

The authors would like to acknowledge support from the US Bureau of Reclamation for their financial support that has financed development of the necessary tools to implement the concept of real-time salinity management. Thanks also to Ric Ortega, General Manager at Grassland water District, an early adopter of many of these technologies and the Lower San Joaquin Committee of CVSALTS – which is proving to be a fertile ground for new ideas and problem solving related to RTSM implementation.

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CROP WATER USE BY CORN IN THE CENTRAL HIGH PLAINS UNDER FULL AND DEFICIT IRRIGATION

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Kendall DeJonge[2]

ABSTRACT

Corn crop water use (evapotranspiration, ETc) was measured during a four year study at the USDA-ARS Limited Irrigation Research Farm near Greeley, Colo. Replicated corn plots were irrigated by surface drip application to meet full water use requirements and at 5 reduced levels to measure the effects of deficit irrigation on crop response and yield. Crop water use was measured by water balance in which precipitation and irrigation inputs were carefully measured, irrigation was scheduled to avoid deep percolation loss, and soil water content was measured at least twice per week. Seasonal corn water use under full irrigation ranged from 616 to 650 mm and averaged 632 mm. With surface drip irrigation and reduced tillage, estimated surface evaporation was about 10% of total ET. Mid-season basal crop coefficients for a tall crop (alfalfa) reference varied between 1.0 and 1.1, which is about 10% higher than is recommended in the literature. Under deficit irrigation, deep percolation was largely avoided and seasonal change in soil water storage was relatively small, so crop water use was nearly equal to the amount of precipitation and irrigation water applied. The reduction in ET with deficit irrigation was related to soil water deficit and a reduction in crop canopy cover.

INTRODUCTION

Irrigation water supplies in the U.S. Central Plains and much of the western U.S. are declining. Supplies originally developed for irrigated agriculture are being diverted to growing urban areas and for ecosystem restoration. Groundwater use in many areas exceeds recharge and must decrease if we are to sustain this valuable resource. Temperature increases due to climate change will likely reduce the mountain snowpack accumulation that is critical to surface water supplies in the West. Irrigated agriculture will very likely have less water available in the future than it had in the past. Sustaining irrigated agriculture will require increasing the economic productivity per unit of water.

Careful irrigation management can lead to increased water productivity – more yield per unit water. Applying the correct amount of water at the correct time is necessary for efficient irrigation water management. A common method to estimate crop water requirement and schedule irrigation is to use the FAO-56 procedure (Allan et al, 1998) of estimating the evapotranspiration of a reference crop, ETr, from weather data and multiplying this reference ET by a crop coefficient, Kc, for the crop being grown. Crop

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coefficients are determined by measuring the crop ET (ETc) and dividing by the reference ET (ETr).

Although crop coefficients are normally measured for well-watered crops, when water is limited, regulated deficit irrigation may be a desired practice. Thus, crop coefficients for deficit irrigation are also useful.

In 2008, USDA-Agricultural Research Service in Fort Collins, Colorado began a field study of the water productivity of four crops under a range of irrigation levels from fully irrigated to about 40% of full irrigation. We measured ET of the crops under each of these conditions and seek ways to maximize productivity per unit water consumed. We also strive to better understand and predict the responses of the crops to deficit irrigation so that limited irrigation water can be scheduled and managed to maximize yields. In this study, we describe the water balance method we use to measure ETc for this study and the resulting water use and crop coefficients for corn under these conditions.

METHODS

A 20-hectare research farm northeast of Greeley, CO – the Limited Irrigation Research Farm, or LIRF - was developed to enable the precision water control and field measurements required to accurately measure ET of field crops. The low rainfall in the area, predominately sandy-loam soils, and on-demand groundwater supply are ideal for deficit irrigation research.

Four crops – field corn, sunflower (oil), dry beans (pinto), and winter wheat were rotated through research fields on the farm. Crops were planted, fertilized, and managed for maximum production under fully-irrigated conditions, but were irrigated at 6 levels that ranged from fully irrigated to about 40% of the fully irrigated amount. Deficit irrigations began after the corn 7^{th} leaf emerged (V7) and irrigations were temporarily increased during pollination and early grain formation (R1 – R3) to attempt to maximize production by reducing stress during critical growth stages.

Each crop field was divided into 4 replications within which the 6 irrigation treatments were randomized (randomized block design). Water was regulated, measured, and delivered to 10 m (12 row at 0.76 m spacing) x 40 m plots. We applied irrigation water with drip irrigation tubes placed on the soil surface along each crop row to insure that the water was applied uniformly and precisely. This was essential to be able to complete the water balance. Figure 1 shows an aerial view of the research fields in 2008.

Figure 1. Aerial view of the water productivity plots at LIRF. Crops from left to right are beans, wheat, sunflower, and corn. Irrigation treatment effects are visible in the corn.

A CoAgMet (Colorado Agricultural Meteorological Network) automated weather station (GLY04) was installed adjacent to the research field near the center of a 1 acre grass plot. Hourly weather data from the station were used to calculate ASCE Standardized Penman-Monteith alfalfa reference evapotranspiration (ETr). Soil water content between 15 cm and 200 cm depth was measured by a neutron probe from an access tube in the center of each plot. Soil water content in the surface 15 cm was measured with a portable TDR system (MiniTrase, SoilMoisture, Inc., Santa Barbara, CA). Soil evaporation was estimated based on techniques described in Allen et al. (1998). Basal crop coefficients were adapted from Table 8.8 in Allen et al. (2007) based on full cover date. Irrigations were scheduled using both predicted soil water depletions based on ETr measurements, and measured soil water depletion.

Crop ET was measured by water balance. Figure 2 shows a diagram of the water balance parameters for an irrigated field with a deep water table (no upward water movement). In the diagram:

$$ETc = I + P - \Delta SW - DP - R$$

where: I = the irrigation amount, P = precipitation, ΔSW = change in soil water content, DP = deep percolation of water below the root zone, and R = surface runoff. Because DP and R are difficult to estimate accurately, the goal was to irrigate efficiently to minimize DP and R. The low seasonal rainfall in the area (220 mm) also reduces DP and R losses. For our trials on relatively flat fields with moderate infiltration, we assume R is zero. Deep percolation was assumed to occur only when irrigation or precipitation amount exceeded the ability of the soil to store water in the root zone (soil water depletion), and soil water content increased in layers below the root zone. This occurred only in 2008 following unusually high rainfall amounts in August.

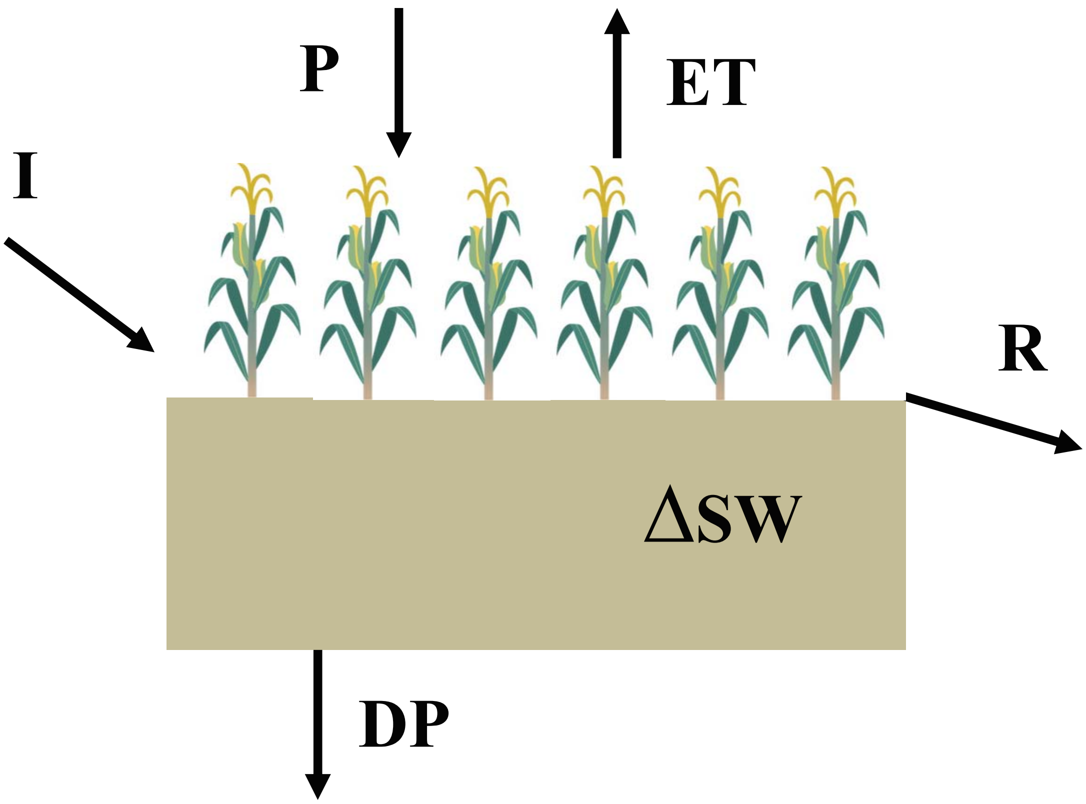

Figure 2. Water balance for irrigated crops.

Plant measurements were taken periodically to determine crop responses to the water levels and relate the crop coefficients to plant growth stage and fractional canopy ground cover, Fc. Canopy cover was measured with a digital camera attached to the boom of a "high boy" mobile platform and driven through the plots weekly (Figure 3). Indicators of crop water stress such as stomatal conductance, leaf water potential, and photosynthesis were measured periodically. Canopy temperature was measured continuously with stationary infrared thermometers and periodically with the mobile platform (Bausch et al., 2010).

At the end of the season, seed yield and quality as well as total biomass were measured from each plot.

Figure 3. High Boy reflectance tractor measuring canopy ground cover, reflectance and temperature.

RESULTS

Figure 4 shows the seasonal water balance for the 2011 corn crop. Seasonal rainfall was 201 mm and irrigation applications varied from 485 mm on the fully irrigated treatment to 157 mm on the lowest irrigation treatment. Soil water storage varied from 38 mm added to the profile for the fully irrigated treatment to 10 mm extracted on the low treatment. There was no evidence of deep percolation. The water balance estimated ETc varied from 650 mm to 368 mm for the high and low treatment, respectively. Due to the relatively small soil water storage in the 1 m deep root zone, soil water storage was a relatively small portion of the total water available to the corn and water use (ETc) was primarily dependent on precipitation and irrigation amounts.

Table 1 lists the seasonal water balance values for the 4 seasons for the fully-irrigated treatment. Seasonal ETc varied from 616 to 650 mm and averaged 632 mm. Alfalfa reference evapotranspiration for the 4 years averaged 968 mm over the 172 day growing seasons, and ETc ranged from 63 – 71% of ETr. Estimated surface evaporation for the drip irrigated crops with 25 – 50% of the soil surface covered with crop residue varied from 58 – 79 mm.

The wide range of irrigation applications resulted in substantial differences in crop growth. Figures 5 and 6 show a comparison of plant height and ground cover in early August, 2008 as the corn was beginning to tassel.

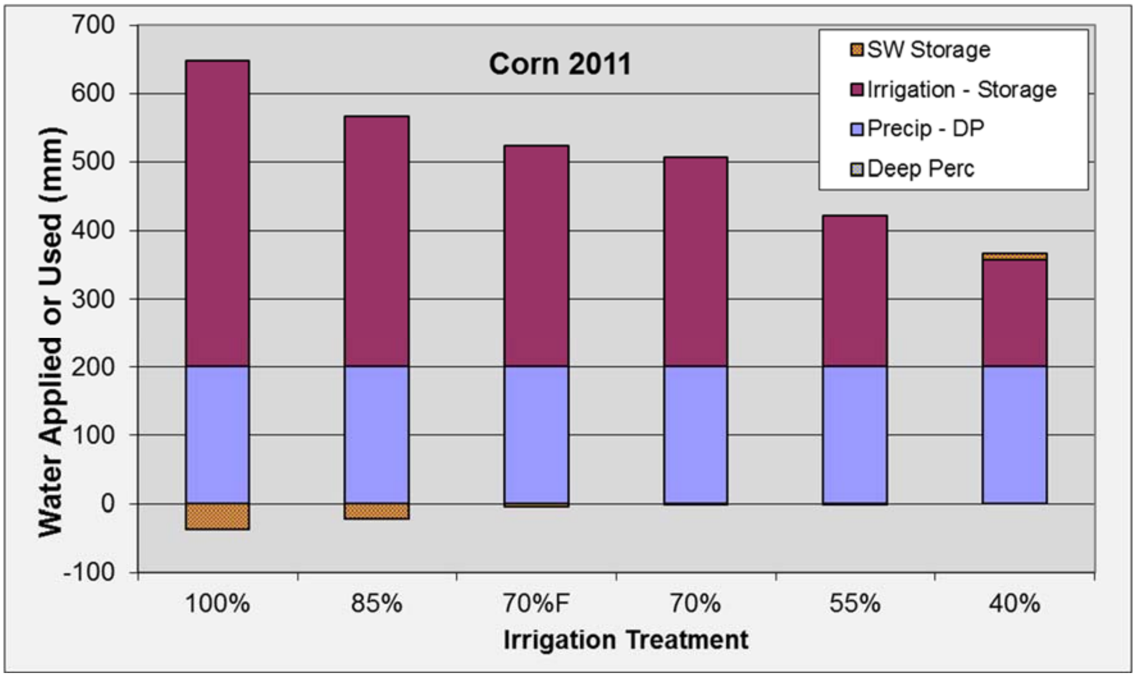

Figure 4. Water balance for the 2011 corn crop showing precipitation, irrigation, and seasonal soil water storage changes. Bars below zero represent additions to storage or deep percolation losses. Dotted areas represent irrigation or precipitation stored or percolated. Treatments represent the target percentage of full ETc.

Table 1. Seasonal water balance values (mm) for the 2008 – 2011 fully-irrigated LIRF Corn.

Year	Precip	Irrig	Deep Percolation	Change in Soil Water Storage	ETc	Evaporation	ETr	ETc/ETr
2008	251	438	80	-25	633	58	983	.64
2009	225	418	0	16	628	78	880	.71
2010	212	366	0	-38	616	66	976	.63
2011	201	485	0	38	650	79	1034	.63
Avg.	222	427	20	-2	632	70	968	.65

Figure 5. Comparison of corn growth condition just before tasseling. Rows at the left and background are fully irrigated; rows at right are the lowest irrigation level.

Figure 6. Canopy ground cover on 7/31/2008. Left photo: Full irrigation with 91% ground cover. Right photo: Low irrigation with 63% ground cover

Figure 7 shows alfalfa reference basal crop coefficient curves for the 2008 - 2011 fully-irrigated corn crop. The data are based on water balance measurements including irrigation and precipitation amounts and changes in soil water content measured before each irrigation. The lines represent a smoothing of these data as an 11 day running average. The black line represents averages for the four years. The time scale is normalized based on time between planting (day 0) and full crop cover (day 100) as proposed by Jensen and Allen (2016) App F. Although there is variation among years, the general shape of the curve is evident.

The figure also shows the alfalfa basal crop coefficient relationship provided in ASCE MOP 70 for grain corn (Table E-2, Jensen and Allen, 2016). These data fit the MOP 70 relationship well in the rapid growth and maturation stages, but indicate mid-season Kcb values somewhat greater than the 0.96 table values. These data also indicate a longer mid-season period as compared to MOP 70 values that project a decline in Kcb beginning 30 days after full cover.

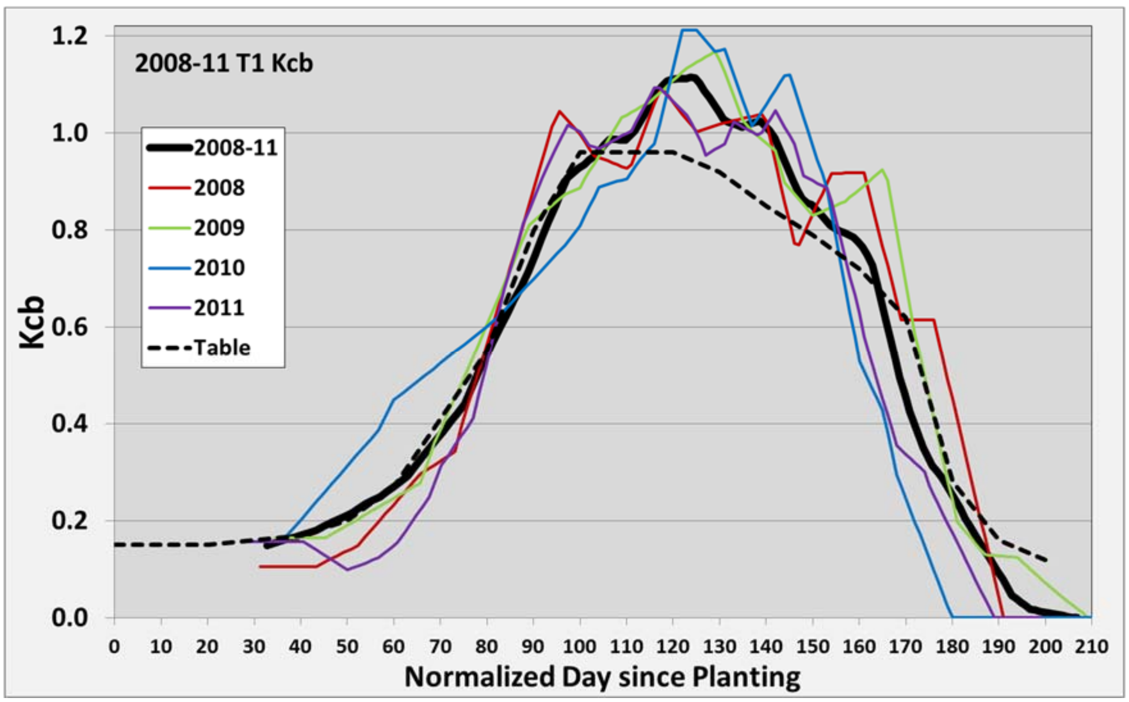

Figure 7. Basal Crop coefficient curves (alfalfa reference) for the 2008-2011 fully-irrigated corn crops measured by water balance, and predicted by Jensen and Allen (2016) (dashed line). Days since planting are normalized between planting (day 0) and full cover (day 100).

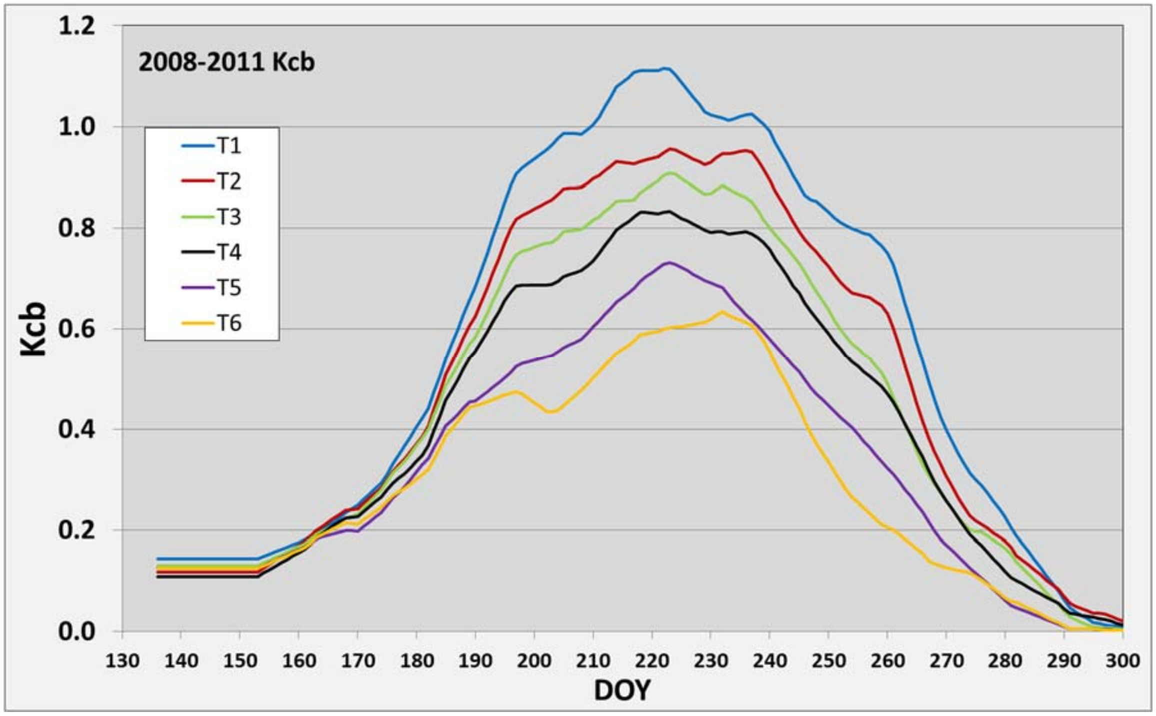

Figure 8. Mean measured basal crop coefficients (alfalfa reference) for the 6 irrigation treatments for the 2008-2011 corn crop. Days since planting are normalized between planting (day 0) and full cover (day 100).

Figure 8 shows the mean measured crop coefficients for each of the six irrigation treatments for the 2008 - 2011 corn crops. Irrigation treatments (T1 – T6) represent decreasing irrigation amounts as listed in Figure 4. As expected, the water balance measured crop coefficient decreases as the water deficit increases. These decreases result in the reduced crop ET shown in Figure 4. They are related to plant water stress that caused decreased canopy ground cover (Fig 6) and reduced stomatal conductance resulting from soil water deficits. The complete dataset from this experiment, including daily values of crop growth and water balance components, daily values of the ETr and ETc, and annual values of yield, are available from the U.S. Department of Agriculture National Agricultural Library Ag Data Commons: https://data.nal.usda.gov/dataset/usda-ars-colorado-maize-water-productivity-dataset-2008-2011 .

CONCLUSIONS

Water balance can be used to measure seasonal crop water use and to estimate crop coefficients when irrigation, precipitation, and soil water content are measured accurately, irrigation is applied uniformly, and water loss to deep percolation and runoff are small. These results, based on four years of field data near Greeley, CO, indicate that ETc of corn in the central high plains is about two-thirds of the alfalfa reference ET and the mid-season basal crop coefficient for corn is somewhat higher and persist longer than values presented in ASCE MOP 70.

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DEFICIT IRRIGATION – SOLUTION TO SUSTAIN IRRIGATED AGRICULTURE?

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Ramchand Oad[2]

ABSTRACT

In many regions of the world, irrigated agriculture consumes most of the available fresh water supplies; therefore, urban and industrial water users view it as a source for satisfying their growing water demand. Use of efficient irrigation practices are encouraged by policymakers to reduce irrigation water losses so that water transfer from agriculture to other uses is possible. Even saving water beyond irrigation losses is considered, *i.e.* give up part of the crop water requirement, or practice of deficit irrigation. The underlying premise of this practice is that farmers reduce their crop consumption and therefore their yield production, but generate more income by leasing or selling the saved water to other societal uses. However, deficit irrigation can be beneficial only when the marginal value of yield production decreases with added amount of irrigation water. When the marginal value is constant, farmers maximize their return by allocating their available water to the most profitable use, either full irrigation farming or water leasing.

DEFICIT IRRIGATION: DEFINITIONS AND CONCEPTS

Deficit irrigation is defined as "the deliberate under-irrigation of the crop" (English, 1990) that reduces crop yield but saves some water at the farm level. The saved water can be sold or rented for off-farm uses including municipal and industrial (M&I) uses. This type of water saving is above and beyond reducing water losses due to irrigation and farm management inefficiencies. It is giving up a part of crop water requirement, which will then reduce the crop yield. Advocates of deficit irrigation argue that with optimal water allocation to on- and off-farm activities farmers can in fact increase their net return from their water right. They reason that the combination of the return from crop production and the return from water market is larger than either one (Fereres et al., 2007; English and Raja, 1996).

Farmers have always practiced deficit irrigation in times of water scarcity. To optimally allocate water and regulate deficit irrigation, the crop yield-water relationship is of utmost importance and must be known. Crop yield can be related to different parameters that describe amount of water used by crop. These are crop transpiration, crop evapotranspiration (ET), amount of available water for crop, or amount of irrigation water. In fact, several mathematical functions are developed based on experiments that

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relate crop yield to one of the above mentioned parameters (de Wit, 1958; Jensen, 1968; Doorenbos and Kassam, 1979).
However, only transpiration water is used by crop for yield production. Since partitioning transpiration from soil surface evaporation is difficult, ET is instead calculated or measured. Research shows that ET and yield are well correlated and ET is the main input to yield production (Tanner and Sinclair, 1983). Therefore the useful practice when developing yield-water relationships is to relate yield to ET. This relationship is called crop water production function (CWPF) which must be used in optimizing water allocation.

Crop water production function is one way of describing yield-water relationship. Another way of modeling yield production against the amount of water is using the "available water" (e.g. Solomon, 1985; Hexem and Heady, 1978). Available water is the amount of water made available to crop through precipitation, irrigation, residual soil moisture, and groundwater capillary rise. The crop typically cannot use all the water that is available to it because of surface runoff and drainage (loss terms). Therefore, total water consumed by crop (ET) is less than the total available water to crop. Past studies show that "available water – yield" relationship is convex (Vaux and Pruitt, 1983). Many scientific works (Rogers et al., 2015; Schneekloth and Andales, 2009) generalize the two forms of water – yield relationship as shown in Figure 1.

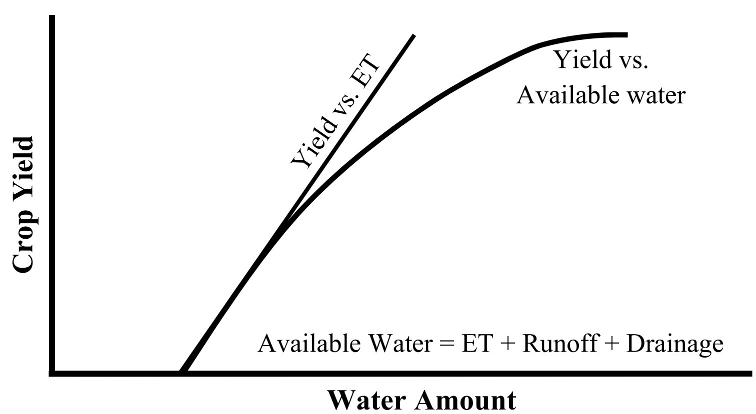

Figure 1. Generalized relationship between yield and water amount (ET or available water) (adapted from Rogers et al., 2015)

"Available water – yield" function is farm specific because the loss terms depend on soil type, farm topography, irrigation systems, and farm management practices. It therefore varies from year to year as well. Yield production is a physiological response to the amount of ET that does not consider any losses or efficiencies of irrigation application type. Therefore, CWPF has to be used when solving water allocation optimization problems. However, many studies, inappropriately, base their analysis on the relationship between available water and yield.

OPTIMAL ALLOCATION OF WATER

Optimal allocation must be defined based on an objective. Then certain metric should be employed in order to compare the value of different options and choose the optimal one.

At the farm level value of water can be determined by the income that it generates for the farmer. As suggested by Griffin (2005) a farm can be considered as an entrepreneurial agent who strives for profit-maximizing decisions. At the farm level, water can be allocated to different crops or leased to off-farm users. We set the objective to allocate water to maximize farmer's profit with limited available water. Then for a certain crop the question is how much of the water should be used for on-farm yield production and how much should be rented for off-farm uses. Therefore the following maximization problem can be written for the farm:

$$\underset{\mathbf{w_y},\, \mathbf{w_{off}}}{\textbf{maximize}}\ Y(w_y)P_y + w_{off}P_{off}$$

$$\text{Subject to} \qquad \mathbf{0 \leq w_y, w_{off} \leq W} \quad \text{and} \qquad \mathbf{w_y + w_{off} = W} \tag{1}$$

where:
w_y= amount of water allocated to crop (yield) production, on-farm water use
$Y(w_y)$= obtained marketable yield as a function of amount of water (CWPF)
w_{off}= amount of water allocated to off-farm activities
P_y= price per unit of yield
P_{off}= off-farm price of water
W= farm total available water

In other words the goal here is to partition the limited amount of farm's available water, W, to w_y and w_{off} in a way that maximum profit is obtained from W. By using w_y unit of water an amount of yield equal to $Y(w_y)$ unit is produced. The product of $Y(w_y)$ unit of yield and the price per unit of yield, P_y, is the profit obtained from allocating w_y unit of water to farming (the first term in the maximization problem). Similarly by leasing w_{off} unit of water a profit equal to $w_{off}P_{off}$ (the second term in the maximization problem) can be obtained.

The two conditions in equation (1) ensure that the amount of water allocated to each use (each of w_y and w_{off}) and the total water allocated to different uses ($w_y + w_{off}$) does not exceed farm's available water (W).

Off-farm price of water (P_{off}) is the net price after any withdrawal costs. Price of yield (P_y) is also the net price after deducting production costs. Other off-farm uses of water, if any, can be added to the above maximization problem. Similarly if total available water is used to grow more than one crop the other crops can be added to the problem.

Here the assumption is that all farm available water can be productively used for yield production. In other words the farm does not own excess water.

The derivative of each term in equation (1) describes that term's maximum or marginal value (mv). Therefore, by equating the two derivative functions the optimal point is obtained. The derivative functions or the marginal value of water for each use with respect to amount of water are as bellow:

Marginal value of water in yield production: $\mathrm{mv_y} = \frac{\mathrm{d}[\mathrm{Y(w_y)P_y}]}{\mathrm{dw_y}} = \mathrm{P_y}\frac{\mathrm{d}[\mathrm{Y(w_y)}]}{\mathrm{dw_y}}$

Marginal value of water allocated to leasing: $\mathrm{mv_{off}} = \frac{\mathrm{d}[\mathrm{w_{off}P_{off}}]}{\mathrm{dw_{off}}} = \mathrm{P_{off}} = \text{constant}$

Optimum allocation is where the marginal values coincide as illustrated in Figure 2.

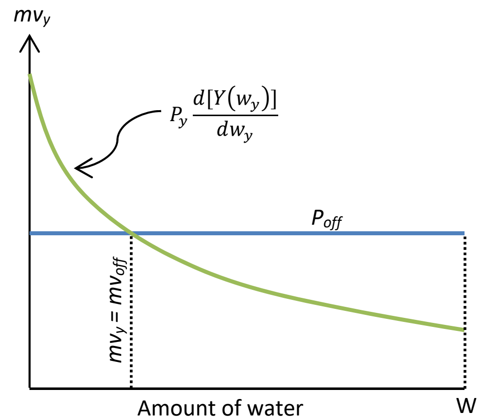

Figure 2. Schematic presentation of optimal water allocation

When CWPF is a linear function in the form of:

$$\mathrm{Y(w_y)} = \mathrm{a\ w_y + b},$$

where a and b are function parameters, the marginal value of water in yield production can be calculated as:

$$\mathrm{mv_y} = \frac{\mathrm{d}[(\mathrm{aw_y + b})\mathrm{P_y}]}{\mathrm{dw_y}} = \mathrm{aP_y} = \text{constant}$$

Suppose $aP_y > P_{off}$ the situation can be graphed as in Figure **3** and it is always economical to allocate all the water to yield production because it has a larger marginal value and generates more economic return.

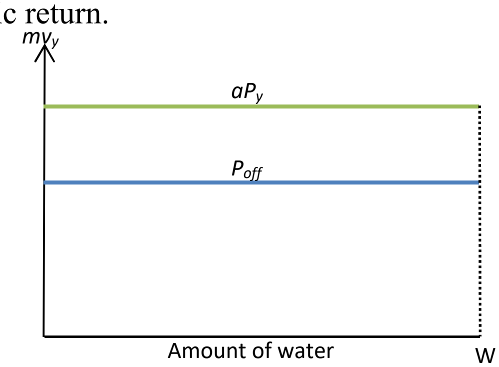

Figure 3. Schematic presentation of optimal water allocation for linear CWPF when $aP_y > P_{off}$

Similarly when $aP_y<P_{off}$ as apparent in Figure 4, it is optimal to allocate all the water to off farm uses.

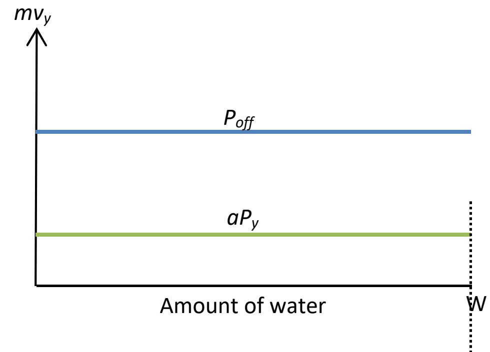

Figure 4. Schematic presentation of optimal water allocation for linear CWPF when $aP_y<P_{off}$

In other words, for linear CWPF, the optimal solution for equation (1) does not justify partitioning of water between on- and off-farm uses but the optimal solution is to allocate it all to the most valuable use[1].

Crop water production function, aside from its linearity or nonlinearity, has an important characteristic. That is it intercepts ET-axis at a point greater than zero (see Figure 1). In other words a minimum amount of water (w_{min}) is required before any yield is produced by the crop. For example it was observed in a research field[2] near Greeley, CO that corn needs at least about 350mm of water before yield production can start. Same observed data supports quadratic CWPF for corn based on results of four growing seasons (2008-2011). There is also a maximum amount of water (w_{max}) above which ET remains constant and the excess water does not contribute to yield production (English, 1990). Therefore, for a non-linear CWPF Figure 2 has to be modified as Figure **5**.

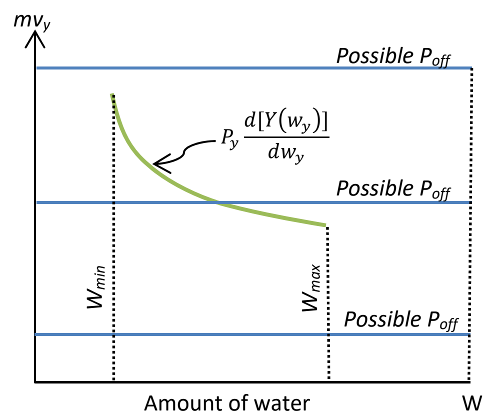

Figure 5 Schematic presentation of optimal water allocation for non-linear CWPF with minimum and maximum

[1] Presentation of the problem as demonstrated here is derived from Shaw (2005), chapter 2. Also course materials from Dr. Christopher Goemans's "Water Resources Economics and Policy" course (spring 2015) have been used.

[2] Limited Irrigation Research Farm (LIRF) of Agricultural Research Center of US Department of Agriculture. Data is provided by Dr. Thomas Trout.

Note that P_{off} can fall above $P_y \frac{d[Y(w_y)]}{dw_y}$ or below it and hence not intercept it. Once again the optimization problem will have an "either/or" solution; that is one of the uses of water alone will generate maximum profit and hence no water should be allocated to the other use.
It appears that in most cases and as long as farmers' profit maximization is concerned, partitioning water between the farm and M&I uses is not reasonable.

DISCUSSION

Deficit irrigation is an on-farm water management strategy. The above analysis describes why the combination of deficit irrigation and leasing water does not return maximum profit and why farmers do not practice such management strategy in times of water scarcity. For example in Colorado buying agricultural water rights for cities and leaving farm lands fallow has been common practice instead (Colorado's Water Plan, 2015).

Literature review shows that advocates of deficit irrigation base their analysis on "available water – yield" function (for example see English and Raja, 1996; Zwart and Bastiaanssen, 2004). This function has a wide plateau at the top (see Figure 1); therefore, yield reduction due to decreased available water is not significant around the top plateau. Perhaps because managing and measuring the available water is more viable and tangible, this relationship is preferred over CWPF. However, as discussed previously, using "available water – yield" relationship in optimization problems is incorrect.

Research on the shape of CWPF is not conclusive, but the commonly used functions (developed by Doorenbos and Kassam, 1979; Jensen, 1968) are linear and relatively reliable (Zwart and Bastiaanssen, 2004). For these kinds of functions deficit irrigation or partitioning water is not justifiable because marginal value of water in farming is constant. Even when CWPF is concave marginal value of water in leasing may always be larger than that of farming, which implies all water has to be leased to maximize farm profit. The reverse is also possible; that is, when the marginal value of water in farming is always greater than that of leasing and all the water has to be used for full irrigation of crop.

We realize that the optimization problem in equation (1) is formulated for farm level and for one year. Therefore, price per unit of yield, Py, can be held constant. This might not be the case when agricultural water transfer to M&I uses continues. Within a watershed (or some political boundary) decrease in agricultural production may affect the price of crop over several years. In that case Py will become a dependable variable of available agricultural water. Moreover, by changing the scope of problem from farm level to ditch company or basin level, the optimization objective will change. For example, at state level policy makers may decide to preserve agricultural economy. Such objective may justify keeping a part of water on farm lands.

CONCLUSION

Conventional farm management practices aim to maximize crop yield and farm production. Instead, deficit irrigation is regarded as a way to maximize farm profit, when water is optimally allocated to on- and off-farm uses. In optimization models CWPF, *i.e.* ET-yield relationship, must be used and using "available water – yield" relationship instead of it, is incorrect.

Practice of deficit irrigation can increase farm profit only when marginal value of water decreases with added amount of water, *i.e.* when CWPF is concave. Although research on the shape of CWPF is not conclusive, most commonly used functions are linear and suggest constant marginal value for water in farming.

Even for concave CWPFs, and hence marginal value of water in farming, is only valid within a certain interval. So again the marginal value of water in leasing can fall above or below that of farming. In which case partitioning farm water will not be profit maximizing.

At farm level and in most cases, deficit irrigation does not provide a profitable alternative to complete transfer of water to M&I but policymakers may still decide to encourage practice of it to preserve agricultural economy.

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