Final Report of

The Lower South Platte Irrigation Research and Demonstration Project

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2014 Final Report of
The Lower South Platte Irrigation Research and Demonstration Project

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A Cooperative Project

of

Colorado Water Conservation District
Parker Water and Sanitation District
Colorado State University and CSU Extension
Colorado Corn Growers Association

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Executive Summary

A partnership between Parker Water and Sanitation District and Colorado State University, with support from Colorado Water Conservation Board and Colorado Corn Growers Association, has been studying irrigation methodologies that create saved consumptive use that could be transferred to municipal but avoid the complete dry-up of irrigated farm land. In previous projects viable water conserving cropping systems were identified and demonstrated at the Lower South Platte Irrigation Research Farm, near Iliff. The cropping systems include rotational cropping, limited irrigation, and partial season irrigation approaches. In a South Platte survey, irrigators expressed a willingness to adopt these water conserving cropping systems. A significant obstacle to adoption of these practices is uncertainty about how associated water transfers would be administered and how consumptive use savings and return flow changes can be quantified.

The first task in this Alternative Agricultural Water Transfer Grant evaluates approaches for quantifying consumptive savings of alternative cropping practices. Three approaches were evaluated and include a stress coefficient, the crop water stress index (CWSI), and satellite based remote sensing using the ReSET model. The intent of a stress coefficient is to apply the use of crop coefficients and standardized energy balance equations used for estimating reference ET to cropping systems that involve water stress. The stress coefficient estimates reductions in ET due to limitations from dry soil conditions. Stress coefficients were quantified for maize plots under well irrigated and deficit irrigated treatments at the Iliff research site during three growing seasons. The deficit irrigation treatment had a 20%-55% reduction in irrigation application and resulted in 10%-34% reductions in consumptive water use. The daily modeling approach outlined in the Irrigation and Drainage Paper No. 56, published by the Food and Agriculture Organization of the United Nations (FAO-56) underestimated maize water use, but the difference (8%-26%) was similar to typical errors reported for other data-intensive and complex water use estimation methods. In addition, seasonally averaged water use errors did not exceed 1.0 mm d^{-1} for any studied treatment and season, suggesting that the FAO-56 procedure can be used as an effective method for quantifying consumptive use and savings in limited irrigation systems. The practical application of this approach requires measurement of soil water content at the beginning of the growing season and site specific estimates of soil water retention properties.

The CWSI was a second method evaluated for quantifying consumptive use in deficit irrigated cropping systems. CWSI is a remote sensing approach based on the use of infrared thermometry to assess the temperature of the crop canopy. The canopy temperature is indexed against air temperature and humidity defined limits to calculate CWSI. As part of this project, upper and lower limits were established for corn in Eastern Colorado conditions. A remote sensing-based Crop Water Stress Index (CWSI) was estimated during a time with variable degrees of stress at the Iliff research farm in 2011. The CWSI was capable of differentiating among irrigation practices and is clearly a candidate method for assessing whether a crop is experiencing water stress. The CWSI values were also used to estimate corn transpiration rate. Applying an independent remotely sensed energy balance model showed that corn ET was 177 mm during the study period (29 days), 29% larger than CWSI-Ta (137 mm) during the same period. Thus the CWSI under-predicted ET. This method appears to have more application toward relative determination of crop water status than for quantification of saved consumptive use.

The third approach for quantifying consumptive use of limited irrigation systems uses a CSU developed model called Remote Sensing of Evapotranspiration (ReSET). The model utilizes thermal band satellite imagery, in combination with local weather observations to calculates evapotranspiration on the day the image was taken. The model can use multiple satellite images taken over the growing season to calculate the season crop consumptive water use and can express the spatial variation within fields. For this project, ReSET was tested against controlled conditions at the Iliff research site, and also on farmer's field. At the Iliff site, ReSET identified small differences in crop ET and produced good estimates of ET. To evaluate the model on farmer's fields, ReSET was tested for four fields. The temporal and spatial actual ET for each of these fields was calculated and documented using the ReSET model. The seasonal actual ET estimated by the ReSET model compared very well to reported irrigation records with an accuracy of up to 98% and not less than 92% for fields with normal growing conditions. ReSET was able to detect abnormal growing conditions on some fields such as late crop development, areas that do not have a good crop stand and the model results quantified the reduction in ET due to such conditions. The results of this research project show the potential for using the ReSET model to monitor and quantify the ET from agricultural fields with limited irrigation. The method does require some specialized technical knowledge, but there are good research publications that provide the details of how the method can be applied.

Each of the three methods evaluated have individual strengths and weaknesses, but any of them could be utilized in evaluating compliance with water transfers, while avoiding the need for complete dry-up of agricultural fields. One recommended approach would be that irrigators involved in water transfers associated with water conserving irrigation practices assume responsibility to track ET using a stress coefficient approach. Technical service providers, such as crop consultants, can support this effort. Farms in such an agreement would benefit from the use of flow meters and soil moisture sensors in their fields. Organizations overseeing water transfers could further utilize one of the remote sensing approach for verification of reported practices and ET rates.

The second task for this project was to evaluate the potential of an allocation approach for administering the transfer of saved consumptive use from irrigated farms to municipalities. In an allocation approach, an irrigated farm would agree to a fixed, reduced allocation of water for irrigation. The approach makes an assumption of zero return flow from the applied irrigation, therefore the full obligation for maintaining historic return flows would be met through a separate diversion of water into an approved augmentation system. In this approach all of the monitoring and verification would occur at points of diversion or pumping and the need for in-field soil moisture sensors or remote sensing would be avoided. Only the saved consumptive use above the amount required for meeting return flow obligations would be transferred to municipal use. To illustrate the concept of the allocation approach, four hypothetical scenarios are outlined and discussed in the report. Further, in 2012 the Iliff field site was used for a demonstration of an allocation approach based on 5 years of baseline measured values. For a sprinkler irrigated corn crop with an allocation of 10 in., there were 4.3 in. of saved consumptive use available for transfer. Based on actual ET and drainage calculations, the amount of water that could be transferred was 4.6 in. The small amount of additional saved water does not well justify the high administrative burden of quantifying ET and return flows, illustrating the advantage of an allocation approach. The Iliff case study illustrates the potential of an allocation approach, event though the quantity of water available for transfer was small. The cost and benefits of a smaller allocation could be evaluated. A benefit from an allocation approach is that it creates an incentive for irrigation efficiency improvements, which is often lacking in water law governed by the prior appropriations doctrine. Another potential benefit is that the return flow assumptions are conservative and additional return flows may provide benefits to rivers and downstream users.

In the final task of the project, detailed modelling was performed to estimate the quantities of water that could potentially be delivered to Parker Water and Sanitation District from consumptive use water savings on irrigated farms Logan County. In general, the exchange potential on the Lower South Platte River is low, with a decreasing trend as the river nears the Nebraska State line. Moving further upstream would have a positive impact on the amount of exchangeable flow available. The exchange potential from the Iliff area to Fort Morgan appears to be too unreliable to serve as a municipal water supply. Rather, a pipeline from the Iliff area to PWSD (i.e., Rueter-Hess Reservoir) produces the most efficient water delivery system. In this scenario, consideration of retiming or storing the water in a reservoir appears to be a critical to the success of the system. Another approach evaluated is to use recharge to re-time irrigation season flows. The analysis and modelling show that there are significant amounts of water resources available in the Lower South Platte River basin that can be sustainably and responsibly used to benefit Front Range municipalities without having a detrimental impact to irrigators on the South Platte River when alternatives to dry-up are facilitated. As such, saved consumptive use can be a valuable part of the total waters diverted and transported back upstream for use, but do not have to be viewed as the sole source of water, to the detriment of rural economies.

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<u>Statement of Problem</u>

The work on this project is centered on a research site in the Lower South Platte Basin located near Iliff, CO (Figure 1). Field research was conducted at the site from 2008-2012 on limited irrigation, rotational cropping, and partial season irrigation approaches for water conservation. The work was overseen by Colorado State University, in cooperation with Parker Water and Sanitation District (PWSD) and with support from PWSD, Colorado Water Conservancy District, and Colorado Corn Growers Association. The earlier project results identified viable cropping practices that reduce consumptive use while avoiding dry-up of irrigated land and were detailed in a previous report submitted to CWCB in 2011, titled 'The Lower South Platte Irrigation Research and Demonstration Project.' The adoption of these approaches is limited by lack of an accepted administrative and enforcement approach. Legal and administrative hurdles stand as major obstacles to adoption of alternative water conserving practices. This project addressed the need for a practical means of calculating and verifying consumptive water use and of addressing return flow concerns.

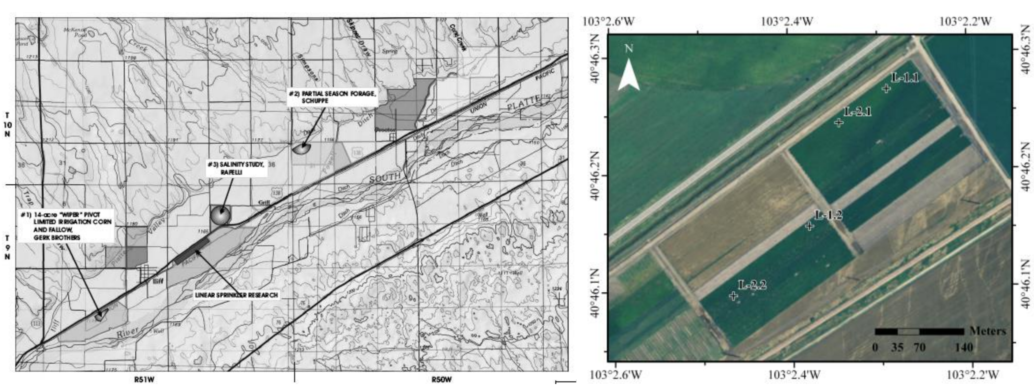


Figure 1. Locations of Lower South Platte Irrigation Research and Demonstration field-site near the town of Iliff and an aerial image of the site in 2011.

Project Purpose and Need

The overall purpose and need of this study has remained unchanged since the initiation of the studies. The purpose is to provide much needed water supplies to urban interests for municipal and industrial use, while protecting the rural economies in areas where some, but not all, of the water is removed from agricultural use. The need for this study is to explore alternative means to agricultural water transfers, without using the traditional “buy and dry” concept that can be harmful to rural economies, so that both rural and urban interests can benefit from a more beneficial approach in a cooperative effort that helps sustain both economies.

Specifc Project Tasks

1. Develop a practical means of calculating and verifying consumptive water use and water savings in alternative systems that will satisfy Water Court requirements.
2. Demonstrate a water allocation approach to simplify the administrative burden to maintain return flows.
3. Parker Objective….

Task 1. Develop a practical means of calculating and verifying consumptive water use and water savings in alternative systems that will satisfy Water Court requirements.

<u>Description of Task</u>

The objective of this task was to develop, test, and validate potential approaches for determination of consumptive use and water savings of limited irrigation cropping practices. Approaches evaluated include evaluation of a stress coefficient, the Crop Water Stress Index, and use of satellite images through application of the RESET model.

Evaluation of a Stress Coefficient

<u>Background</u>

Energy balance equations are commonly accepted means for estimating evapotranspiration rates. The American Society of Civil Engineers have standardized the use of the Penman-Monteith equation (ASCE Standardized Equation) and it has been widely used and accepted (ASCE, 2005). Similarly the international Food, Agriculture Organization has published a standard equation (Allen et al., 1998). In simple terms, energy balance equations calculate the amount of energy from climate factors available to drive evapotranspiration and estimate the evapotranspiration for a reference surface condition (ET_r). Locally observed weather measurements required for the ET calculation include solar radiation, temperature, relative humidity, and wind speed. Weather station networks in Colorado, such as the Colorado Agricultural Meteorological Network (www.coagmet) and the Northern Water Network (http://www.northernwater.org/WaterConservation/WeatherandETInfo.aspx) provide the necessary data for ET_r calculation from weather stations located in key agricultural areas of the state. Historical weather observations are built into the *StateCU* model, which is widely used in Colorado for ET determination. Colorado uses a tall crop reference condition, which is based on an alfalfa crop with approximate height of 0.50 m, full-cover, and well water conditions. The weather networks provide on-line access to observed weather data and ET calculations. A complete COAGMET weather station is maintained at the Iliff research site used to evaluate the stress coefficient approach.

The actual crop water use (ET_c) is determined by modifying the ET_r to reflect non-reference crop surface conditions. This is achieved by by multiplying ET_r by a crop and growth stage specific crop coefficient (K_c), as illustrated in the following equation:

$$ET_c = ET_r \text{ x } K_c$$

Crop coefficients have been developed for the major crops irrigated in Colorado. However, the crop coefficients were developed under the assumption of well water conditions and, therefore, cannot predict ET_c of a crop experiencing periods of drought stress, such as would occur under limited irrigation management. In order to calculate consumptive water use under limited irrigation scenarios ($ET_{c\text{-}adj}$), and additional modification of ET_r is needed. One approach is to calculate a stress coefficient (K_s). The Ks estimates the reduction in consumptive water use caused by the presence of stress from a soil water limitation.

$$ET_{c\text{-}adj} = ET_r \text{ x } K_c \text{ x } K_s$$

Stress coefficients can be used with standardized methods of calculating reference evapotranspiration, such as the ASCE-Standardized method. However, the dependability of using Ks factors to verify ET_c under limited irrigation practices has not been demonstrated. One objective of this project was to evaluate the effectiveness of the use of a K_s factor for limited irrigation practices in Colorado.

Approach

The study was done based on data from the Lower South Platte Irrigation Research Farm near Iliff (Figure 1) with data collected at the site from 2008 to 2010. Corn (*Zea mays L.*) was planted in 18×38 m plots on 29, 20, and 25 May in 2008, 2009, and 2010, respectively. Two irrigation treatments of well-irrigated (WI) and deficit-irrigated (DI) were implemented, each with four replicates. The WI treatment attempted to mimic the traditional irrigation practice of local farmers, which is to avoid any water stress. This approach resulted in a total applied irrigation depth of 457 mm (18 in), 399 mm (16 in) and 470 mm (19 in) in 2008, 2009 and 2010, respectively. The DI treatment, on the other hand eliminated irrigations during vegetative growth periods. Compared to the WI treatment, the reduction of applied irrigation water through DI was 50%, 55%, and 20% in 2008, 2009 and 2010, respectively. Other farming operations were carried out following as close as possible to the common practices applied by the local farmers, particularly in terms of weed and pest control and fertilizer application. Soil water content was measured weekly using a neutron attenuation meter at 30 cm (12 in) increments to 150 cm (5 ft). The stress coefficients (Ks) and corn ET were obtained following two different approaches. The first approach was through solving the root zone water balance (RZWB) for corn ET using neutron probe measurements. Thus, its estimates were regarded as the actual corn ET (ET_{act}) and Ks ($K_{s\text{-}act}$), integrated over the several days in between two consecutive neutron probe readings. The second approach was based on the daily modeling of K_s and ET following the FAO-56 procedure outlined in Allen et al. (1998). These results were regarded as estimated K_s ($K_{s\text{-}est}$) and estimated corn ET (ET_{est}). Daily $K_{s\text{-}est}$ was determined according to the FAO-56 procedure through the following formula:

$$K_{s\text{-}est} = (TAW - D_r) / (TAW - RAW)$$

where TAW is the total available water in the root zone, D_r is the root zone depletion, and RAW is the readily available water, all in units of water depth (mm). The RAW is estimated by multiplying the TAW with a crop-specific depletion factor (p). In this study, a value of p = 0.55 was selected for corn from the FAO-56 tables and modified accordingly for each day when the ET_c was different than 5.0 mm d^{-1}. An upper limit of unity is applied to the output of $K_{s\text{-}est}$

equation when the depletion in the water content of the root zone is smaller than RAW. As the depletion becomes larger, $K_{s\text{-}est}$ decreases until it reaches a value of zero at a soil water content equal to the permanent wilting point. After obtaining $K_{s\text{-}est}$, corn daily ET was obtained using the following equation:

$$ET_{est} = K_{s\text{-}est} \times K_c \times ET_o$$

Except for model initiation, neutron probe readings were not used in the FAO-56 procedure explained above. In other words, the measurements of SWC were only used as initial conditions on the first date of modeling period, namely the sowing date. This approach was used to mimic the proposed application of the FAO-56 procedure for verification of crop ET under deficit irrigation, where users would require initial SWC and soil water retention properties to apply the model.

Results

For the WI treatment, the FAO-56 procedure provided $K_{s\text{-}est}$ values that were generally in agreement with $K_{s\text{-}act}$ values (Figure 2). Both $K_{s\text{-}act}$ and $K_{s\text{-}est}$ remained close to unity during the first 35 days after seeding (DAS) in 2008. This was due to: *i*) corn having a small water use as it was in the initial stage of growth for about two-thirds of this period; and, *ii*) applying a large amount of water (223 mm) during this period. In the following week, however, stress coefficients decreased significantly since only 33 mm of rainfall occurred during a period with 50 mm of ET. The next period (ending on DAS 49) was the first time in the 2008 season when $K_{s\text{-}act}$ and $K_{s\text{-}est}$ values had a substantial difference. While the measurements showed a slight decrease in stress, the FAO-56 procedure predicted an increase in water stress (i.e. decrease in $K_{s\text{-}est}$). The differences between $K_{s\text{-}act}$ and $K_{s\text{-}est}$ values were not statistically significant for the next two periods. Stress coefficients reached values close to unity again during the period ending on DAS 67. This is not surprising, since the average water application depth (irrigation and precipitation combined) was 11.0 mm d^{-1} during this period, which is larger than the average corn standard-condition ET_c of 10.0 mm d^{-1} and consequently larger than corn actual ET under the non-standard conditions of the study. Although the same amount of irrigation was applied during the next period (ending on DAS 77), the precipitation amount was significantly smaller, resulting in an average water application depth of only 5.7 mm d^{-1}. Considering that average corn ET_c was about 8.4 mm d^{-1} during this period, the observed decrease in stress coefficient was expected. The $K_{s\text{-}act}$ and $K_{s\text{-}est}$ values were 0.9 and 0.8, respectively, during the last period (ending on DAS 119: the harvest date). This was also expected as corn ET_c decreased significantly due to crop senescence, as well as the reduction in atmospheric demand. The variations in K_s and ET of WI treatment as affected by climate and water applications can be inferred similarly for 2009 and 2010 seasons (Figure 2).

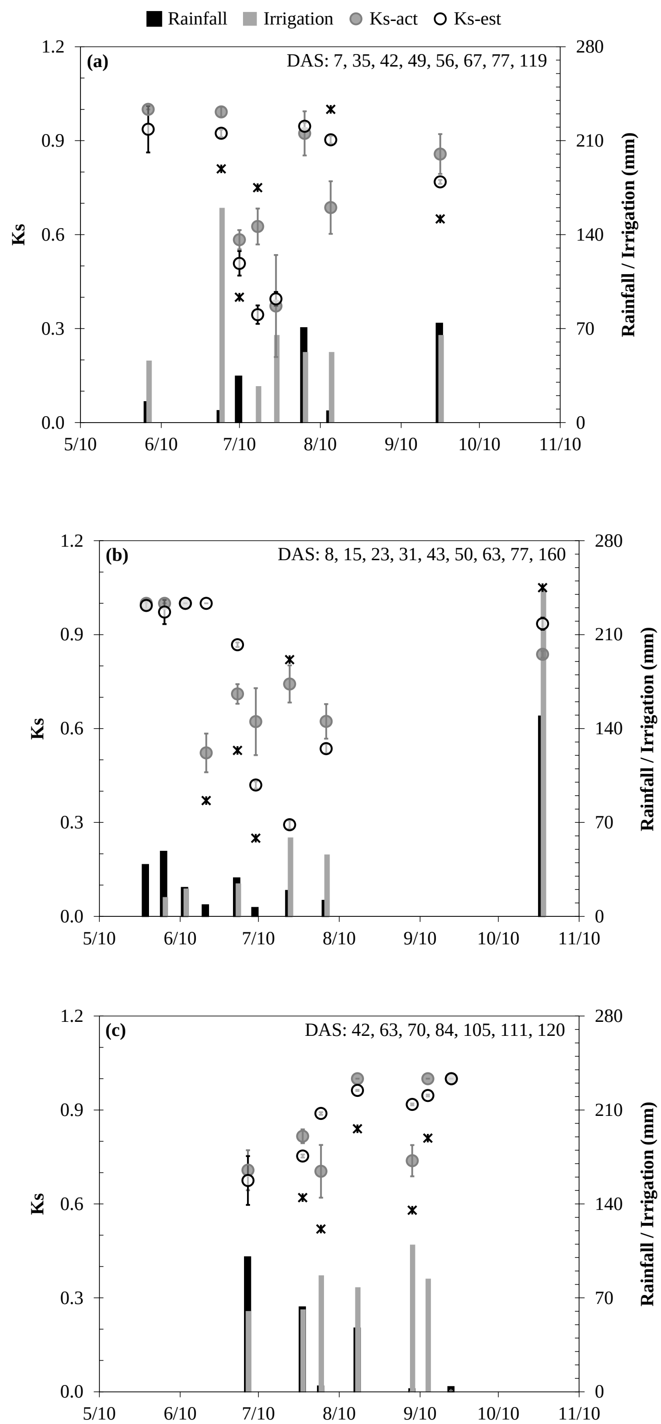


Figure 2. The evolution of average $K_{s\text{-}act}$ and $K_{s\text{-}est}$ for corn under the well irrigated (WI) treatment during (a) 2008; (b) 2009; and, (c) 2010 cropping seasons. For each period, the last day is reported in Days after Seeding (DAS). The vertical bars represent the cumulative value of applied water through irrigation or precipitation during the same period. The asterisk indicates that the average $K_{s\text{-}act}$ and $K_{s\text{-}est}$ values are statistically different at a 5% significance level.

As expected, deficit irrigated corn plots experienced a larger water stress than those observed for the WI treatment (Figure 3). Unlike the $K_{s\text{-}act}$ values, the FAO-56 procedure estimated mid-season SWC near the PWP, and thus $K_{s\text{-}est}$ values that were near the minimum limit (zero) in 2008 and 2009. Near-zero $K_{s\text{-}est}$ values do not seem to be realistic, as this lower limit represents the condition at which the crop is permanently wilted. Our field observations were consistent with non-zero (minimum values greater than 0.2) $K_{s\text{-}act}$ values in that DI corn recovered after the dry periods. Compared to 2008 and 2009, K_s values of the DI treatment were much closer to those of the WI treatment in 2010, due to the fact that only 20% reduction in applied irrigation was achieved in this year. Considering all seasons and treatments, the FAO-56 procedure generally underestimated the K_s (i.e. predicted a more severe water stress). The difference, however, was dependent on the irrigation treatment. Seasonal averages of $K_{s\text{-}est}$ were from 7% to 18% smaller than their corresponding $K_{s\text{-}act}$ values for WI plots, while the same difference ranged from 14% to 26% for plots under the DI treatment. Table 1 summarizes the average measured and modeled K_s for each season and treatment, along with their corresponding error indicators.

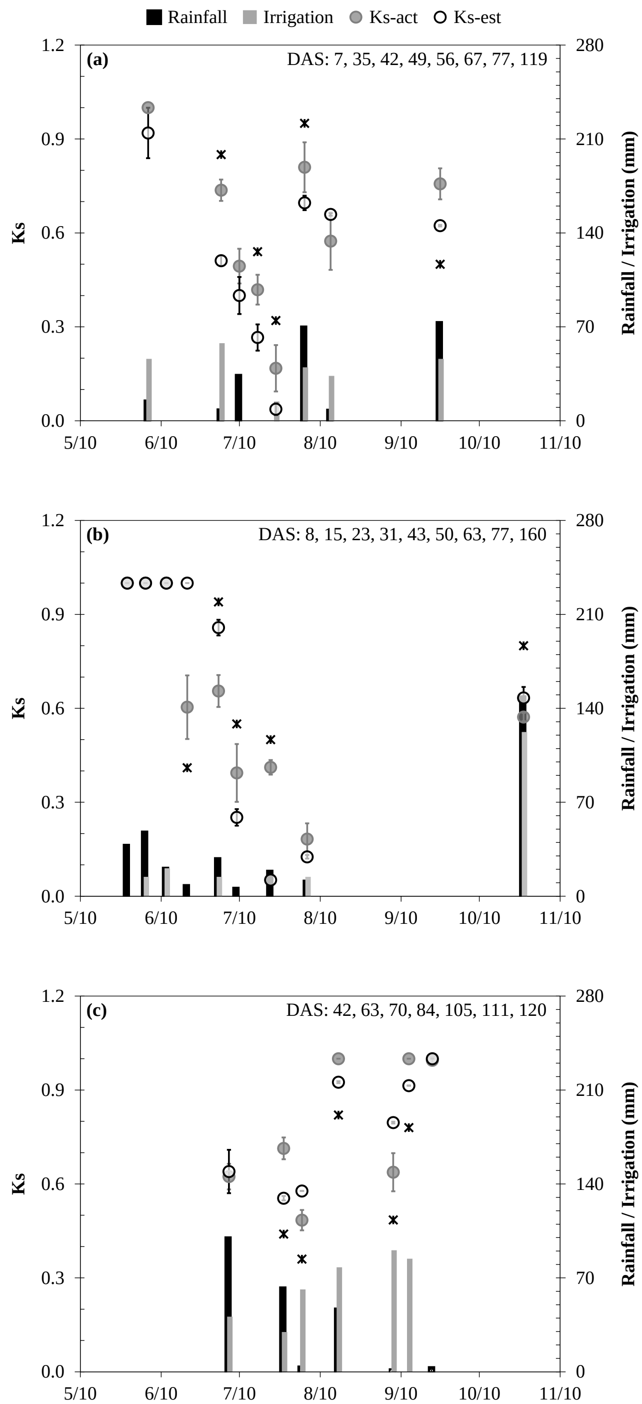


Figure 3. The evolution of average $K_{s\text{-}act}$ and $K_{s\text{-}est}$ for corn plots under DI treatment during (a) 2008; (b) 2009; and, (c) 2010 cropping seasons. The average values for each period between two consecutive neutron probe readings are plotted on the last day of that period. For each period, the last day is reported in Days after Seeding (DAS). The vertical bars represent the cumulative value of applied water through irrigation or precipitation during the same period. The error bars indicate the standard deviation (not visible when covered by the symbol). The asterisk indicates that the average $K_{s\text{-}act}$ and $K_{s\text{-}est}$ values are statistically different at a 5% significance level.

Table 1. Seasonal averages of measured ($K_{s\text{-}act}$) and estimated ($K_{s\text{-}est}$) stress coefficients.

Year	Treatment	$K_{s\text{-}act}$	$K_{s\text{-}est}$
2008	WI	0.85	0.70
	DI	0.65	0.48
2009	WI	0.85	0.75
	DI	0.56	0.47
2010	WI	0.86	0.80
	DI	0.78	0.67

The variations in measured and estimated corn ET had a pattern similar to that of K_s. The closure of the RZWB using neutron probe readings indicated that even for the WI treatment, seasonal corn water use never reached the potential rate under standard conditions. In other words, none of the years were fully irrigated. During the three years of study, seasonal ET_{act} of WI and DI treatments were 14%-15% and 23%-44% smaller than the seasonal ET_c, respectively. The ET_{act} values for DI plots were 24%, 34%, and 10% smaller than those of WI plots in 2008, 2009 and 2010, respectively. By comparison, the total irrigation depth for the DI treatment was 50%, 55%, and 20% smaller than the WI treatment. These observations demonstrate that water application efficiency increased under deficit irrigation regime, mainly due to less deep percolation. Implementing deficit irrigation practices to transfer saved ET to other users may result in reductions in historical irrigation return flows, which will require that other approaches by taken to mimic historical return flows so as not impact downstream water users.

Compared to the RZWB estimates, the FAO-56 model underestimated corn water use for all treatments and years. Howell et al. (2004) argued that the FAO-56 assumption of a simple linear relationship between K_s and SWC (after the depletion of RAW) exaggerates the onset of water stress occurrence. If that is the case, it could explain the consistent underestimation error observed in this experiment. Among the three studied seasons, the range of differences between seasonal ET_{act} and ET_{est} was 8%-17% and 13%-26% of the ET_{act} results for WI and DI treatment, respectively, with a total average of 15%. While these differences are potentially important, they should be considered in the context of the accuracy of other methods of ET estimation. According to Allen et al. (2011), the typical errors of the data-intensive Bowen ratio and Eddy-covariance energy balance methods are from 10% to 30%, with the potential for introducing large additional errors if the numerous required sensors are not functioning properly or, more importantly, if the analyses are not performed by "an experienced expert, trained and steeped in the physics of the process." Therefore, it can be concluded that the FAO-56 procedure had an acceptable performance in predicting corn consumptive water use under non-standard conditions of this study. Similar satisfactory performances were reported for cotton (*Gossypium hirsutum* L.) in central Greece (Kotsopoulos et al., 2003), as well as for several cover crops planted under the semi-arid climate of eastern Austria (Bodner et al., 2007). Howell et al. (2004), however, stated that the FAO-56 procedure had a significantly improved performance under well-watered compared to deficit irrigation and dryland regimes, suggesting that the approach should be further studied under the two latter conditions. The estimated error indicators in this study never exceeded 1.0 mm d^{-1} (0.04 in/day; Table 2), smaller in magnitude compared to those reported by Howell et al. (2004) for cotton under the highly advective climate of the northern Texas High Plains.

Table 2. Total corn ET under standard-conditions (ET_c), measured (ET_{act}) and estimated (ET_{est}) corn ET under non-standard conditions of this study (in mm), as well as the MBE and the RMSE in (mm d^{-1}).

Year	ET_c	Treatment	ET_{act}	ET_{est}
2008	744	WI	629	524
		DI	481	357
2009	760	WI	644	567
		DI	427	360
2010	716	WI	639	590
		DI	575	498

The use of this approach to estimate ET requires 1) initial soil water content values, and 2) site specific soil water holding capacity information. Under these experimental conditions, one reason for the reasonably good model performance was the availability of high quality soil moisture data at the beginning of the season. Like any model, the FAO-56 procedure is sensitive to the accurate identification of the initial condition. In its practical application, obtaining a dependable initial SWC estimate may be less precise, which will increase errors compared to those observed in this study. One approach to minimize this source of error is to initialize the model one or two days after a significant precipitation or irrigation event, when the SWC could be assumed equal to field capacity (Allen et al., 2005). The existence of such an event before the onset of a growing season is likely in many environments, especially if farmers apply a pre-plant irrigation to fill the root zone. Another factor that may have contributed to the relatively small errors of the FAO-56 model results in this experiment is site specific determination of soil water holding capacity. In this study, the soil field capacity limit was based on actual *in situ* measurements that were taken following significant wetting events. When applying the method more generally, the field capacity and permanent wilting point values needed to obtain soil water holding capacity will be most probably identified using previously-published values for different soil textural classes. This may introduce additional errors as the tabulated values may not accurately represent the actual soil conditions of study area. Another approach would be to use calibrated soil moisture sensors in the field to obtain estimates of soil water holding capacity.

Evaluation of the Crop Water Stress Index

Background

An evaluation was made of a second potential approach for quantifying ET under limited irrigation cropping practices. This approach is based on measuring the temperature of the crop canopy and relating the temperature to the level of crop water stress and rate of ET. When a plant experiences water stress, the stomates on the leaf surfaces close, which slows the rate of transpiration, and results in an elevation of the temperature of the canopy surface. However, canopy temperature alone is not a useful indicator of stress or ET rate, because it varies widely as a function of weather conditions, time of day, and the specific type of leaf surface. The Crop Water Stress Index (CWSI) was developed as an approach to normalize over these variable parameters.

Crop Water Stress Index is a widely-used indicator that provides an estimate of crop water status with respect to minimum and maximum levels of stress that can occur due to availability or unavailability of water. CWSI can be estimated using the following equation (Idso et al., 1981; Jackson et al., 1981):

$$CWSI = (dT_m - dT_{LL})/(dT_{UL} - dT_{LL})$$

where dT is the temperature difference between canopy and air ($T_{canopy} - T_{air}$) and subscripts m, LL, and UL represent measured, lower limit, and upper limit of dT, respectively. Upper and lower limits of dT can be estimated through either the empirical approach of Idso et al. (1981), or the theoretical approach proposed by Jackson et al. (1981). The empirical approach is based on the fundamental assumption that there is a linear relationship between dT_{LL} and vapor pressure deficit (VPD) for a given non-water-stressed crop under a specific climatic condition. Likewise, there is a linear relationship between dT_{UL} and vapor pressure gradient (VPG) for the same crop when its transpiration is halted due to severe water stress:

$$dT_{LL} = m\,(VPD) + b$$

$$dT_{UL} = m\,(VPG) + b$$

where "m" and "b" are slope and intercept of the linear relationship, respectively. VPG is estimated as the difference between saturated vapor pressure at air temperature and at a higher temperature equal to air temperature plus the coefficient "b." As part of this project, we evaluated seven previously developed baselines and idenfied that baselines developed under climatic conditions similar to that of the study area in northeastern Colorado were successful in appropriately bounding upper and lower limits of dT_m (Taghvaeian et al., 2012). CWSI is inversely related to water use of a crop Jackson et al. (1981) through the following relationship:

$$T_a = (1 - CWSI) \times T_p$$

where T_a and T_p are actual and potential crop transpiration, respectively. Since CWSI is a dimensionless parameter, resulting T_a would have a unit similar to that of T_p (e.g., mm d^{-1}). The reason that the above equation predicts actual transpiration and not actual evapotranspiration (ET_a) is that CWSI estimates are based on canopy thermometry and characteristics of underlying soil are not included. Evaporation of water from the soil surface occurs after a wetting event and its duration is limited to one to three days depending on soil type and environmental conditions. Therefore, T_a approaches the definition of ET_a between irrigation events.

Approach

The CWSI was evaluated using corn grown at the Iliff research site in 2011. The corn (DKC52-59 Brand, DEKALB ®) was planted on May 4, 2011 at 34,000 seeds ac^{-1}. After a 163-day long growing season, harvest took place on October 13, 2011. Irrigation water was applied using a linear-move sprinkler irrigation system (T-L Irrigation Company, Nebraska, USA), while a 3-m deep drainage ditch along the northern edge of the farm removed deep percolated water from the soil. Two limited irrigation treatments were included in this study. The first treatment had two replicates (L-1.1 and L-1.2, hereafter) and received a total amount of 114 (4.5 in) of water through four irrigation events. The second treatment had also two replicates (L-2.1 and L-2.2, hereafter) but received three irrigations, totaling 89 mm (3.5 in) of applied water. The extra irrigation of L-1 treatment occurred in early July, while the other three irrigations occurred at approximately the same time for all treatments in mid-July, late July, and mid-August. This amount of irrigation water was accompanied by a significant amount of precipitation (400 mm; 16 in) that fell between planting and harvest dates.

The main sensor at each treatment was an infra-red thermometer (IRT, model SI-111, Apogee Instruments, Inc., Logan, Utah, USA) with a 44˚ field of view, an accuracy of 0.2 ˚C, and a filter that passes radiation only in the thermal part (8 – 14 μm) of the electromagnetic (EM) spectrum. The IRT was installed on a mast at a 45˚ angle below horizon (facing south) to avoid viewing any background soil. Installation height was 2.7 m from the ground surface and remained above the canopy at all times, since corn did not grow taller than 2.0 m. Canopy temperature was scanned with the IRT units every one minute and readings were averaged over a 30-minute time interval (period). In order to reference target temperature and to correct readings for any contribution from heat of the sensor itself, the temperature of the IRT body was also measured by a thermistor embedded inside the sensor. Corrected target temperatures (i.e., canopy) were obtained by applying the body temperature correction algorithm provided by the IRT manufacturer (Apogee). Controlling the measurements, measuring and storing corn canopy temperature, and reporting measured data were all performed using data-loggers (models CR800 and CR1000, Campbell Scientific Inc., Logan, Utah, USA). At treatment L-2.1, soil water content from the top soil was also measured using water content reflectometer sensors at a depth of 5.0 cm (model CS616, Campbell Scientific Inc., Logan, Utah, USA).

The first step in estimating CWSI was to develop the non-water-stressed and non-transpiring baselines for corn under the semi-arid climatic conditions of the study area in northeastern Colorado. In order to do so, a procedure similar to that implemented by Idso et al. (1981) was followed. More specifically, corn-air temperature differential (dT_m) measurements that were collected by IRT during one day after two significant precipitations were plotted with their corresponding VPD data. It was assumed that one day after a major wetting event, soil water deficit was fully replenished and corn had access to sufficient soil water. Thus, non-water-stressed conditions existed and dT_m values represented dT_{LL} values. Plotting dT_{LL} versus VPD for a 24-hour period resulted in a curve which had a linear section during the period of a few hours after sunrise and a few hours before sunset. This linear segment was extracted and used as non-water-stressed baseline.

Corn hourly potential transpiration (T_p) was obtained by multiplying corn basal crop coefficients (K_{cb}) by the hourly alfalfa-based reference ET (ET_r) values. Hourly ET_r was calculated using weather data collected at the adjacent CoAgMet station and through the standardized alfalfa reference ET Penman-Monteith equation (ASCE, 2005). Estimates of K_{cb} were obtained from tabulated values presented in the FAO-56 paper publication (Allen et al., 1998). Since tabulated values are to be used with grass-based reference ET (ET_o) under sub-humid climate, they were first converted into values that could be used with ET_r through a division by 1.2 (as recommended in Allen et al., 2005). To account for the effect of the study area's semi-arid climate, further modifications were then performed using average daily wind speed and daily minimum relative humidity. Hourly CWSI-T_a values were compared with hourly ET_a estimates of a RSEB model on four dates during the study period. The implemented RSEB model was specifically developed by Chávez et al. (2005) for corn planted in central Iowa, USA. Remotely sensed input data into this model comprised of surface reflectance and radiometric temperature data that were collected using a hand-held multispectral radiometer. More details on collecting radiometer data and running the model are explained in (Taghvaeian et al., 2012). There are several major differences between the CWSI and the RSEB approaches. The first difference lies in the fact that the CWSI was based on canopy temperature, while the implemented RSEB model also incorporates surface reflectance in the visible and near infra-red portions of the EM spectrum. In addition, radiometric surface temperatures used in CWSI were detected by IRT's that had a 45˚ viewing angle in order to view only corn canopy; measuring canopy temperatures. In contrast, input data into the RSEB model were collected by a radiometer that had a nadir viewing angle, resulting in the presence of both corn canopy and some underlying soil in the sensor field of view. These two differences explain why the remote sensing-based CWSI model provides an estimate of crop transpiration, while RSEB results also include evaporation from soil surfaces (if any after a wetting event).

Although hourly estimates of corn water use are useful in understanding crop water status, irrigation managers are usually more interested in estimates that represent periods longer than hourly. As a result, several methods have been developed to extrapolate hourly water consumption rates to daily and seasonal estimates. One method that has been mainly utilized by recent remotely sensed energy balance (RSEB) models is known as "*the alfalfa reference ET fraction*" or ET_rF, which is based on the assumption that the ratio of ET_a to ET_r at the time of data collection remains constant during the day (Allen et al., 2007). Once this ratio is calculated based on hourly data, it can be multiplied by daily estimates of ET_r to provide an approximation of ET_a on daily basis. A similar approach, which we called "*potential ET fraction*" or ET_pF (T_a/T_p), was employed in this study to extrapolated CWSI-based estimates. It was assumed that the ratio of hourly CWSI-T_a to hourly T_p is constant throughout the day.

Results

The development and applicability of the upper and lower limits are detailed in a peer reviewed manuscript (Taghvaeian et al., 2012). The remote sensing-based CWSI was calculated from August 5 to September 2, 2011 for each of the one-hour periods between 10:00 and 14:00 (MST). As expected, each time frame resulted in a slightly different CWSI value estimate. Figure 4 depicts the variation in hourly CWSI's for two field-plots, L-1.2 and L-2.2, during the four-week period of study.

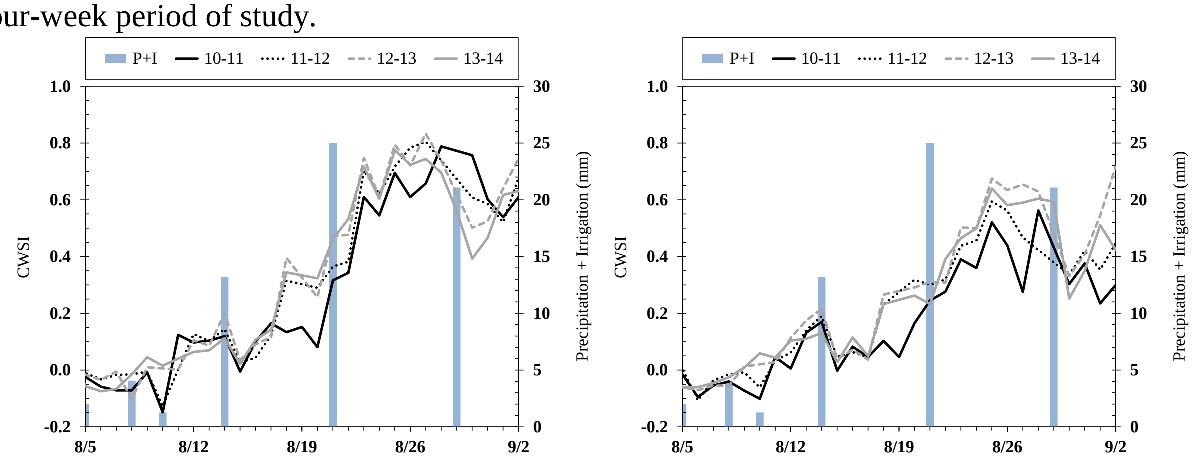


Figure 4. Hourly graphs of CWSI for plots L-1.2 (left) and L-2.2 (right) during the study period (Aug. 5 – Sep. 2, 2011).

The corn crop experienced almost no stress during the first week of the study. This is mainly due to the fact that about 31 mm (1.2 in) of rain fell on the field on August 4, 2011. This precipitation event was followed by three more rainfalls during the first week that were not significant in amount, but probably enough to compensate for part of the August 4 rainfall that was evaporated from soil surface or transpired by corn. CWSI then increased to less than 0.2 before the next precipitation event happened on August 14, 2011. The effect of this precipitation on lowering stress level can be clearly observed (Figure 4). After this event, however, CWSI increased steadily until August 25, which is when the average daily air temperature reached its maximum value of 27.9 ˚C during the study period. Decreased air temperatures and 21 mm of rainfall on August 29 caused CWSI to remain constant or decrease over the last week of the study. Based on the results, the irrigation that occurred on August 20 for the L-1 treatment replicates and one day later for L-2 treatment replicates was not able to reverse the trend in CWSI variation, even though it provided 25 mm (1 in) of water. Table 3 presents the mean and median hourly CWSI values for all experimental treatments during study period.

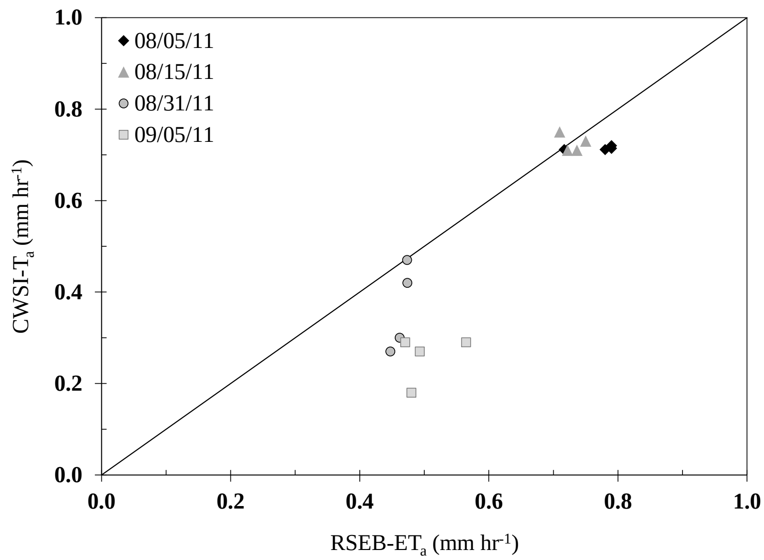
Table 3. Mean and median CWSI for each one-hour period during the 29 days of experiment.

Plot	10-11		11-12		12-13		13-14	
	Mean	Median	Mean	Median	Mean	Median	Mean	Median
L-1.1	0.17	0.10	0.21	0.18	0.25	0.18	0.22	0.17
L-1.2	0.29	0.15	0.33	0.30	0.34	0.33	0.32	0.33
L-2.1	0.33	0.22	0.36	0.34	0.37	0.34	0.33	0.31
L-2.2	0.18	0.16	0.23	0.27	0.28	0.28	0.25	0.23

For each field-plot, the average CWSI increased from a lower value during the 10-11 hour to a maximum value during the 12-13 hour and then it decreased slightly during the last hour (13-14). Irmak et al. (2000) also stated that the period between 12:00 and 13:00 is when CWSI is largest and thus, CWSI-based irrigation scheduling should use the data collected during this period of the day. They also found out that seasonal average of CWSI for corn planted under Mediterranean semiarid climate should be kept below 0.22 in order to avoid any yield loss [9]. This is similar to the findings of Steele et al. (1994) that no significant yield loss occurred under an irrigation scheduling based on CWSI threshold of 0.2.

As the first step toward evaluating the performance of CWSI method in estimating corn water use, hourly CWSI-T_a and RSEB-ET_a were compared on four dates when multispectral radiometer data were collected (Figure 5). Hourly data were used for comparison in order to exclude any effect that extrapolating from hourly to daily values may have had on water use estimates.

Figure 5. CWSI-T_a versus RSEB-ET_a estimates for four days in summer 2011.



The results showed that the difference between the two estimates increased over time as the crop matured and senesced. For the first date (Aug. 5), RSEB-ET_a was equal to CWSI-T_a for plot L-2.2 and less than 11% larger for the other plots. A high Soil Adjusted Vegetation Index (SAVI) of 0.68 indicates that canopy was at full cover on this date. Thus, it is not surprising that T_a and ET_a estimates are very close to each other, since both nadir-looking radiometer and oblique IRT were viewing only plant leaves. On the second date (Aug. 15) ET_a was about 5% smaller than T_a for plot L-1.2, but up to 4% larger for the other plots. Average SAVI was still rather high (0.63) on this date, meaning that canopy remained close to full cover (previous studies show that corn reach full cover at SAVI value of 0.64 (Bausch, 1993). On the third comparison date (Aug. 31), corn had entered into maturity/senescence phase and growth stage was also more variable among treatments. While plots L-1.1 and L-2.2 had an average SAVI value of 0.55, plots L-1.2 and L-2.1 showed more signs of senescence and had an average SAVI of 0.43. So the hand-held multispectral radiometer was viewing both canopy and soil surface. On this date, ET_a estimates were within 13% of T_a results for the former two plots, but they were up to 66% larger for the latter two plots. It is worth mentioning that this date was preceded by a significant precipitation event (21.0 mm) that occurred two days earlier. Soil surface was still saturated when the field was visited for data collection and thus evaporation from soil surface was taking place at a relatively high rate. On the last date (Sep. 5), all treatments were partially senesced and average SAVI dropped to 0.37, resulting in ET_a estimates that were from 62 to 167% larger than T_a estimates. Taking RSEB-ET_a results as reference, Mean Absolute Error (MAE) of CWSI-T_a was calculated as 0.06, 0.02, and 0.10 mm hr^{-1} on the first three comparison dates, respectively. Limiting the analyses to plots that had larger biomass and therefore less exposed soil (L-1.1 and L-2.2) decreased MAE to 0.04, 0.03, and 0.03 mm hr^{-1}, respectively. Since these MAE estimates are obtained by comparing CWSI-T_a values to modeled (and not measured) values, they may not be regarded as actual error of CWSI results. However, it is perhaps safe to conclude that the remote sensing-based CWSI method can yield water use estimates that are as accurate as the RSEB results, since MAE values are all within the accuracy range of the RSEB algorithm. This is a promising finding, as RSEB models are by far more complicated and time-consuming than the CWSI approach. Furthermore, the CWSI method could potentially be implemented using radiometric surface temperature from aerial and satellite platforms (to cover areas at different spatial and temporal scales) if the surface temperature imagery are calibrated, when the vegetation is not fully covering the soil, to obtain spatially distributed canopy temperature.

Use of satellite images through application of the RESET Model

Background

Satellite image methods are a potential means of documenting irrigation approaches, water use, and water savings. Use of satellite images to determine water use has been successfully documented and used by Bastiaanssen et al. (1998a and b and 2000). They developed SEBAL that uses Landsat 5/7 imagery and can be used with other image formats as well and METRIC that stems from SEBAL (Allen et al., 2005) but adds an internal calibration and a better method for calculating seasonal ET. A model called Remote Sensing of Evapotranspiration (ReSET), has been developed at Colorado State University (Elhaddad and Garcia, 2008). It expands the capabilities of SEBAL and METRIC and has been applied using Landsat 5/7 imagery. The objective of this project phase was to demonstrate the potential for satellite imagery to verify and quantify water savings from water saving cropping practices other than land dry-up. In comparison to the previous two methods, this prject component demonstrates a multi-farm to basin scale approach to determine ET by measuring instant, daily, and seasonal actual ET. The ReSET model has a seasonal module which estimates cumulative ET for the season which is essential in calculating water savings, the seasonal module uses ET grids derived each day a satellite image is available and a network of weather stations or soil moisture sensors to develop a detailed seasonal ET grid for a particular area of interest (field, canal service area, region) with a 30m by 30m resolution when using Landsat 5 imagery. The objective of this part of the research was to use the ReSET estimated actual ET (ET_a) for three corn plots to calculate actual corn crop coefficient, stress factor and the seasonal crop water used in the three plots.

Approach

There are two components to this phase of the research. First, the ReSET model was applied to field results from the Iliff experimental location, where there were experimentally controlled field-plots with varying irrigation. Second, the ReSET model was applied to farmers fields to demonstrate the capability of the model to estimate ET without detailed information about irrigation practices.

For the Iliff site, the ReSET Raster model was used to estimate actual hourly and daily evapotranspiration (ET_a) for three target corn plots (noted in Figure 6 as 1, 2, 3) for the 2011 growing season starting on 5/4/2011 and ending on 10/13/2011. The available usable satellite images for this area during this period from Landsat 5 and 7 collections are listed in Table 4. Landsat 7 imagery was used “as is” with its striping problem without any interpolated data or gap filling.

Table 4. Landsat imagery dates used in the plot monitoring.

Collection Dates for Landsat 5&7 Images
5/16/2011
6/10/2011
6/25/2011
6/26/2011
7/3/2011
7/4/2011
7/19/2011
7/20/2011
8/5/2011
8/13/2011
9/5/2011
922/2011
9/30/2011

An example close-up view of the Iliff experimental plots boundaries is shown with a backdrop of Landsat 5 imagery in Figure 6. From the image, the effect of the boundaries of the corn plots can be seen. To address this, the plot boundaries were buffered in 30 meters to reduce the thermal contamination caused by the edges of each plot. All plot-level calculated values are averages of all the pixels within the buffered plot boundary.

Figure 6. Close up view of plots boundaries with a backdrop of Landsat 5 imagery.

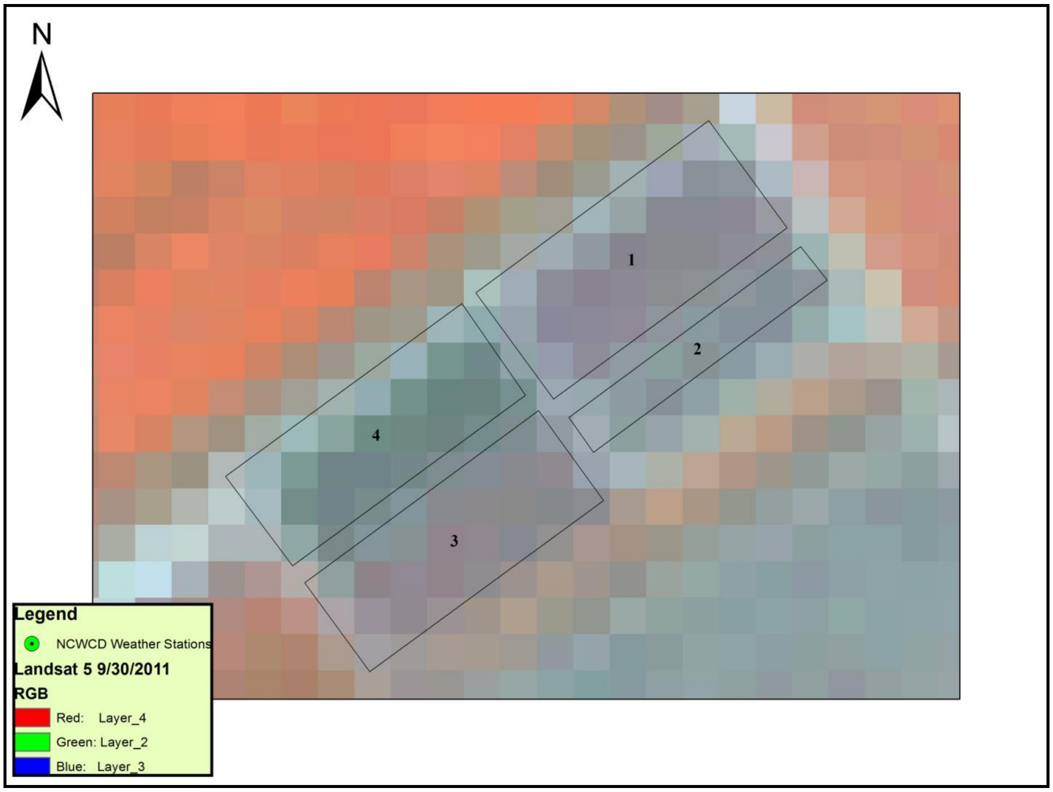
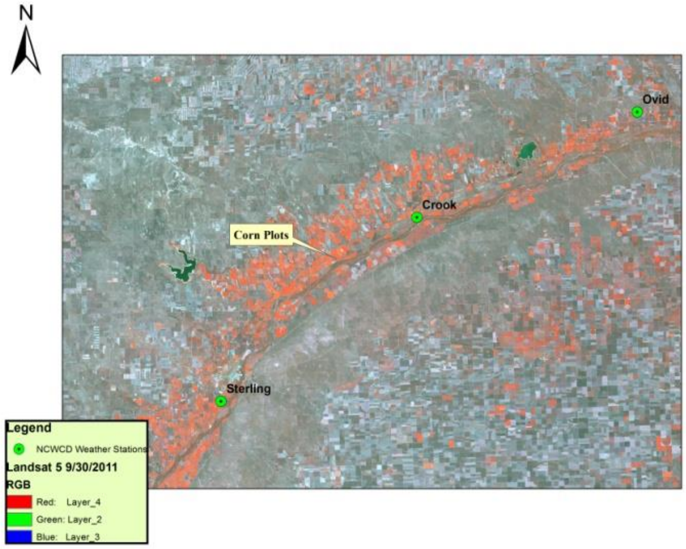


Figure 7. The location of the Iliff research site relative to the weather stations used for ReSET analysis.



The ReSET Raster model was used in the calibrated mode where the model uses the reference ET calculated from multiple weather stations for its internal calibration. The Sterling and Crook weather stations were used, both are managed by Northern Colorado Water Conservancy District (NCWCD), which are the closest to the plots and therefore have the biggest impact on the model calibration (Figure 7). Daily and hourly weather data (reference ET, Wind run) for the Sterling and Crook weather station were obtained. The hourly ET_a grid estimated by the ReSET model at the time of the satellite overpass (10:30 am local time) was used to estimate hourly ET_a for the corn plots then the hourly value was extrapolated to estimate the 24 hour actual ET_{a24}. The hourly ET_a estimated by ReSET is used with the weather station reference ET grids developed from the nearby weather stations (Sterling, Crook) to calculate Corn K_{ca} in the three study plots.

For the farmers fields component, the intent was to estimate daily and seasonal evapotranspiration (ET) for selected fields using the ReSET model and the seasonal ET tool both developed by the Integrated Decision Support Group (IDS) at Colorado State University. In consultation with a crop consultant, four farmers' fields were selected that were knows to have experienced some drought stress during the drier than average 2006 growing season. Further, fields were chosen where irrigation amounts could be estimated. Four fields (Franson 5, Franson 8, Boo north of house and Boo south of house), met these criteria. Rainfall was obtained from closest weather stations and calibrated pump station records were used to estimate irrigation (Table 5).

Table 5. Area and ET estimated by ReSET for the selected fields.

Field	Area (acres)	Crop	ReSET ET from 5/15 to 9/6 (mm)	Irrigation & Rain from 5/15 to 9/6 (mm)
Franson 5	130	Corn	606	637
Franson 8	130	Corn	605	615.8
Boo North of House	128	Corn	529	708
Boo South of House	125	Soy beans	566	520

Seven Landsat 5 images were processed to create the single ET grids. The images are for path/row 32/32 and were obtained from the USGS earth resources observation systems (EROS) center. The image dates are 5/11/2006, 5/27/2006, 6/28/06, 7/14/2006, 7/30/2006, 8/31/2006 and 9/16/2006. The IDS seasonal tool that creates seasonal ET estimates from individual ET grids created by the ReSET model were used to estimate the seasonal ET for the selected study fields for the season starting on 5/15/2006 and ending on 9/6/2006.

Results

The ReSET model was used to estimate actual hourly and daily evapotranspiration (ET_a) for the three target corn plots (1, 2, 3) for the 2011 growing season starting on 5/4/2011 and ending on 10/13/2011. Table 6 shows values of corn actual crop coefficient (K_{ca}) for the Iliff study site. ASCE corn crop coefficient K_{cm} is also calculated based on the planting date of May 4th of 2011. Figure 8 shows the actual hourly ET values for the three plots plotted along with the potential corn ET_p based on the K_{cm} and adjacent weather stations. The ReSET model was able to differentiate the ET from the individual plots that resulted from different irrigation and previous crop scenarios.

Table 6. ReSET estimated ET, actual Kc for corn, and stress coefficients for three field-plots at the Iliff research location on 13 dates in 2011. For comparison, reference ET, ASCE Kcm, and potential corn ET are shown.

Collection Dates for Landsat 5&7 Images	ReSET estimated ET for field #1 in inc.	ReSET estimated ET for field #2 in inc.	ReSET estimated ET for field #3 in inc.	Referance ET from weather station in inc.	ReSET based crop Kc for field #1	ReSET based crop Kc for field #2	ReSET based crop Kc for field #3	ASCE based crop Kcm	Crop stress factor for field #1	Crop stress factor for field #2	Crop stress factor for field #3	Potential Corn ET for all fields
5/16/2011	0.20	0.24	0.17	0.66	0.30	0.36	0.26	0.20	1.00	1.00	1.00	0.13
6/10/2011	0.23	0.26	0.37	0.67	0.35	0.39	0.56	0.35	0.99	1.00	1.00	0.23
6/25/2011	0.61	0.60	0.60	0.94	0.65	0.64	0.64	0.60	1.00	1.00	1.00	0.56
6/26/2011	0.49	0.50	0.50	0.81	0.61	0.62	0.62	0.63	0.96	0.98	0.98	0.51
7/3/2011	0.57	0.55	0.54	0.82	0.69	0.67	0.66	0.77	0.90	0.87	0.85	0.63
7/4/2011	0.63	0.61	0.61	0.98	0.64	0.62	0.62	0.79	0.82	0.79	0.79	0.77
7/19/2011	0.70	0.60	0.67	0.82	0.85	0.73	0.82	0.95	0.90	0.77	0.86	0.78
7/20/2011	0.79	0.57	0.61	0.90	0.88	0.63	0.67	0.96	0.92	0.66	0.70	0.86
8/5/2011	0.67	0.58	NA	0.72	0.92	0.80	NA	0.95	0.97	0.84		0.69
8/13/2011	0.67	0.55	0.60	0.73	0.92	0.75	0.82	0.94	0.98	0.80	0.87	0.69
9/5/2011	0.64	0.54	0.58	0.92	0.70	0.59	0.63	0.83	0.84	0.71	0.76	0.76
9/22/2011	0.52	0.44	0.47	0.59	0.88	0.75	0.80	0.74	1.00	1.00	1.00	0.44
9/30/2011	0.54	0.50	0.50	0.76	0.71	0.66	0.66	0.43	1.00	1.00	1.00	0.33

Figure 8. Hourly ET values estimated by ReSET model and hourly potential corn ET based on adjacent weather stations.

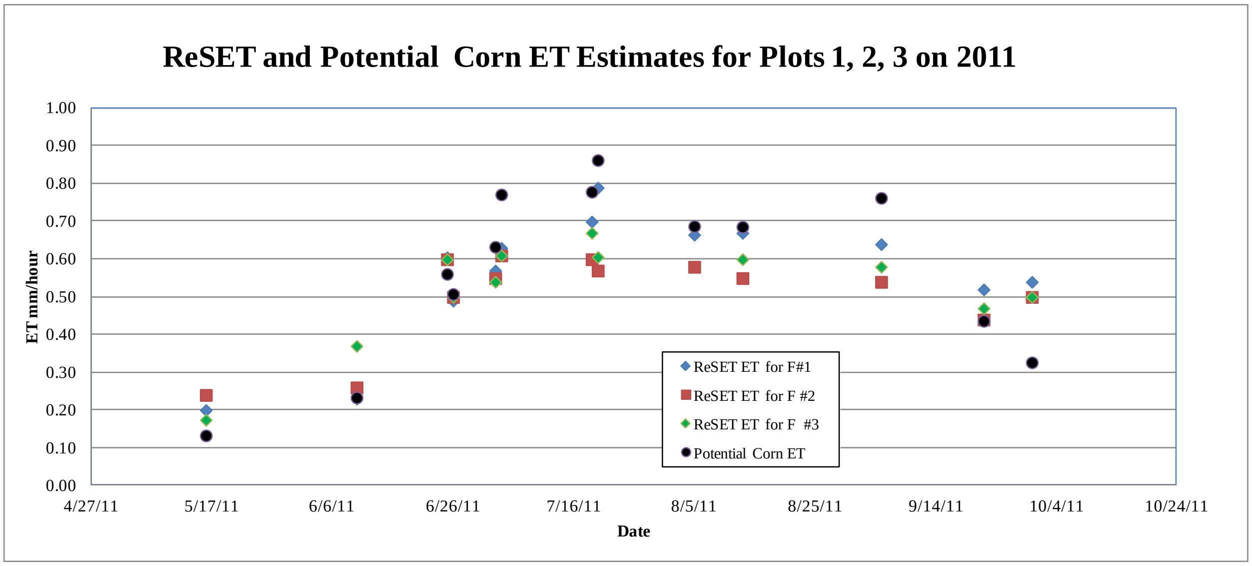
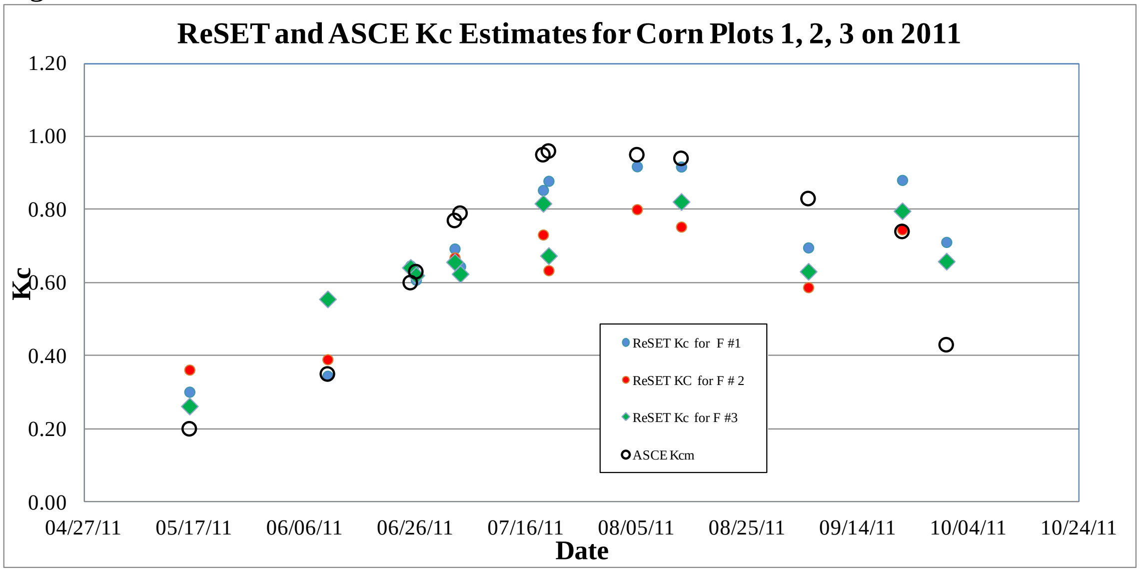


Figure 9. ReSET K_{ca} and ASCE K_{cm} estimates for Corn Plots 1,2,3 on 2011.

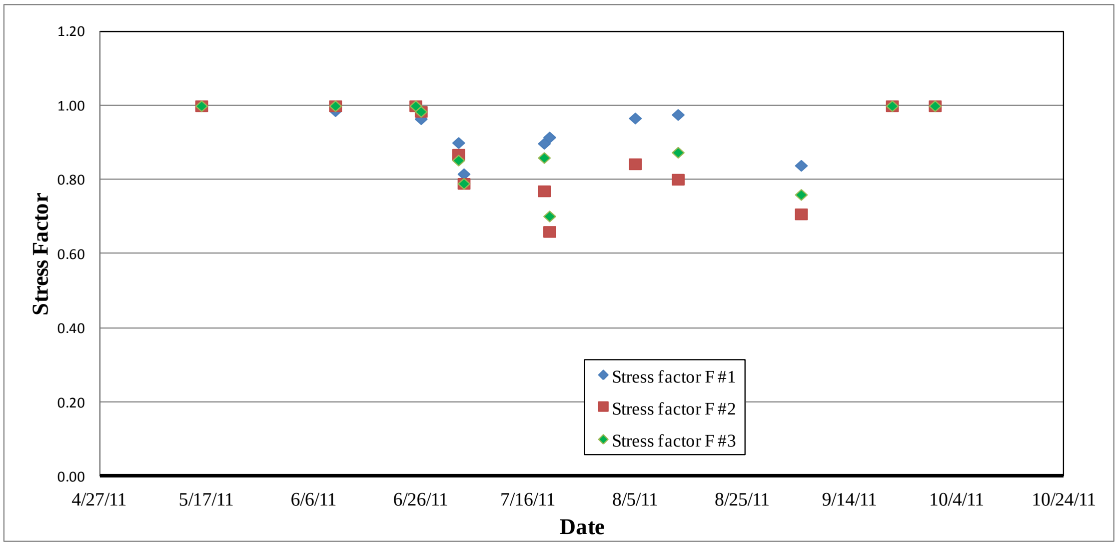


Using K_{ca} and K_{cm}, stress factors are calculated for the three corn plots (Figure 10) as follows:

$$\text{Stress Coefficient} = (K_{cm} - K_{ca}) / K_{ca}$$

where K_{cm} is the corn ASCE crop Coefficients based on planting date and K_{ca} is ReSET actual crop coefficients based on model estimates.

Figure 10. Stress factor for each plot on 2011 growing season (5/4 to 10/13).



To illustrate the farm-scale application of the ReSET model, an example of a Landsat 5 image (Figure 11), and how the image was processed in the ReSET model to create an ET grid for that day is shown in Figure 12. The ReSET images can reveal temporal and spatial details within the study area. For example, an in-progress irrigation even can be visulated on 5/27/2006 for the Boo farm Figure 13. Figure 14 shows that the corn fields at the Boo farm (north of house) was not homogenous until mid-July, which greatly impacted the values of ET on 7/14/2006 and even on following dates (Figure 15). Using the ReSET model for monitoring of field ET enabled us to detect under irrigated areas on some of the fields other than the study fields (Figure 16).

When the images from individual times are viewed in a sequence, the crop development on that field can be traced and the evolution of ET during the season can be illustrated using the

ReSET model approach. Figure (17) and Figure (18) show an example of this for the Franson #8 field. The first image shows the first irrigation event of the growing season on 5/19/06, while the final image shows the crop is senescing.

A key goal for evaluation of the ReSET model in the project was to identify whether this model could be used to verify consumptive water use savings in fields using limited irrigation practices. The farmers fields selected in this study were not deliberately practicing limited irrigation, but were selected because they were known to have had some water limitations during the 2006 growing season. Seasonal ET for the growing season of several center pivot irrigated fields is shown in Figure 19. The ReSET model was able to discern seasonal ET differences from among these closely clustered fields, with variation from 565 mm (22 in) to 621 mm (24 in). Figure 20 shows the seasonal ET estimated by ReSET for each of the four fields selected for this study. An example of the actual and buffered field boundaries is also shown for the Franson#8 field. Seasonal ET for the study fields estimated using the ReSET model matched closed the irrigation and rain data for those fields except for the Boo north of the house field which was cultivated with corn (Figure 21) which had a 25% difference between the ReSET estimated seasonal ET and the irrigation and rain data from that field. This field had two issues that were detected using the remote sensing. First the field had a late crop development (Figure 21). This could have been due to a number of different local conditions which are field dependent (not cultivated on time, no irrigation water on time, lack of fertilizer, soil problems) this means the ET from this field until 7/14/06 was lower when compared to the field just south of it (Boo farms south of the house) that had soy beans. This late development decreased the final seasonal ET monitored by ReSET. The second issue with this field is that parts of the field never had a good crop throughout the season, which is obvious when looking at the west and east edges of the field where low ET areas can be seen. The crop development in these areas was poor as it can be seen on the false color Landsat image. Even if the poor crop development in those areas is caused by reasons other than the lack of irrigation water, still the irrigation water in those areas is not fully used by the crop and that is why it cannot be detected by the ReSET model. These two issues most likely contributed to the 25% difference between the ReSET actual ET estimates and the irrigation and rain field data. The difference between the ReSET actual ET estimate and the irrigation, rain data for the other three fields ranged between 1.7% and 8% which supports the accuracy and practicality of using the ReSET model in irrigation management for agriculture fields.

Figure 11. Landsat 5 imagery Path 32 Row 32 on 7/14/2006 for the Boo and Franson farms.

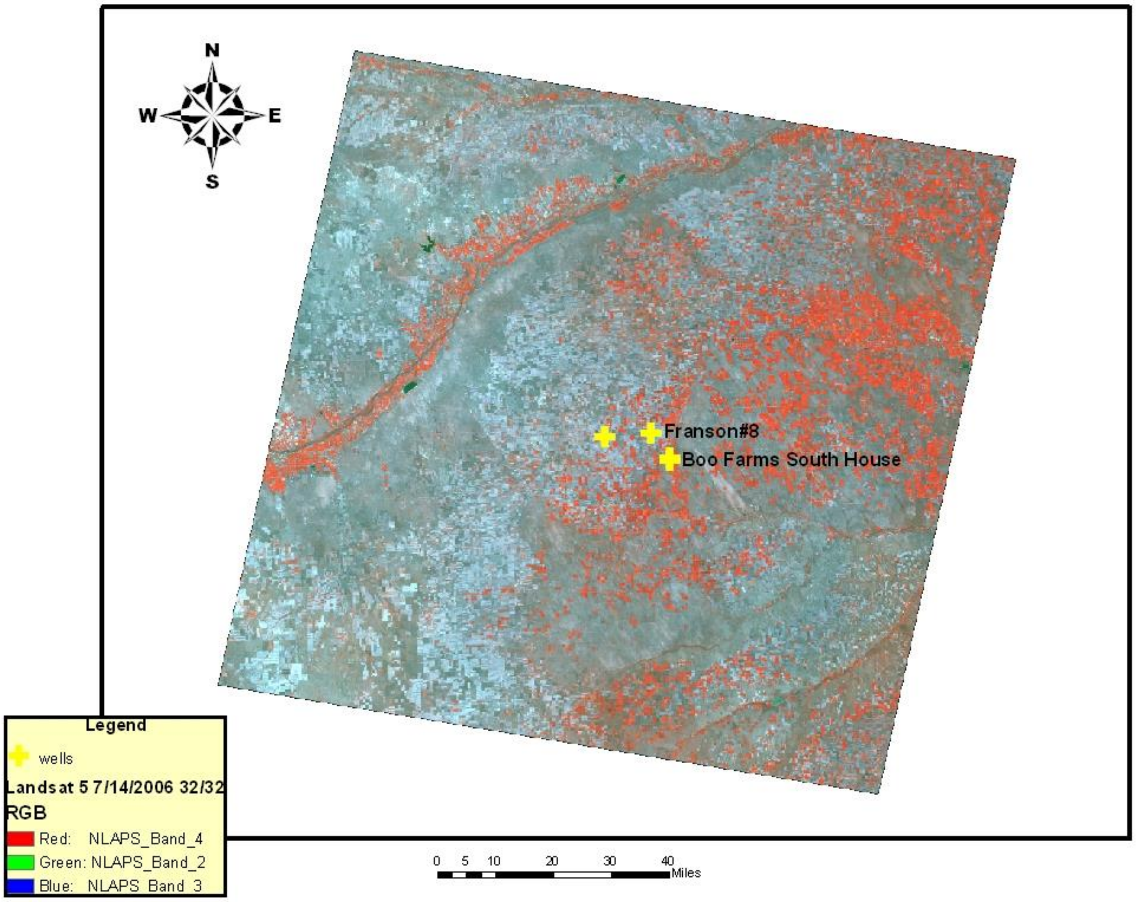


Figure 12. Daily ET (mm/day) for Path 32 Row 32 on 7/14/2006 for the Boo and Franson farms.

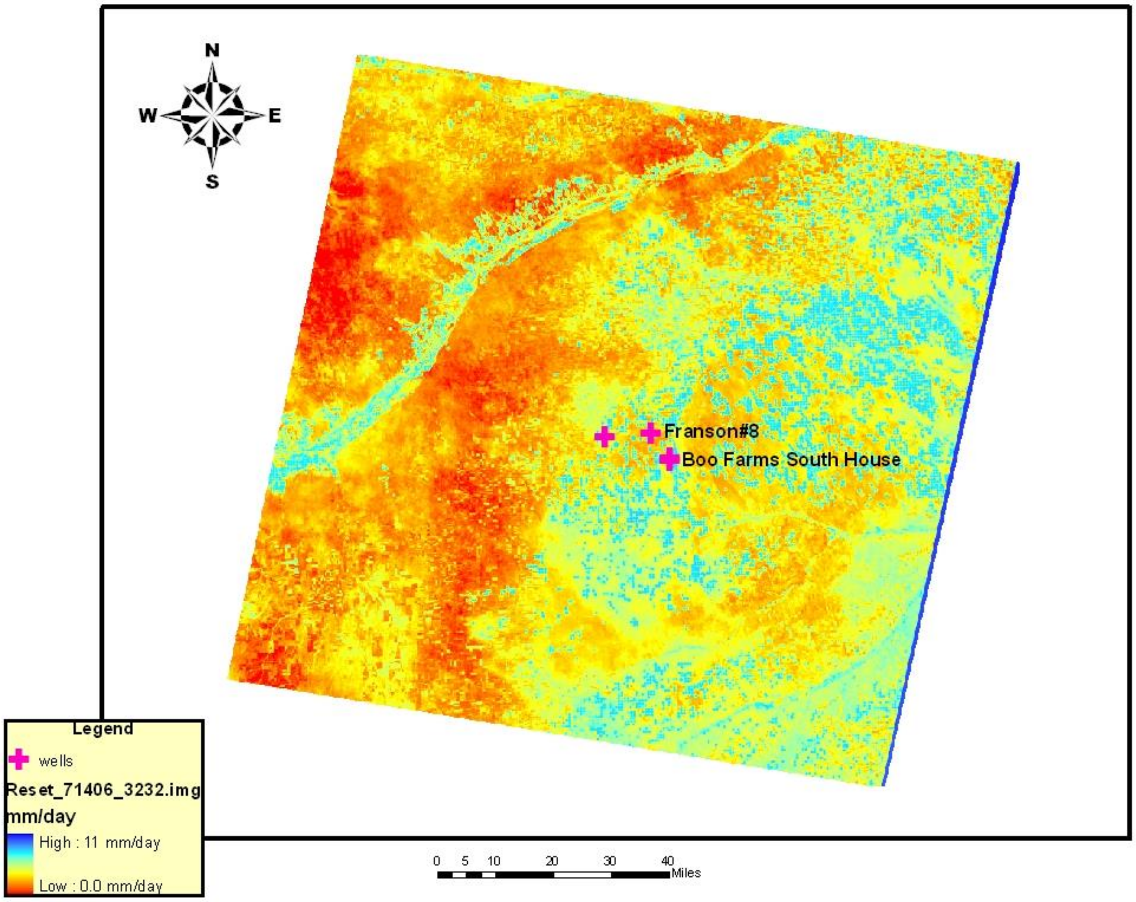


Figure 13. Boo farms fields with irrigation event showing on ET grid of 5/27/2006.

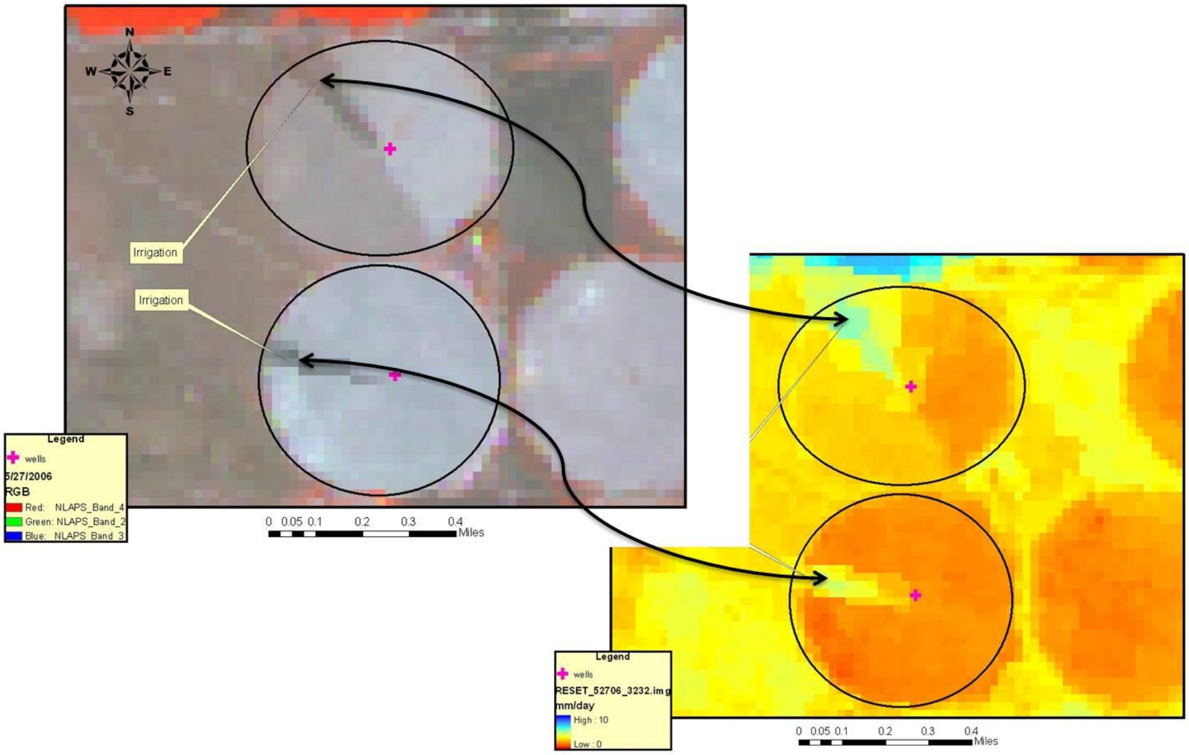


Figure 14. Boo farms fields on 7/14/2006   partially cultivated fields.

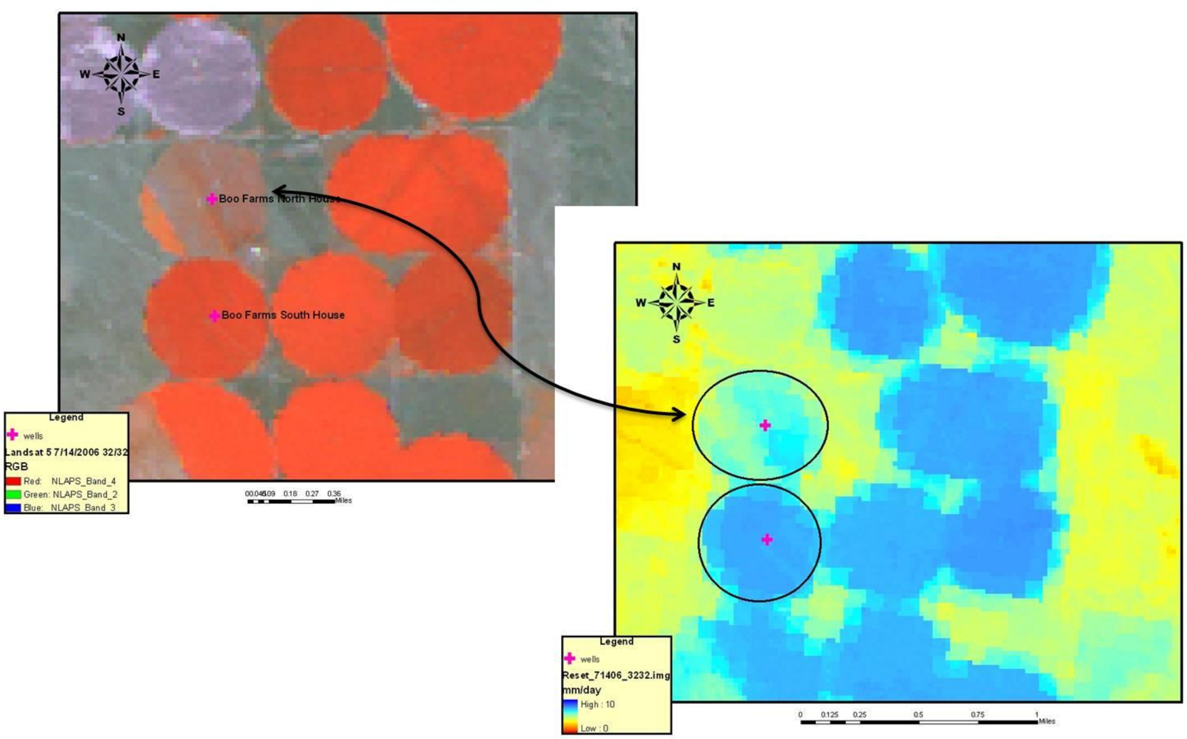


Figure 15. ET variability within the Boo farms fields on 7/30/2006 and on the ET grid.

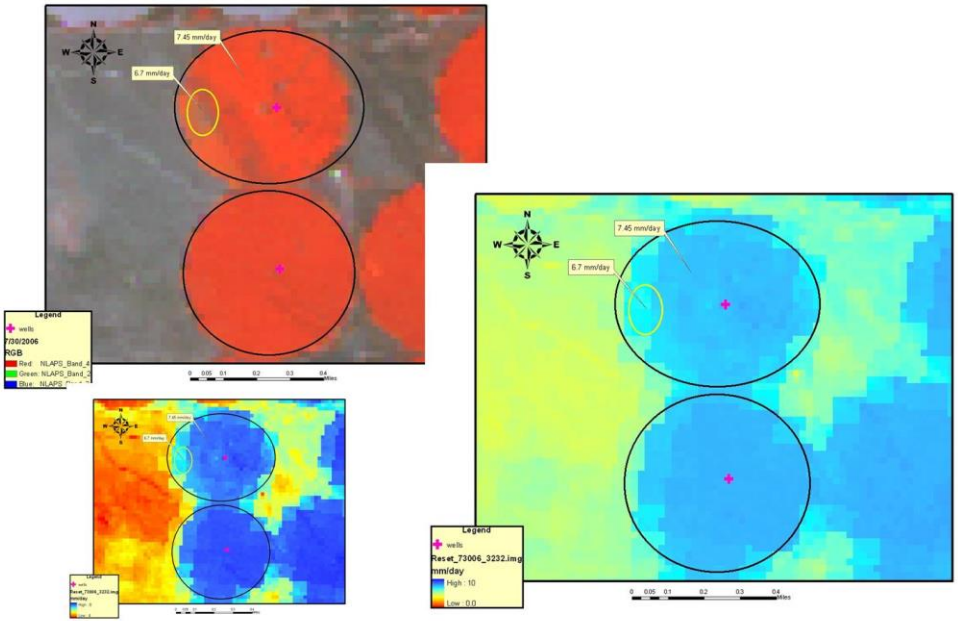


Figure 16. Fields with under irrigated areas.

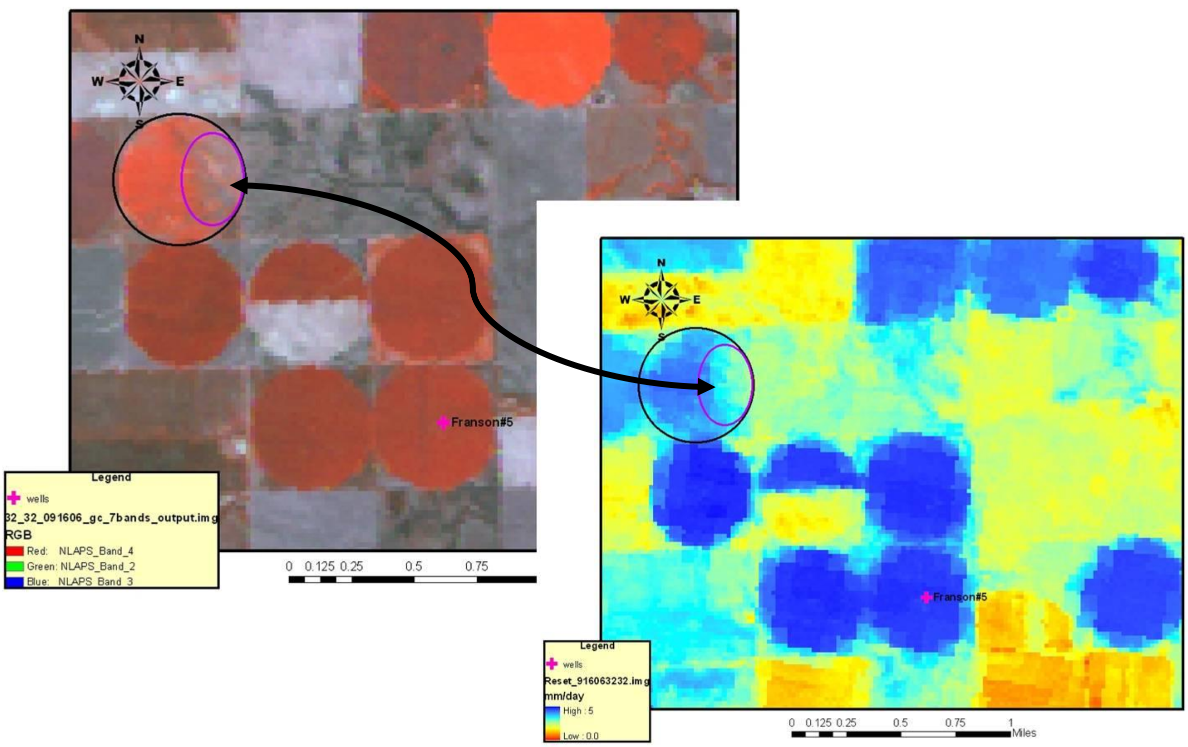


Figure 17. Showing false color Landsat images (top row) and ReSET estimated Crop ET (bottom row) at different times for Franson field #8 in the in first half of the season.

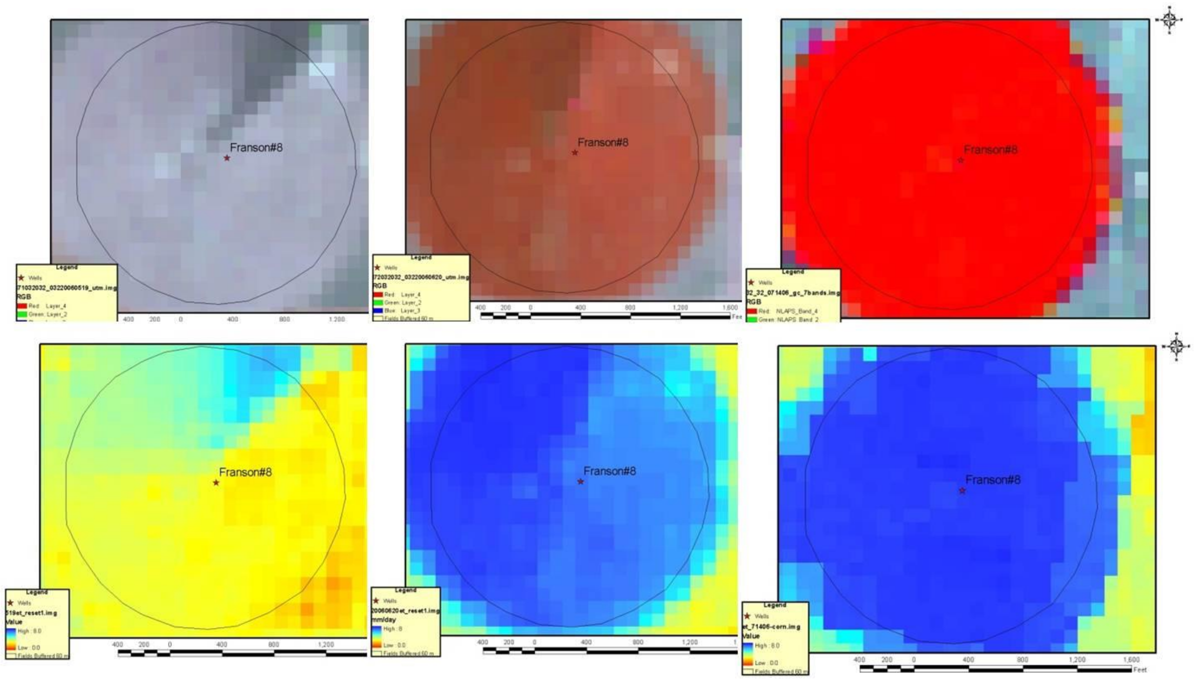


Figure 18. Showing false color Landsat images (top row) and ReSET estimated Crop ET (bottom row) at different times for Franson field #8 in the in second half of the season.

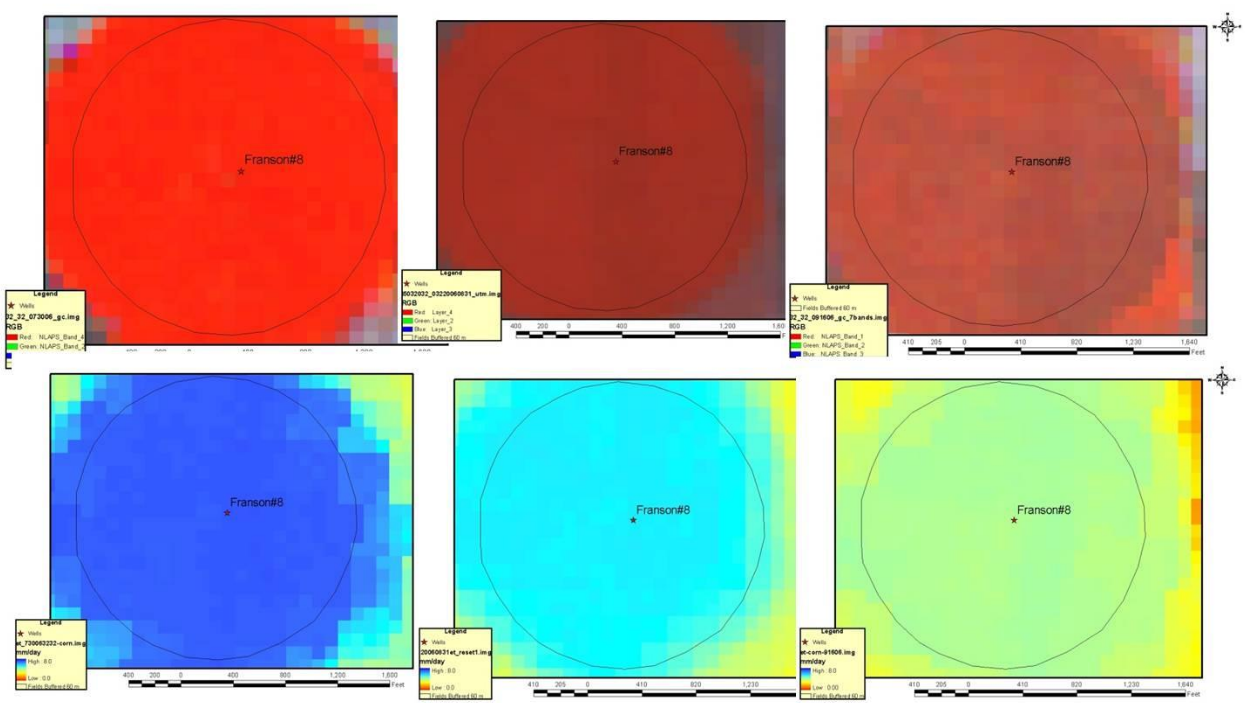


Figure 19. Seasonal ET from 5/15/06 to 9/6/06 with 60m buffered boundaries (Franson 8).

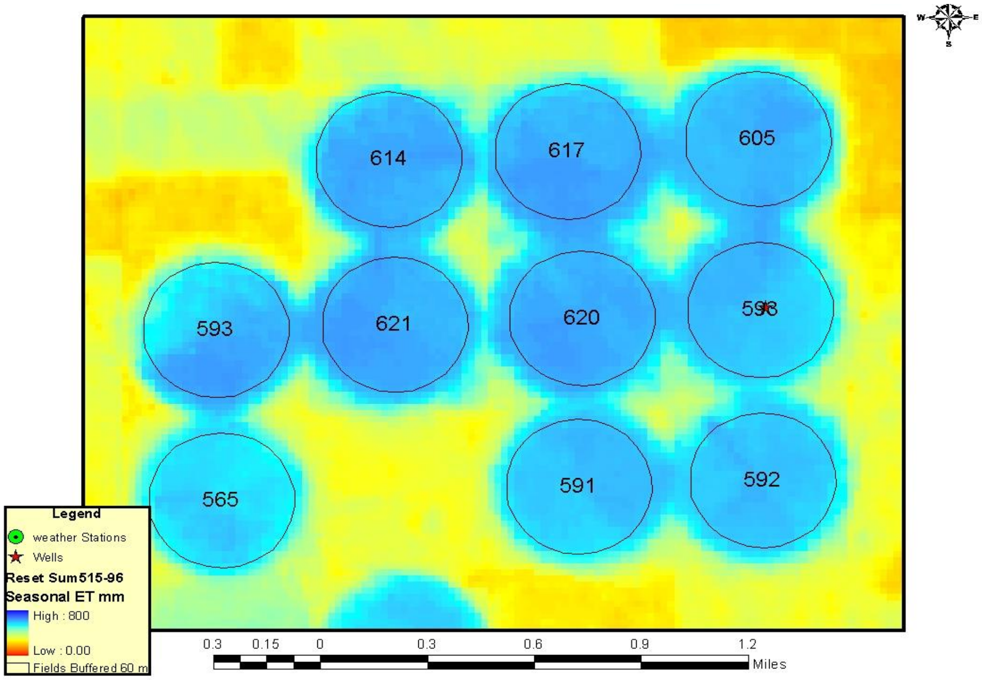


Figure 20. Seasonal ET (mm) for Franson#5, Franson#8 and Boo farms fields.

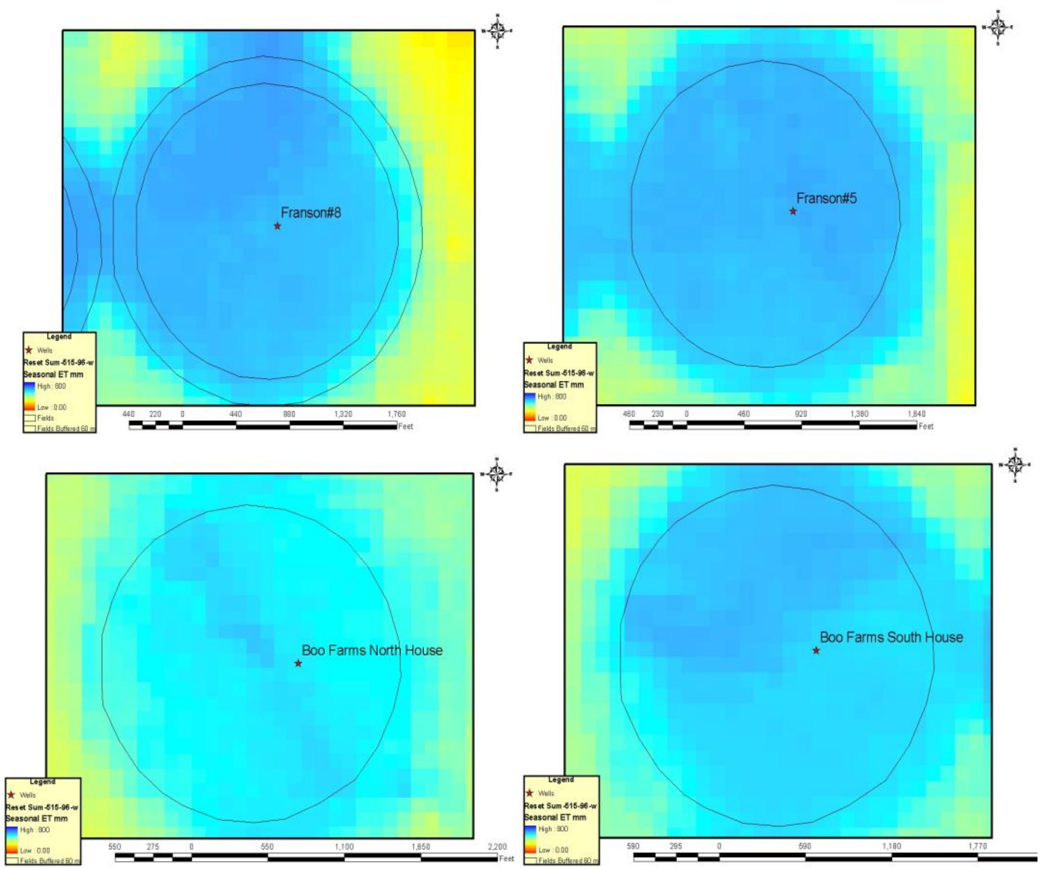
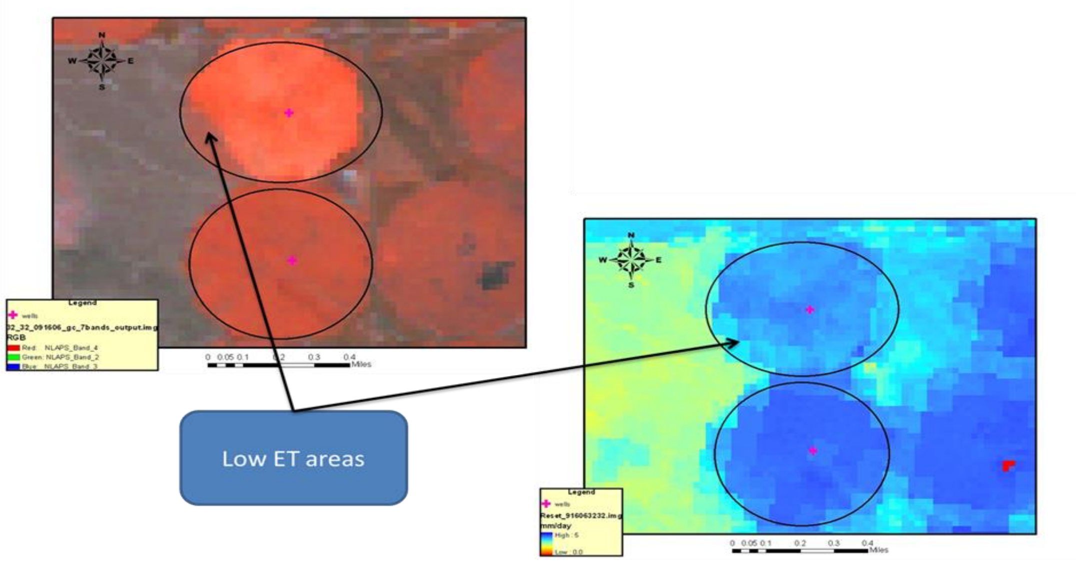


Figure 21. Boo Farms fields for Landsat 5 image and ET on 9/16/06 showing low ET areas.



Task 2. Demonstrate a water allocation approach to simplify the administrative burden to maintain return flows.

<u>Description of Task</u>

Implementation of cropping practices that reduce consumptive use without complete dry-up or fallow is dependent on a reliable approach to maintain historical return flows and verify consumptive use savings. For example, results from Task 1 show that verifying reduced ET associated with a limited irrigation cropping practice is feasible, but the methods are complex in nature and subject to some uncertainty. The methods outlined in task 1 estimate ET but do not directly address the effects of limited irrigation on the quantity of return flow associated with limited irrigation. Previously reported results from Lower South Platte Irrigation Research and Demonstration site in Iliff have documented that limited irrigation practices reduce the volume of water moving below the root zone, suggesting that return flows would be diminished under these practices. Under a change-use case involving limited irrigation, a secondary approach to maintain historical return flows would be required (recharge ponds, wetlands, etc). Approaches to determine and verify return flow under limited irrigation have the potential to be very complex and expensive, making this a significant barrier to adoption of these alternative methods. In this task, a water allocation approach is proposed as a means to simplify the administrative burden of maintaining return flows when a limited irrigation or alternative crop rotation is implemented to reduce consumptive water use.

The allocation approach is proposed to simplify and reduce the costs to administer a change use case and protect historic return flows even while maintaining some level of irrigation on the farm. In this approach, 100% of the historic return flows would be met with a secondary method (ie: constructed wetlands or recharge ponds) and the allowable diversion would be capped at the fraction of historic consumptive use kept for irrigation. The cap in diversion allocation guarantees the target CU savings and historic return flow, and the irrigator is allowed to fully consume the diverted water. A major advantage to this approach is that it motivates the use of efficient irrigation practices. This approach avoids the need for expensive and complicated instruments such as soil moisture sensors, drainage gauges, etc at the field level. From the perspective of return flow maintenance, the allocation approach is conservative because water diverted for irrigation that becomes return flow is additional flow above the requirement. The basic idea behind an allocation approach is that the change in applied irrigation between historic use and a change to a water conserving cropping system such as limited irrigation would be partitioned into i) the water volume being transferred to an alternative use, ii) a fixed allocation of water for use as irrigation, and iii) the volume of water required to meet historic return flow. By this, only saved consumptive water use is used in the exchange and return flows are protected and quantified, with no need to track the water use beyond the diversion to the farm.

To further illustrate the idea of an allocation approach, four hypothetical scenarios are presented with a simple water accounting to compare irrigation practice changes with the allocation approach.

Scenario 1: Irrigation Efficiency Change

Practice changed – A furrow irrigated system is changed to a sprinkler irrigated system

Assumptions – Continuous corn rotation for both systems with no change in consumptive use

Water Accounting	Furrow Irrigation	Sprinkler Irrigation	Difference
	ac-in		
Applied irrigation	36	18	18
Effective Precipitation	9	9	0
Consumptive use	24	24	0
Return Flow	21	3	18
Water for Potential Exchange			0

In this hypothetical scenario, the applied irrigation is reduced by 50%, but there is no change in the consumptive water use by the crop. All of the water saved in the irrigation efficiency change is accounted for in a reduction of return flow. As such, there is no water available for a potential exchange of use.

Scenario 2: Consumptive Use Change

Practice changed – A sprinkler irrigated farm changes from full irrigation to limited irrigation practice.

Assumptions – Continuous corn rotation in both systems

Water Accounting	Full Sprinkler Irrigation	Limited Sprinkler Irrigation	Difference
	ac-in		
Applied irrigation	18	10	8
Effective Precipitation	9	9	0
Consumptive use	24	18	6
Return Flow	3	1	2
Water for Potential Exchange			6

In this hypothetical scenario, the applied irrigation is reduced by 45% from 18 in. to 10 in., while the consumptive use is reduced by 25% from 24 in. to 18 in. This reflects an efficiency improvement associated with limited irrigation practice. The system change resulted in a reduction in return from 3 in. to 1 in. In this case, if a change-use case were implemented, the loss in return flow must be augmented in an approved way. The water available for a potential exchange is 6 in., equivalent to the consumptive use savings. This hypothetical exchange would require detailed accounting of the water management on the limited irrigation farm for determination of ET and calculation of saved ET and return flow.

Scenario 3: Water Allocation Approach

Practice changed – As part of a change-use exchange, a sprinkler irrigated corn farm is allowed a total allocation of 10 ac-in of water for future irrigation. The farm chooses to practice limited irrigation and maintain a continuous corn rotation.

Water Accounting	Full Sprinkler Irrigation	Limited Sprinkler Irrigation	Difference
	ac-in		
Applied irrigation	18	10	8
Effective Precipitation	9	9	0
Consumptive use	24	18	6
Return Flow	3	ASSUME ZERO	3
Water for Potential Exchange			5

In this hypothetical illustration of an allocation approach, the irrigated farm has a fixed upper limit of 10 in. of irrigation (same as for scenario 2). The only difference between scenario 2 and 3, is that in an allocation approach, the return flow is assumed to be zero. This assumption is made to eliminate the administrative burden at the irrigated farm level, with the exception of the need to document compliance with the allocation limit (10 in. in this example). By assuming zero return flow, all of the historic return flow (3 in.) must be met by some means other than irrigation return flow, such as an approved augmentation system. Compared to scenario 2, this reduces the water available for potential exchange from 6 in. to 5 in., but reduces administrative burden and uncertainty about the preservation of return flow. If the zero return flow assumption is not actually true, then the allocation approach would actually result in a benefit of additional return flow in the system.

Scenario 4: Water Allocation Approach

Practice changed – As part of a change-use exchange, a flood irrigated, alfalfa farm is allowed a total allocation of 10 ac-in of water for future irrigation. The farm evaluates whether to continue flood irrigation of alfalfa or to convert to a sprinkler irrigated corn system.

Water Accounting	Flood Irrigation Alfalfa	Allocation Flood Irrigation Alfalfa	Difference	Allocation – Sprinkler Irrigation Corn	Difference
	ac-in				
Applied irrigation	60	10	50	10	50
Effective Precipitation	9	9	0	9	0
Consumptive use	36	14	22	18	18
Return Flow	33	ASSUME ZERO	33	ASSUME ZERO	33
Water for Potential Exchange			17		17

This scenario illustrates that an allocation approach has the potential to motivate irrigation efficiency changes, but avoids the complication of on-farm water accounting. If the farm were to maintain a flood irrigation system as part of the change case, the inefficiency of the irrigation system results in return flows in excess of the amount required. When the irrigation efficiency is improved, some or all of that water can be utilized in crop production.

Example of Allocation Approach - Iliff Research Farm

An illustration of the allocation approach was conducted at the Lower South Platte Irrigation Research Farm near Iliff. Assumptions used to set historical or baseline conditions were based on the research observations from the period between 2008 and 2012, using irrigated corn. The average consumptive use for corn during this time period was 24.1 in. During the same study period, the average growing season precipitation was 9.6 in. and average applied irrigation was 17.1 in. Return flow was not directly measured during in the research project, but water budget estimates of drainage below the root zone was estimated for full-irrigation corn to be 10.6% of the combination of precipitation and irrigation, which is 2.8 in.

In this example, measurements from the actual 2012 cropping season at the Iliff research site are used for comparison with the baseline data and the allocation approach. During the 2012 growing season, the research site was divided between corn grown under full and limited irrigation practices (Table 7). Precipitation during the growing season totaled 6.9 in. Soil moisture was determined weekly at 12 in. depth intervals to 60 in. using a neutron attenuation meter. The soil moisture data was used as a part of a water balance to estimate drainage and to calculate crop evapotranspiration. Under full irrigation, water use from the soil totaled 1.1 in. and drainage was estimated to be 3.1 in. Under limited irrigation, there was a net of 0.2 in. of water accumulation in the soil and drainage of 0.3 in. Total observed ET for full and limited irrigation were 24.5 and 17.2 in., respectively. The calculations shown in the allocation scenario below are based on a 10 in. allocation of irrigation water and an assumption of zero return flow. With this assumption the full 2.8 in. of historic return flows must be taken from the quantity of saved irrigation water, leaving the potential of 4.3 in. of water for exchange. Under observed conditions in 2012 at Iliff with an irrigation allocation of 10 in., the actual consumptive use and return flow values were 17.2 and 2.3 in. with growing season precipitation of 6.9 in. The growing season precipitation and the consumptive use were lower than average for the baseline period. When the observed water balance figures were considered, the potential water for exchange totaled 4.6 in., just 0.3 inches more than for the allocation approach. This example illustrates the cost, in terms of the amount of water available for exchange, of the allocation approach. The key question is whether the potential for additional water exchange is worth the cost associated with the quantification of ET and return flow. In the 2012 example, simplifications associated with an allocation approach likely worth more than the small amount of water lost.

Example of an Allocation Approach - Iliff Research Farm

Baseline conditions were set based on measurements of full-irrigation corn from 2008-2012.

Water Accounting	Baseline Conditions	Assumptions for Allocation	Difference	2012 Observed Limited Irrigation	Difference
	ac-in				
Applied irrigation	17.1	10	7.1	10	7.1
Effective Precipitation	9.6	9.6	0	6.9	2.7
Consumptive use	24.1	19.6	4.5	17.2	6.9
Return Flow	2.8	ASSUME ZERO	2.8	0.3	2.5
Water for Potential Exchange			4.3		4.6

Table 7. Dates and quantities of irrigation for full and limited irrigation corn during 2012 at the Iliff research site. The irrigation comparison was part of a demonstration of an allocation approach to water exchange.

Date	Full Irrigation	Limited Irrigation
06/20/12	2.0	2.0
06/28/12	2.0	
07/18/12	2.0	
07/25/12	2.0	2.0
07/29/12	2.0	
08/06/12	2.0	2.0
08/13/12	1.5	1.0
08/17/12	1.5	1.5
09/02/12	1.5	1.5
TOTAL	16.5	10.0

Task 3: Water Supply Delivery Evaluation

Background

Parker Water and Sanitation District (PWSD) is a municipal water provider located south of Denver, Colorado. Similar to the rest of the Front Range area, PWSD has experienced significant growth in recent years and PWSD currently is serving over 17,000 single-family equivalent taps, with an annual water demand of approximately 8,500 acre-feet per year (ac-ft/yr). PWSD is currently relying primarily on non-renewable Denver Basin aquifer ground water supplies to meet a significant portion of its current water demand. With water levels in the Denver Basin aquifers declining, PWSD is exploring different options to develop a more sustainable water supply to meet an expected buildout demand of approximately 22,000 ac-ft/yr. To reduce, or eliminate, its dependence on the non-renewable Denver Basin aquifer water supplies, PWSD has evaluated numerous options related to the use of surface water.

As part of this goal to reduce Denver Basin aquifer water supply dependence, PWSD developed a water supply management plan that included surface water storage to capture new renewable in-basin water supplies, as well as managing reuse opportunities. To achieve this objective, PWSD initiated permitting activities for Rueter-Hess Reservoir in 1999 to provide local storage in Parker. Rueter-Hess Reservoir is an off-stream reservoir adjacent to Cherry Creek on Newlin Gulch. Through the permitting process, PWSD received approval to construct a 72,000 ac-ft reservoir that will serve as a regional water storage facility for PWSD and multiple other municipal providers in the Parker area. While Rueter-Hess Reservoir is a regional storage facility that provides many water management options, local renewable water supplies and reuse cannot meet all of PWSD's, and other users along the Front Range, future water supply needs. As such, with Rueter-Hess now fully constructed and operational, PWSD is actively seeking other trans-basin water supplies that can be transported to Rueter-Hess Reservoir and then used in the Parker area.

As part of the process of developing additional renewable water supplies, PWSD has purchased 13 farms and their associated water rights in the Iliff, Colorado area. The general locations of the PWSD farms, as well as the water rights to serve these farms, are shown in Figure 22. The locations of the 13 farms are shown in Figure 23. Since the PWSD farms in the Iliff area have historically been used for irrigation, it is possible to quantify the historic effect that using water from the South Platte River for irrigation had on river flows, i.e., the consumptive use of the crops, and change irrigation water to municipal use. The historic methodology for this process has been “buy and dry,” i.e., quantify the historic use, change the use in Water Court, and then remove all of the water from the land and transport it to a municipality. PWSD does not want to follow this historic paradigm, which is the reason that PWSD entered into the partnership with Colorado State University (CSU) for this alternative agricultural transfer grant.

Project Synopsis

As part of multiple grants from CWCB, CSU has been studying irrigation methodologies which would allow some portion of historic-irrigation water consumptive use to be transferred to municipal use, while still maintaining historic irrigation practices and, therefore, sustain the rural economies. The first two tasks in this Alternative Agricultural Water Transfer Grant were designed to assess the means to quantify historic consumptive use, as well as ongoing consumptive use, so that changes in use for water rights can be successfully decreed in Water Court. This task represents the last step in the process, as it is designed to evaluate the most efficient means to deliver water which has been changed in Water Court from municipal use back to the Front Range water users. As such, Lytle Water Solutions, LLC (LWS) has evaluated (a) timing of water supply availability based on crop irrigation practices, (b) varying means to convey water through in-stream exchanges, (c) re-timing of water availability through recharge ponds, pipelines, and storage, and (d) the required pre-treatment prior to delivery to Front Range terminal storage. In conducting these evaluations, LWS assessed the efficiency of conveyance methods, and the costs associated with them, to provide our conclusions and recommendations on the most cost-efficient means for water conveyance and treatment. While PWSD has historic irrigation water rights that can be changed in use, as described above, we have not limited our analysis of water conveyance alternatives to PWSD’s water rights, as there is an economy of scale related to transporting water over 100 miles back to the Front Range. Rather, there is a large demand for supplemental renewable water supplies by many municipal water providers along the Front Range in addition to PWSD, so this analysis is applicable to a regional water delivery system to the Front Range.

Water Supply Availability

The senior surface water rights that exist on the Lower South Platte River are predominantly irrigation water rights. To evaluate water supply availability from these water rights, LWS used the *StateCU Model* to develop crop consumptive use, which is a measure of water availability for changes of use. While crop water demands vary, and water demands will vary from year to year, we used corn as the reference crop and its average consumptive use over the period 1999–2010 as a measure of the timing and amount of flow availability, which was considered representative for this study.

The StateCU program was run to establish two datasets. The first StateCU run was performed to estimate the irrigation water requirement (IWR) for the crop. This IWR was used to develop the diversion limit curve because it would most accurately represent the monthly distribution of ditch diversions. The summary results and the monthly diversion distribution curve can be found in Figure 24. The full raw StateCU output data are presented in Appendix A1, Table A-1. The second StateCU run estimated the potential consumptive use of the crop. This analysis is helpful in estimating the amount of corn that would have to be retired to obtain a given amount of historic consumptive use credits, but will have no effect on the results of the model itself. The raw StateCU results for the potential consumptive use run can be found in Appendix A1, Table A-2, and indicate that the average unit historic consumptive use (HCU) for corn is 2.0 ac-ft (ac-ft) per acre.

For both runs, the programs were set to use the Sterling, Colorado weather station for the years 1912–2008. This larger timeframe was used because the timeframe 1999–2010 is missing five years of data, and so the longer dataset also provides a better long-term average with dry and wet years. Ditch loss and irrigation efficiency were not factored into this analysis because those variables are fixed percentages, and so would have no effect on the monthly diversion percentage distribution curve or the final consumptive use of the crop.

Based on these StateCU model results, we then estimated the amount and timing of water availability that can be diverted from the South Platte River. This is an important initial component of evaluating means of delivering water to the Front Range, as water is only available on a temporally-variable monthly volume, and is also only available during the irrigation season. This is not an efficient means to transport water over long distances, as it is much more efficient to deliver water on a relatively consistent flow rate on a year-round basis. As such, the State CU results form the basis for evaluating delivery methods, including storage needs to equilibrate flows to a year-round basis.

It is well known that water availability and water delivery schedules do not mesh well. A previous water supply study (August 2006) was completed for Lower South Platte River water delivery options to PWSD by States West Water Resource Corporation (States West), LWS, Integra Engineering, and Miller Geotechnical Consultants, Inc. The results of this study indicated that a minimum of 20,000 ac-ft per year (ac-ft/yr) of water would need to be conveyed from the Lower South Platte River to PWSD and into terminal storage at Rueter-Hess Reservoir to provide a cost-efficient regional water supply delivery project. As such, LWS also used the minimum conveyance volume of 20,000 ac-ft/yr for this study. Based on an average unit HCU of 2.0 ac-ft per acre for corn, there would be a need to either retire or rotationally fallow 10,000 acres to achieve a water supply availability of 20,000 ac-ft/yr. If a *deficit irrigation* method is utilized, whereby there is less unit consumptive use water available for transfer, more acres of irrigated land would be affected. However, this acreage would still remain in agricultural production, but at a lower irrigation application rate.

Using 20,000 ac-ft/yr as our initial target delivery volume, LWS then evaluated potential means to convey this water from its place of historic use to Front Range water users, specifically to terminal storage in Rueter-Hess Reservoir at Parker.

Means To Convey Water

There are a number of methodologies that can be utilized for the conveyance and delivery of water, which include:

- Exchange water upstream, then divert from the river via surface water diversions and deliver this water directly via a pipeline;
- Exchange water upstream, then divert from alluvial wells and deliver this water directly into a pipeline;
- Divert at the historic place of use via surface water diversions and deliver water to recharge facilities to re-time water availability, exchange water upstream, and then ultimately divert with alluvial wells and deliver water directly via a pipeline;
- Divert at the historic place of use via surface water diversions and deliver water directly via a pipeline; and/or

- Utilize storage to manage water either diverted directly or exchanged upstream before the water is delivered via a pipeline.

Given the distance to potential municipal end users and that irrigation water is only available in highly variable amounts during the irrigation season (typically May through October), either upstream or downstream storage is a necessity. This is because it is not cost-effective to treat and deliver highly-varying water supply rates and volumes for only a portion of the year. Storage can help to manage water supply deliveries so they can be maintained on a year-round basis and at a relatively consistent flow rate.

To facilitate our analyses, through its CWCB *Alternative Agricultural Transfer Grant*, the Lower South Platte Water Conservancy District (District) developed a point-flow and exchange potential model of the South Platte River from the Burlington Ditch to the Nebraska State Line. As a cooperative effort, the District provided LWS with this model for us to evaluate both the water supply availability associated with direct diversions and to assess the exchange potential. The maximum exchange reach evaluated as part of this study was from Iliff (the *exchange-from* point) to Fort Morgan (the *exchange-to* point) (Figure 22). This reach was assumed based on Iliff being the general location where PWSD currently owns farms, and Fort Morgan being where the previous 2006 study took diverted water south and west to the Front Range for terminal storage in Rueter-Hess Reservoir (States West, August 2006). The following sections describe the analyses LWS has conducted to compare various water delivery systems, given the physical water supply availability and exchange potential.

Model Development

The LWS model used for our analyses is derived from a flow model originally developed by Brown & Caldwell under a CWCB grant. The original Brown & Caldwell model uses call data, water rights data, and stream flow data to develop the modeled flows on a daily basis for the years 1999−2010. The model is in an Excel spreadsheet format so that it can be easily opened and utilized without special software or training.

The exchange model used by LWS was developed by adding specific functionality to the Brown & Caldwell model that was needed for our analyses. The Brown & Caldwell model only evaluates the exchange potential along the South Platte River based on surface diversions. Since we needed to evaluate the most efficient means of delivering water to the Front Range, the exchange potential from the Iliff area to Fort Morgan can be limited at times, and year-round deliveries are preferred from a cost standpoint, the Brown & Caldwell model needed to be modified to input the water availability schedule from our StateCU model analysis. The LWS model also needed to be able to estimate the volumes and flow rates that could be transported to PWSD using recharge, exchanges, wells, and storage reservoirs. The modifications to the Brown & Caldwell model, as well as how LWS has simulated various aspects of evaluating water availability, are described below.

The Brown & Caldwell model estimates the exchangeable flow at each headgate by subtracting the water diverted by rights from the physical flow in the river at the headgate. LWS modified the Brown & Caldwell model so that the model first uses the daily physical flow data at each headgate to assess the amount of water that can be diverted, but then limits the water diverted to the crop consumptive use curve which was developed by LWS using the StateCU model. The consumptive use curve allows LWS to model exchanges and direct diversions consistent with the volumes that will be available temporally based on the expected schedule of water availability. In this way, we are evaluating the efficiency of various water delivery options based on a representative reflection of the historical agricultural diversions.

The flow diverted based on the StateCU curve can then be evaluated as (a) directly exchanged upstream to Fort Morgan and temporarily stored in a reservoir before being pumped to PWSD, (b) diverted and sent to a recharge pond to be re-timed if there is insufficient flow to exchange to Fort Morgan, (c) diverted and stored at the downstream end until exchange opportunities are better, or (d) piped directly from the downstream end of the exchange reach to the upstream end. At the upstream end of the exchange reach, the water is either (a) pumped directly to a pipeline via alluvial wells and delivered to Rueter-Hess Reservoir or (b) is temporarily stored until flow in the pipeline from inflows alone does not fill the pipe, and then water from the reservoir can be pumped as well. In this way, there are multiple options for taking water from the river at the downstream end and managing the water to the upstream end of the reach. A total of five scenarios were evaluated for the purposes of this report. A schematic of these scenarios is presented in Figure 25.

Direct diversions and/or exchanges can be tracked on a daily basis. When recharge ponds and/or alluvial wells are used in the analysis, tracking of this water becomes more complicated. When flows are sent to a recharge pond because they can’t be exchanged (but HCU credits are available and have to be diverted from the river), they infiltrate from the recharge pond, slowly recharge the alluvial aquifer, and begin to flow back to the South Platte River. As such, we have to track the movement of the water back to the river, and can only claim the water when it has reached the river. These return flows are lagged in time back to the river using unit response functions (URFs) developed using the Glover equation and alluvial aquifer data from the 1972 USGS maps developed by Hurr and Schneider. The LWS model tracks the water back to the river using this methodology, then uses the exchange potential function built into the model to evaluate if the water can then be exchanged upstream at the times when it accrues to the South Platte River. Recharge flows are either exchanged upstream, if possible, or otherwise left to flow downstream unclaimed, which affects the efficiency of the water delivery option.

A similar methodology is used for alluvial wells, except that URFs are calculated to simulate lagged depletions to the stream. The LWS model takes exchanged flows diverted from the South Platte River near Fort Morgan using an extraction well field modeled as immediately adjacent to the river. Because these wells create a delayed depletion to the South Platte River, LWS developed URFs for these extraction wells and lagged the depletions to the river using the Glover equation. The extraction well field is only operated on days when there is no call on the reach of the South Platte River between the accrual point of the recharged water and the extraction well field. All out-of-priority depletions associated with extraction well field pumping are tracked so that the volume of augmentation water required is known. Any un-exchanged recharge accruals from the recharge pond can be used to offset out-of-priority depletions from the upstream extraction well field if they accrue on the same day as the recharge and there is no intervening call. The pumped exchange water is then either delivered to a pipeline and pumped to Parker or, if the exchanged water pumped is beyond the capacity of the pipeline to carry it, the water is temporarily stored in a reservoir adjacent to the extraction well field until there is available capacity in the pipeline to deliver it to Rueter-Hess Reservoir. All variations of the exchange model use these extraction wells as the means of diverting water from the South Platte River near Fort Morgan.

All theoretical storage reservoirs used in the model to manage and equalize water deliveries to the pipeline use the same elevation-area-capacity (EAC) curve as the Prewitt Reservoir. Since Prewitt Reservoir is in the same general area, the EAC curve provides a reasonable estimate of what could be developed in the Iliff and Fort Morgan areas. All reservoirs are subject to losses from evaporation calculated on a daily basis. Evaporation from all reservoir free-water surfaces is modeled using the surface area estimated by the EAC curve and evaporation values from the Colorado Decision Support System (CDSS).

A variation of the exchange scenario that was also evaluated does not involve any recharge process. Instead, there is assumed to be a reservoir located in the vicinity of the downstream headgate, as well as a second reservoir in the vicinity of Fort Morgan at the upstream end of the exchange reach. Flows that cannot be exchanged on any given day are stored in the downstream reservoir until there is additional exchange capacity. Then the water is exchanged at a later date when exchange capacity exists from the Iliff area to Fort Morgan. Similar to the other options described above, the exchanged water is then either delivered to a pipeline and pumped to Parker, or if the exchanged water is beyond the capacity of the pipeline to carry it, the water is temporarily stored in the upstream reservoir until there is available capacity in the pipeline to deliver it to Rueter-Hess Reservoir.

Given that exchange potential is limited many times during the irrigation season (when HCU credits are available and have to be diverted from the river), one option that was evaluated was a direct pipeline from the Iliff area to Rueter-Hess Reservoir. However, since there is a highly-variable water delivery schedule from the river, surface storage is still needed on the downstream end to regulate flows into the pipeline. This option did not require the use of the LWS model, as it is a simple diversion from the river, and then analysis of the volume of storage required to equalize flows into the pipeline. The pipeline economic breakpoint volume of 20,000 ac-ft of HCU credits was used to evaluate this scenario.

However, we also evaluated a variation related to the direct pipeline from the Iliff area to Rueter-Hess Reservoir. For this option, we modified the model to evaluate using a pipeline to deliver water directly from Iliff to Rueter-Hess Reservoir using recharge to re-time the water instead of the need to store water in a surface reservoir. The recharge URFs used in this recharge scenario are the same as the URFs used in the exchange scenario. Since there is no surface reservoir in this model, evaporation is not considered, which minimizes the losses due to surface storage. The largest limiting factor in this scenario is the capacity of the recharge site(s) to re-time large quantities of water.

The LWS model parameters that were adjusted to conduct our analyses included HCU credits, reservoir capacities, pipeline capacity, recharge flow capacity, and extraction well field capacity. The LWS model can also be modified to remove reservoirs, bypass recharge, change the exchange reach, and change between well fields and headgates. This flexibility allowed us to evaluate several scenarios to assess the most efficient means for water delivery of historic irrigation credits.

LWS modeled all of the water delivery scenarios from Iliff to Fort Morgan, and also from the area of the Prewitt intake to Fort Morgan. The analysis from Prewitt was performed because initial analyses showed that the exchange potential from Prewitt to Fort Morgan is much better than from Iliff to Fort Morgan. Since we have evaluated the potential for delivery of historic irrigation water to Rueter-Hess Reservoir from the Lower South Platte River in general, and not just limited to PWSD's water rights, we believe that evaluating two exchange reaches provides additional information relevant to this study.

Model Sensitivity Analyses

Once the original Brown & Caldwell model had been modified for our intended uses, we evaluated the model relative to its sensitivity to a number of the key parameters in our analyses. The LWS model has four main variables that can be altered which may affect the efficiency of the exchange. These variables are (a) the amount of HCU credits, (b) maximum recharge rate, (c) maximum extraction well field rate, and (d) reservoir storage capacity. Sensitivity evaluations of each of these parameters are presented in the following sections.

HCU Credits

The efficiency of the exchange with variable HCU credits was performed on the recharge exchange model from Iliff to Fort Morgan, and also Prewitt to Fort Morgan. While we evaluated the exchange of 2,500 to 25,000 ac-ft/yr of HCU credit, the previous 2006 study demonstrated that, from a cost standpoint, 20,000 ac-ft/yr was a breakpoint where volumes less than this would have a very high unit cost of delivery.

The results of this sensitivity analysis are presented in Figure 26, and show the efficiency of the exchange, expressed as the ratio of water captured and delivered to Parker to the HCU credits. The exchange efficiency is very low from Iliff (30−35 percent), even at a low amount of HCU credits (2,500 ac-ft/yr). Conversely, Figure 26 shows that an exchange from Prewitt to Fort Morgan can be very efficient (>90 percent) at low volumes of HCU credit (2,500–5,000 ac-ft/yr), but quickly reduces in efficiency as the HCU credits are increased (>5,000 ac-ft/yr). For example, at 7,500 ac-ft/yr, the efficiency of the Prewitt exchange is approximately 80 percent, reduces to an efficiency of 75 percent at 10,000 ac-ft/yr, and reduces even further to an efficiency of 57 percent at 20,000 ac-ft/yr.

Both exchange reaches are sensitive to variation in HCU credits, with the overall Iliff exchange efficiency dropping from 35 to 16 percent over an exchange rate from 2,500 to 25,000 ac-ft/yr, and the Prewitt exchange efficiency dropping from 95 to 50 percent over the same exchange rate range. Given that previous studies have identified an economic breakpoint of delivery to the Front Range of approximately 20,000 ac-ft/yr, a straight exchange of HCU credits does not provide favorable results, either from Iliff or Prewitt (19 to 57 percent of the HCU credits able to be exchanged from these points, respectively). Because of the economic breakpoint and the low efficiencies of direct exchanges, the remaining sensitivity analyses were run using a pipeline capacity equal to this economic breakpoint value of 20,000 ac-ft/yr, and are designed to evaluate if options other than a direct exchange can increase the overall efficiencies. All other variables for this portion of the analysis were set at very high, non-restrictive values to isolate the HCU component. Figure 26 can, therefore, be seen as a best-case scenario for the exchange, since no other factors are being restrictive.

Due to the poor results produced in the Iliff exchange analysis, the remaining sensitivity analyses were only performed on the Prewitt-to-Fort Morgan scenario, with the exception of the evaluation of the scenario of a direct pipeline from Iliff.

Recharge Rate

Since a direct exchange does not appear to be an efficient method for capturing HCU credits for delivery to the Front Range, LWS then tested the Prewitt to Fort Morgan exchange model’s sensitivity to changes in maximum recharge rates. This analysis assumed that recharge ponds would be constructed at the downstream end of the reach to potentially re-time water to more favorable exchange conditions, i.e., the non-irrigation season. In these scenarios, HCU credits are diverted based on timing and volumes associated with historic irrigation practices and StateCU results. Water is first exchanged directly, and then the remaining water is recharged in recharge ponds to re-time the extraction of the water so as to evaluate if this re-timing improves exchange capacity. The maximum recharge rate was varied from 0 to 150 cubic feet per second (cfs), while all other variables remained constant.

The high end of the recharge flow range (150 cfs) is advantageous in capturing the very large peaks of flow coming down the South Platte River. A total of 20,000 ac-ft/yr of HCU credit was used in this analysis. The variation in maximum recharge rate related to the number of days per month that recharge would occur and the volume to be recharged. Figure 27 presents the results of varying maximum recharge rates versus the efficiency of the exchange using recharge (expressed as the ratio of water captured and delivered to Parker to the HCU credits).

The model assigns a daily limit of HCU credits that can be taken, i.e., the monthly limit from the consumptive use curve divided by 15 to allow some flexibility in the diversion of HCU credits. Once the daily maximum HCU is diverted in the model simulation, the water is exchanged upstream until the maximum exchange potential is reached and the remaining flow is sent to recharge. If the HCU credit cannot be exchanged and/or recharged, then that flow is lost back to the river and can't be claimed. Likewise, if the excess water is recharged, but at the time the recharged flows return to the river not all of the flow can be exchanged, then that water is also lost back to the river and can't be claimed. As such, in this scenario, the ability to re-time water to the river to optimize exchange potential is critical.

Due to the highly transmissive nature of the South Platte River alluvial deposits, it was very difficult to control the re-timing, either through changes in recharge rates or changes in recharge locations. The results show that, at 20,000 ac-ft/yr of HCU credit, the exchange is highly insensitive to changes in the rate of recharge, and that increased recharge capacity beyond 25 cfs is actually detrimental to the overall exchange efficiency. As such, our sensitivity analyses indicate that re-timing available water through recharge and subsequent exchange is not desirable, and creates significant additional infrastructure costs with virtually no increase in efficiency.

It should be noted that a second reservoir located in the Prewitt area, instead of the recharge, was briefly considered, but results indicated that the additional losses in evaporation from a second reservoir made it marginally less efficient than the recharge scenario, given the cost of a large lined reservoir.

Extraction Well Field Data

While the previous sensitivity analyses evaluated the ability to exchange water from the downstream end of the exchange reach where the HCU credits would be available to the upstream end of the exchange reach, once the water is exchanged to the upstream end near Fort Morgan, it was assumed that this water would be captured by well fields. As such, LWS also evaluated the Prewitt to Fort Morgan exchange model's sensitivity to changes in upstream extraction well field capacity. For this analysis, the maximum extraction rate was varied from 30 to 125 cfs, and the maximum well field capacity was assessed for downstream recharge rates of 25 and 30 cfs, as those maximum recharge rates yielded the highest efficiency of exchange (Figure 27). Figure 28 presents the results of this sensitivity analysis compared to the efficiency of the exchange using a variable well field pumping capacity (expressed as the ratio of water captured and delivered to Parker to the HCU credits). A minimum extraction well field capacity of 30 cfs was selected because the water being diverted from the South Platte River at the upstream end of the exchange reach in Fort Morgan can be put directly into the pipeline to the Front Range, which has a capacity of 30 cfs. The model was run with 20,000 ac-ft of annual HCU credits. As Figure 28 shows, the results of this sensitivity analysis indicate that the efficiency of the exchange is insensitive to the recharge rate at the downstream end of the exchange reach, as both curves provide essentially identical results. Furthermore, the efficiency is very low at an extraction flow rate of 30 cfs (approximately 40 percent). While the efficiency improves at higher flow rates, these rates exceed the expected capacity of a pipeline to the Front Range, so there would need to be surface storage to manage this excess water, which creates a significant additional infrastructure (and potentially permitting) cost to this option.

Storage Capacity

To evaluate how much storage would be needed at the upstream end at the higher well field extraction rates, LWS then tested the Prewitt to Fort Morgan exchange model's sensitivity to changes in reservoir storage capacity. In this analysis, upstream surface storage was evaluated as a variable, using storage capacities ranging from zero to 6,000 ac-ft, while all other variables remained constant. Water is extracted with the use of alluvial wells and then either sent to PWSD via the pipeline or stored in the reservoir if the pipeline is full. The sensitivity analysis was run twice, with well field extraction rates at 50 cfs and 75 cfs at the upstream well field. The results of the sensitivity analysis are presented in Figure 29. When the reservoir capacity is equal to zero, the extraction rate for the upstream well field is limited to the pipeline capacity of 30 cfs, since there is no other method to deliver the water. Once the reservoir reaches full capacity, the well field extraction rate is again limited to 30 cfs plus the rate of any losses (such as evaporation). For the 50-cfs extraction rate scenario, the maximum active storage was reached at 2,380 ac-ft, with a corresponding overall exchange efficiency of 48 percent. For the 75-cfs extraction rate scenario, the maximum active storage was reached at 4,739 ac-ft, with a corresponding overall exchange efficiency of 55 percent. In both scenarios, increases in yield per ac-ft increase in reservoir storage capacity quickly reduce, especially as storage capacity exceeds 2,000 ac-ft. Given the relatively low efficiencies and much greater infrastructure costs to have both a high-production well field and surface storage, this option does not seem to be economically feasible.

Direct Pipeline

Given that the efficiencies are not high in any scenario that includes exchanges, and can also result in increased costs due to additional infrastructure needs, LWS then evaluated a pipeline that would deliver water directly from Iliff to PWSD. However, because of the high flow rates that need to be diverted from the South Platte River to the pipeline and the limited capacity in the Front Range delivery pipeline (30 cfs), there was also a recharge component to deal with the excess HCU credits beyond the pipeline capacity. Any HCU that cannot be sent directly to PWSD via the pipeline or recharged was considered to be forfeited. Figure 30 shows the efficiency of delivering water by pipeline from Iliff to Fort Morgan, using recharge on the downstream end to equalize water deliveries from the irrigation season to year-round deliveries. This scenario is highly sensitive to maximum recharge rates, and can achieve very high efficiencies, although the system would require a very large recharge system to achieve these high efficiencies. For example, a 40-cfs recharge system would be approximately 65 percent efficient, while an 80-cfs recharge system would be approximately 82 percent efficient. Given the presence of many recharge pond systems in this reach of the Lower South Platte River, this may be a cost-effective means to re-time water for year-round diversions.

Model Results

The sensitivity analyses were conducted initially to narrow the scope of the actual model runs. Based on the results of the sensitivity analyses, there were a number of options for water supply delivery that were not economically-feasible due to the low percentage of HCU water credits that could actually be captured and delivered. Without some regional cooperation relative to calls on the river among the operating ditches, exchanges for the most part are not an efficient option. The model results for viable water delivery options are presented below.

Direct Pipeline and Storage

In the pipeline scenario, LWS modeled the diversion of HCU credits in Iliff into a direct pipeline to Fort Morgan, and then to PWSD. Since HCU credits are only available during the growing season, a method of re-timing or storage was still necessary. LWS created model variations for both recharge re-timing and storage reservoirs.

The scenario using reservoir storage with a direct pipeline simply diverts HCU credits from the South Platte River and stores them in a reservoir until there is capacity in the pipeline from Iliff to PWSD to transport the water. Given that the HCU credits would be available in the river since the historically-irrigated fields would be dried up, the assumption in the model is that the previously-determined HCU credits would be available each year, so the reservoir scenario follows the same pattern each year, delivering the same amount of water to PWSD. The losses in this scenario are due to evaporation from the storage reservoir. The results of this model run are summarized in Table 8, which indicates that approximately 85 percent of the HCU credits can be captured, stored, and delivered. This scenario does require approximately 10,000 ac-ft of storage at the downstream end of the reach to achieve this efficiency.

Instead of surface storage, it is possible to use alluvial aquifer storage to re-time HCU credits to more efficiently deliver water. Therefore, a similar scenario was evaluated with the model, diverting HCU credits from the South Platte River into recharge ponds, and the accruals back to the stream were then re-captured from the river and delivered to the pipeline. Given the timing of available HCU credits and an evaluation of optimum spacing of recharge ponds from the river to provide the most efficient re-timing of water credits, i.e., spreading out the flows to a year-round basis, could not match the efficiency of surface storage. As shown in Table 9, the efficiency of capture dropped from 85 percent with surface storage to approximately 60 percent with recharge ponds and underground storage. The drop in efficiency is because there is less control over when water returns to the river and can be claimed versus surface storage, where water can be pumped on demand to keep the 30-cfs pipeline full. However, this option has a significantly lower infrastructure cost due to not having to construct surface storage. This variation of the model is highly sensitive to maximum recharge rate, distance of the recharge ponds from the stream, and the capacity of the pipeline. As an example, the results from the sensitivity analysis regarding varying recharge rates (Figure 30) should also be considered when determining the economic viability of this scenario.

Table 8. Details related to a direct pipeline from Iliff with a reservoir.

Pipeline Capacity:
30 cfs

Iliff Headgate Capacity:
150 cfs

Reservoir Storage:
50,000 ac-ft

Credits Available for Exchange:
20,000 ac-ft

Acres of Corn Needed to Dry-up:
10,000 acres

Efficiency:
85.1%

Year	Water to Parker (ac-ft)	Water Taken into Reservoir (ac-ft)
1999	28	28
2000	13,190	20,000
2001	17,456	20,000
2002	17,456	20,000
2003	17,456	20,000
2004	17,456	20,000
2005	17,456	20,000
2006	17,456	20,000
2007	17,456	20,000
2008	17,456	20,000
2009	17,456	20,000
2010	11,981	19,972
99-'09 Avg:	17,029	20,000

Red Text: Not a complete year of data.

Month	Average Water to Parker (ac-ft)	Average Water in Storage (ac-ft)
1	1,677.0	3,067
2	1,525.5	1,462
3	676.1	148
4	29.1	0
5	426.4	0
6	1,785.2	543
7	1,844.7	3,450
8	1,844.7	7,662
9	1,785.2	9,849
10	1,679.5	8,232
11	1,622.9	6,394
12	1,677.0	4,744
Annually:	1,381	3,796
Max Storage:	-	10,179

Table 9. Details related to a direct pipeline from Iliff with recharge permitting.

Pipeline Capacity:
30 cfs

Iliff Ditch Right:
150 cfs

Iliff Reservoir Storage:
50,000 ac-ft

Credits Available for Exchange:
20,000 ac-ft

Acres of Corn Needed to Dry-up:
10,000 acres

Storage in Downstream Reservoir:
0 ac-ft

Recharge Capacity:
30 cfs

Year	Water to Parker (ac-ft)	Water Direct to Parker (ac-ft)	Water to Parker from Recharge (ac-ft)	Recharge Water in Transit in Alluvium at End of Year (ac-ft)
1999	28	28	0	0
2000	9,259	7,272	2,004	4,563
2001	11,614	5,834	5,794	6,066
2002	12,253	5,675	6,580	6,842
2003	12,297	5,661	6,636	7,568
2004	12,302	5,667	6,633	8,291
2005	12,268	5,678	6,590	9,055
2006	12,292	5,663	6,629	9,786
2007	12,299	5,660	6,639	10,509
2008	12,302	5,667	6,633	11,232
2009	12,268	5,678	6,591	11,996
2010	9,992	5,663	4,061	14,999
99-'09 Avg:	11,915	5,846	6,073	

Month	Average Water to Parker (ac-ft)
1	643.2
2	515.6
3	482.6
4	391.8
5	436.2
6	1,785.2
7	1,844.7
8	1,844.7
9	1,785.2
10	628.6
11	685.9
12	699.4
Average:	979

Red Text: Not a complete year of data.

Exchange Efficeincy:
59.6%

Surface and Ground Water Storage with an Exchange

The previous options used a pipeline to move water from Iliff to Fort Morgan, by using either surface or underground storage to equilibrate flows to a year-round basis. Even though the sensitivity analyses have indicated much lower efficiencies of deliveries with exchanges, we evaluated several possibilities, based on the fact that exchanges are much less expensive to implement because less infrastructure is needed.

Based on the previous results, exchanges from the Iliff area were quite inefficient, but some form of exchange from the Prewitt area could provide economically-efficient exchanges. LWS performed an analysis of an exchange with recharge re-timing from the Prewitt area to Fort Morgan in an attempt to improve overall exchange efficiencies. The results from this analysis are summarized in Table 10. Using the information gathered from the sensitivity analyses, the estimated overall efficiency of the exchange was increased to approximately 50 percent from the Prewitt area. While this is a relatively low efficiency, it saves the cost of a pipeline from Iliff to Fort Morgan and any infrastructure on the downstream end of the reach.

Two additional scenarios from Iliff, surface storage with an exchange and recharge with an exchange, were also evaluated in the modeling. Neither option provided favorable results, because the timing of the exchanges still required that there be surface storage at the upstream end of the reach in the vicinity of Fort Morgan. Therefore, these options did not result in infrastructure savings and also had low efficiencies of water deliveries. Summaries of these options are presented in Tables 11 and 12.

Table 10. Results of exchange from Prewitt to Fort Morgan with downstream recharge and upstream reservoir.

Pipeline Capacity:
30 cfs

Extraction Wellfield Capacity:
50 cfs

Upstream Reservoir Storage:
50,000 ac-ft

Credits Available for Exchange:
20,000 ac-ft

Acres of Corn Needed to Dry-up:
10,000 acres

Storage in Downstream Reservoir:
0 ac-ft

Downstream Recharge Capacity:
25 cfs

Exchange Effeicency:
48.1%

Year	Water to Parker (ac-ft)	Augmentation Water Needed (ac-ft)	Water Recharged (ac-ft)	Recharge Water in Transit in Alluvium at End of Year (ac-ft)
1999	28	0.00	0	0
2000	7,432	30.14	4,823	3,149
2001	11,026	3.43	5,138	4,145
2002	9,626	0.00	6,022	5,273
2003	8,591	0.00	4,865	5,105
2004	10,379	0.00	5,340	5,757
2005	8,331	1.56	5,341	6,234
2006	10,324	0.00	5,257	6,651
2007	10,479	0.75	5,044	6,976
2008	9,339	1.58	4,678	7,154
2009	10,609	2.02	5,599	8,246
2010	9,332	0.00	5,199	10,246
99-'09 Avg:	9,614	3.95	5,211	-

Month	Average Water to Parker (ac-ft)
1	175.0
2	100.7
3	119.5
4	145.4
5	509.6
6	1,578.1
7	1,790.9
8	1,832.9
9	1,785.2
10	1,157.9
11	225.5
12	169.9
Average:	799

Red Text: Not a complete year of data.

MODEL VARIATIONS:
Priority to Direct Exchange, then Recharge

Maximum Reservoir Storage:
2,380 ac-ft

Days with over 60 ac-ft of Storage:
1,433

Table 11. Results of exchange with Iliff reservoir and Fort Morgan Reservoir.

Pipeline Capacity:
30 cfs

Fort Morgan Extraction Wellfield Capacity:
50 cfs

Fort Morgan Reservoir Storage:
10,000 ac-ft

Credits Available for Exchange:
20,000 ac-ft

Acres of Corn Needed to Dry-up:
10,000 acres

Iliff Reservoir Storage:
10,000 ac-ft

Iliff Headgate Inlet Capacity:
150 cfs

Year	Water Diverted at Iliff (ac-ft)	Water Exchanged to Upstream Storage (ac-ft)	Water to Parker (ac-ft)	OOP Depletions (ac-ft)
1999	28	28	28	0.0
2000	4,109	3,293	2,980	46.7
2001	11,981	10,599	8,663	31.9
2002	197	149	149	4.0
2003	4,731	3,213	2,448	15.2
2004	5,109	3,082	3,017	88.3
2005	3,615	4,177	3,272	57.5
2006	1,175	931	878	24.8
2007	5,276	4,390	3,583	37.1
2008	4,960	2,142	2,050	66.9
2009	15,172	14,993	12,250	57.7
2010	9,139	4,060	3,764	12.7
99-'09 Avg:	5,632	4,697	3,929	43

Month	Average Water in Upstream Storage (ac-ft)	Average Water in Iliff Storage (ac-ft)
1	11	343
2	0	342
3	6	302
4	2	226
5	8	173
6	155	443
7	34	976
8	10	1,592
9	69	1,971
10	123	1,464
11	184	911
12	160	519
Annually:	64	772
Max Storage:	2,245	6,472

Red Text: Not a complete year of data.

Exchange Effeciency:
19.6%

Table 12. Results of exchange from Iliff to Fort Morgan with downstream recharge and upstream reservoir.

Pipeline Capacity:
30 cfs

Extraction Wellfield Capacity:
50 cfs

Upstream Reservoir Storage:
50,000 ac-ft

Credits Available for Exchange:
20,000 ac-ft

Acres of Corn Needed to Dry-up:
10,000 acres

Storage in Downstream Reservoir:
0 ac-ft

Downstream Recharge Capacity:
50 cfs

Exchange Effeicency:
13.7%

Year	Water to Parker (ac-ft)	Augmentation Water Needed (ac-ft)	Water Recharged (ac-ft)	Recharge Water in Transit in Alluvium at End of Year (ac-ft)
1999	28	0.00	0	0
2000	1,285	11.99	2,541	1,840
2001	6,757	3.07	5,796	4,370
2002	1,054	0.00	176	1,221
2003	2,045	11.92	2,795	2,705
2004	2,456	0.00	3,452	3,428
2005	1,991	0.00	1,911	2,607
2006	515	0.00	913	2,304
2007	2,664	0.00	2,783	3,451
2008	1,604	2.17	3,632	4,559
2009	7,023	2.76	7,444	7,538
2010	4,799	0.00	5,006	8,335
99-'09 Avg:	2,739	3.19	3,144	-

Month	Average Water to Parker (ac-ft)
1	131.4
2	67.5
3	99.2
4	67.7
5	225.2
6	772.0
7	329.4
8	305.6
9	473.3
10	159.8
11	160.5
12	137.6
Average:	244

Red Text: Not a complete year of data.

MODEL VARIATIONS:
Priority to Direct Exchange, then Recharge

Maximum Reservoir Storage:
572 ac-ft

Days with over 60 ac-ft of Storage:
251

Water Treatment

During most times of the year, any water diverted from the South Platte River or its associated alluvium needs pre-treatment to reduce total dissolved solids (TDS) prior to delivery to Rueter-Hess Reservoir. The need for, and the level of, water treatment was evaluated in the previous study (States West, August 2006) by Integra Engineering (*nee* Dewberry). Because the principal concern is TDS concentrations above drinking water standards and water quality regulations in Rueter-Hess Reservoir, it is likely that reverse osmosis (RO) treatment is necessary to remove the salts. However, because not all of the water needs to receive RO treatment, a *split-stream* can be employed, whereby a portion of the water is treated by RO, with the remainder of the water treated by conventional means. In this way, TDS concentrations can be diluted to acceptable levels for delivery to Rueter-Hess Reservoir.

The estimated capital costs for a 10 million gallons per day (mgd) water treatment plant, including disposal of the RO brine by residual drying beds and concentrate evaporation ponds, is approximately $60 million. Assuming the delivery of approximately 17,030 ac-ft (Table 8) results in a unit cost for treatment of approximately $3,500. The operations and maintenance costs associated with a 10-mgd RO/conventional treatment plant are estimated to be approximately $1.25 per thousand gallons.

Treatment through the RO process is proposed to be conducted in the Fort Morgan area, since the brine disposal process is land-intensive, and land is less expensive in this area than along the Front Range.

Delivery Costs

For each of the water delivery options evaluated, preliminary costs associated with that option, including the cost of storage, water treatment, and pump and pipeline delivery have been prepared. Conceptual level cost estimates to supply water from the South Platte River to a location near Fort Morgan have been developed for the purpose of preliminarily assessing economic feasibility. Conceptual level designs were developed by States West for a pipeline to supply a constant flow of approximately 30 cfs. Two alternatives for the point of diversion of the HCU credits were evaluated; (1) diverting water from the South Platte River near Iliff, and (2) diverting water from the South Platte River near Prewitt.

Alternative 1 – Iliff to Fort Morgan

This alternative assumes a 34-in steel pipeline and pump stations would be required to supply the 30 cfs flow. The alignment was developed by following major roads and I-76 as much as possible. It was assumed that road crossings, railroad crossings and stream crossings would require the pipeline to be bored under them. Profiles of the alignment were developed to determine pumping requirements, air/vac station locations and blow-offs. The plan and profile sheets for this conceptual design are attached in Appendix A2.

Alternative 2 – Prewitt to Fort Morgan

This alternative was taken from the report developed in 2006. The report developed conceptual level design for a pipeline capable of supplying approximately 30 cfs. This design provided an alignment that would supply water from a location near the existing Prewitt Reservoir diversion on the South Platte River. The alignment for this report was taken from a portion of the alignment designed in the 2006 report. This alignment starts at the existing Prewitt Diversion and terminates at a location just south of Fort Morgan. The plan and profile sheets for this conceptual design are attached in Appendix A2.

Costs

Costs for the two alternatives were based on the unit costs developed in the 2006 report and adjusted to current day costs using the Bureau of Reclamation's Construction Cost Trend indexing. Multipliers were calculated from the index values of 2006 and 2013. These multipliers were applied to the unit costs developed in the 2006 report and used to determine the conceptual costs for this report. The detailed cost estimates for the Iliff to Fort Morgan Alternative and the Prewitt to Fort Morgan Alternative are presented below in Tables 13 and 14, respectively. The costs also estimate engineering, permitting and legal fees and costs for easement acquisition. Assuming the delivery of 17,030 ac-ft (Table 8) from Iliff and an estimated pipeline/pumping infrastructure cost of $205,000,000, the unit cost of delivery would be approximately $12,000 per ac-ft. In today's water market, that is a very reasonable delivery cost.

Table 13. Cost estimates – Iliff to Fort Morgan.

ITEM	UNIT	QUANTITY	UNIT COST	TOTAL COST
Mobilization (5%)	L.S.	--	--	$3,000,000
34" Steel Pipe	L.F.	330,000	365	$120,450,000
Bores	L.F.	2,500	1,265	$3,162,500
Air-Vacs	Ea.	40	38,000	$1,520,000
Blow-Offs	Ea.	45	8,000	$360,000
Diversion Structure	L.S.	1	3,000,000	$3,000,000
WTP Pump station	L.S.	1	1,000,000	$1,000,000
Booster Pump Sta.	Ea.	3	3,800,000	$11,400,000
Power Supply	Ea.	2	240,000	$480,000
Stream Crossing	L.F.	2	1,300	$2,600
Wetland Mitigation	Ac.	20	25,000	$500,000
Branch Outlets	Ea.	5	245,000	$1,225,000

Construction Cost Sub-Total:	**$146,100,100**
10% Engineering:	$14,610,010
Sub-Total:	**$160,710,110**
15% Contingency:	$24,106,517
Construction Cost Total:	**$184,816,627**
Preparation of Final Designs & Specifications:	$12,000,000
Permitting:	$1,800,000
Legal Fees:	$900,000
Acquisition of Access and Rights of Way	$4,500,000
Total Project Cost:	**$204,016,627**
USE:	**$205,000,000**

Table 14. Cost estimates – Prewitt diversion dam to Fort Morgan.

ITEM	UNIT	QUANTITY	UNIT COST	TOTAL COST
Mobilization (5%)	L.S.	--	--	$3,000,000
34" Steel Pipe	L.F.	135,000	365	$49,275,000
Bores	L.F.	2,000	1,265	$2,530,000
Air-Vacs.	Ea.	13	38,000	$494,000
Blow-Offs	Ea.	3	8,000	$24,000
Diversion Structure	L.S.	1	3,000,000	$3,000,000
WTP Pump station	L.S.	1	1,000,000	$1,000,000
Booster Pump Sta.	Ea.	1	3,800,000	$3,800,000
Cherry Creek Connection	L.S.	0	0	$0
Power Supply	Ea.	1	240,000	$240,000
Stream Crossing	L.F.	6	1,300	$7,800
Wetland Mitigation	Ac.	10	25,000	$250,000
Branch Outlets	Ea.	1	245,000	$245,000

Construction Cost Sub-Total:	**$63,865,800**
10% Engineering:	$6,386,580
Sub-Total:	**$70,252,380**
15% Contingency:	$10,537,857
Construction Cost Total:	**$80,790,237**
Preparation of Final Designs & Specifications:	$5,000,000
Permitting:	$800,000
Legal Fees:	$400,000
Acquisition of Access and Rights of Way	$2,000,000
Total Project Cost:	**$88,990,237**
USE:	**$90,000,000**

Storage Cost

In addition to the pipeline/pumping infrastructure, the analyses indicate that surface storage would also be necessary (Table 8). Assuming the need for up to 10,000 ac-ft of storage, the additional costs of that storage were estimated. The 2006 report evaluated potential reservoir sites and, from that report, a unit cost estimate for storage was determined to be approximately $4,000 per ac-ft of storage. The reservoir estimates in the 2006 report appear to be much larger than the assumptions for this report. Because of this, unit storage costs would be anticipated to be larger for a smaller reservoir, because the economy of scale would not be as great. Assuming the unit cost of storage to be $7,500 per ac-ft would result in an additional unit cost for the project of $4,400 per ac-ft.

Figure 22. General location map of the Parker Water and Sanitation District farmland in Logan County.

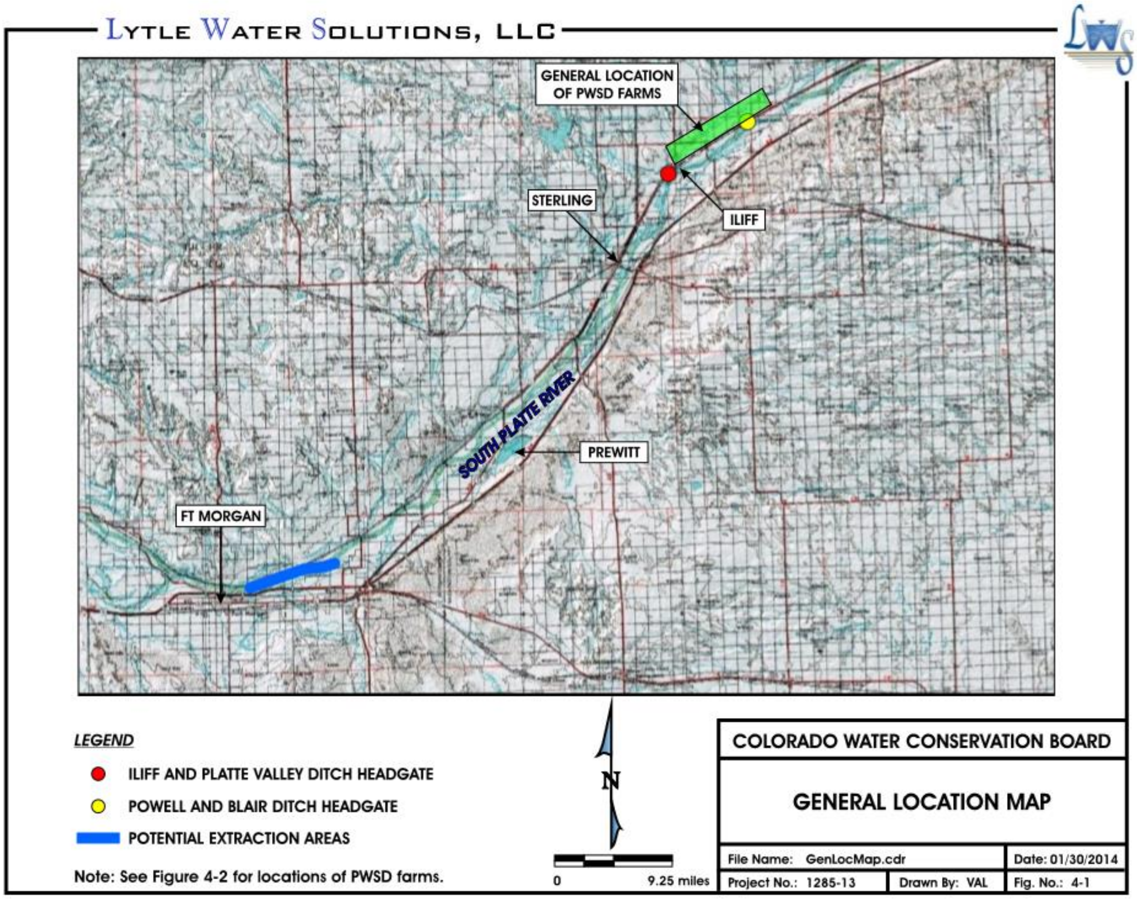


Figure 23. Map of Parker Water and Sanitation District Logan County Farms.

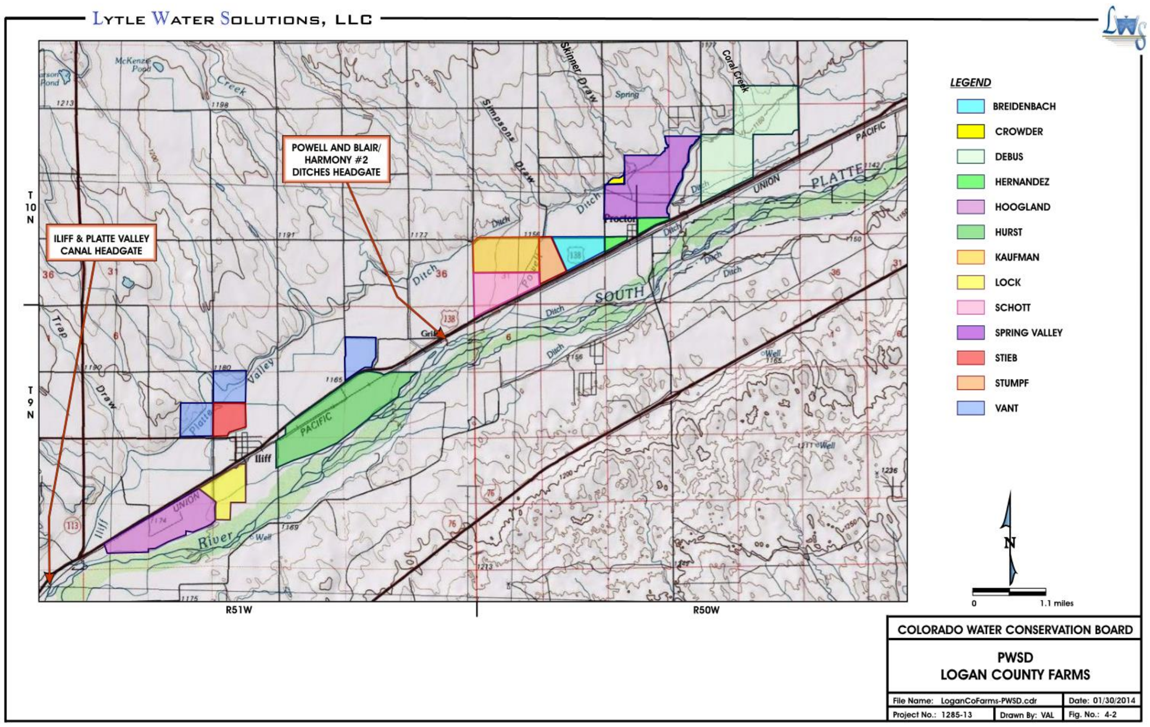


Figure 24. Consumptive use (CU) curves for corn in the Iliff area.

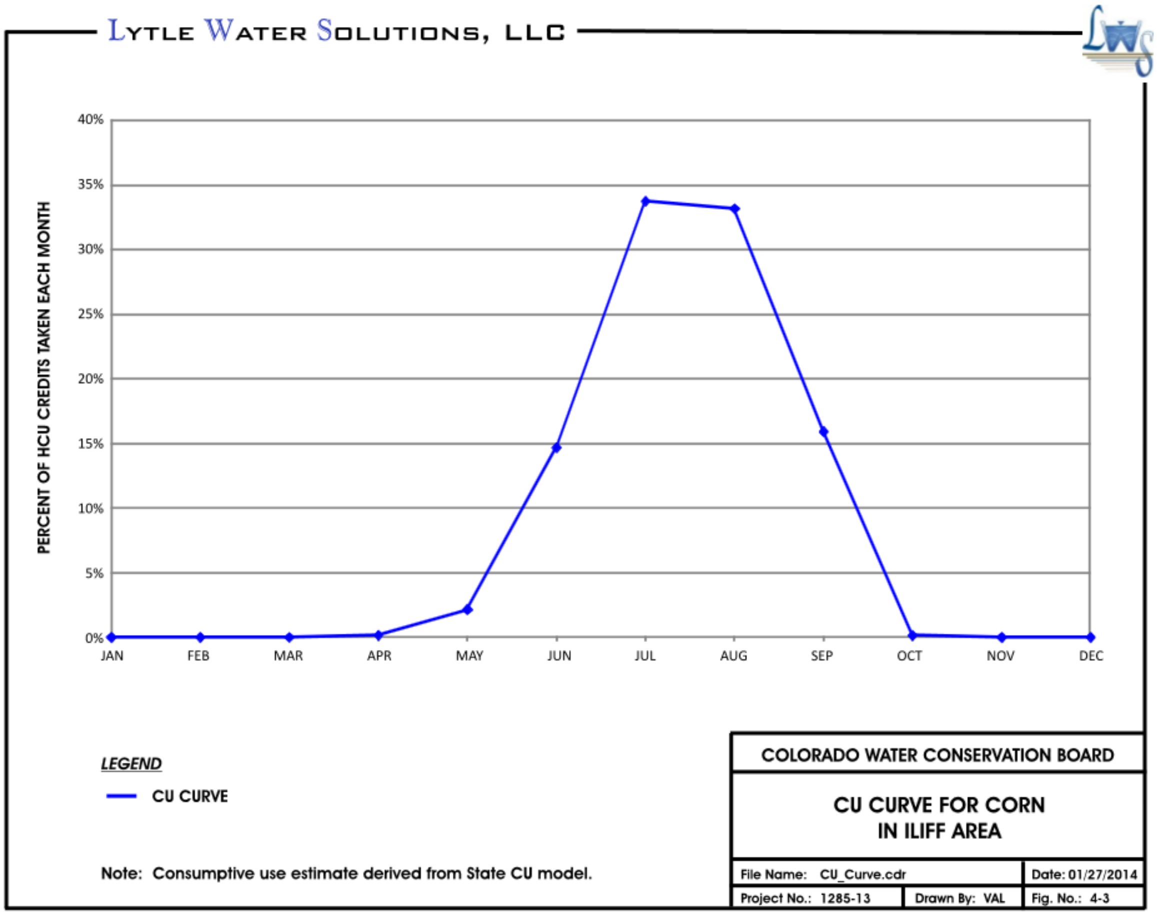


Figure 25. Schematic of analyzed scenarios for water exchange of movement.

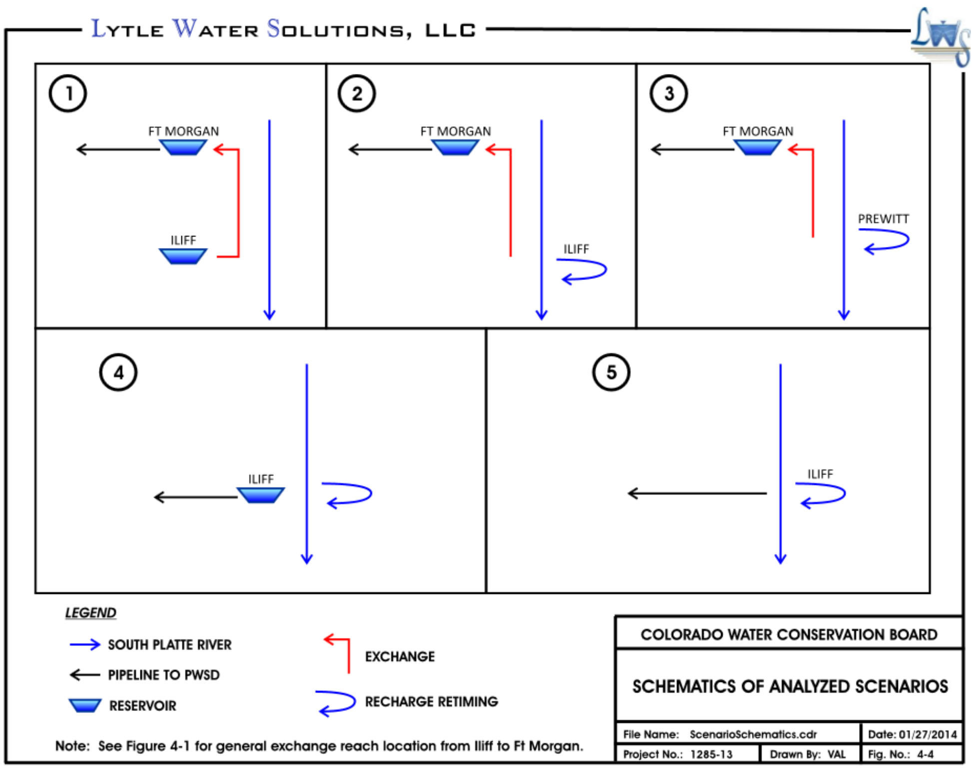


Figure 26. Average exchange efficiencies at Iliff and Prewitt.

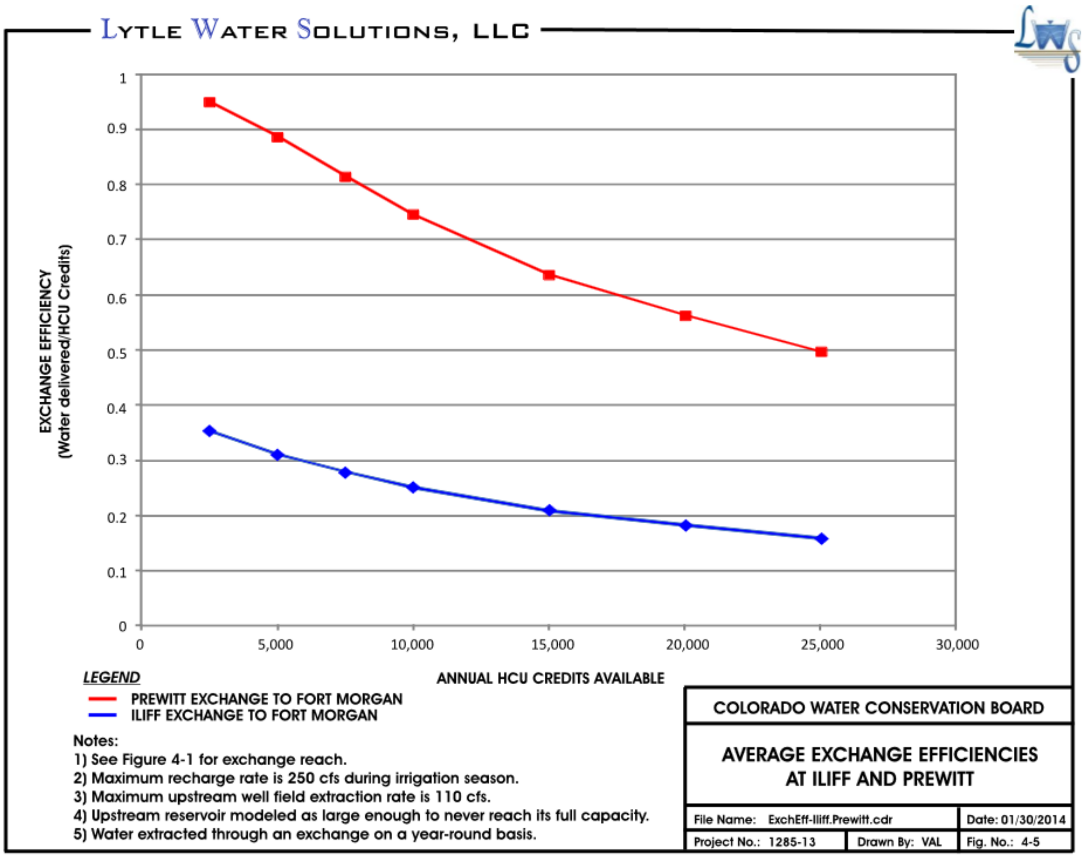


Figure 27. Exchange efficiencies with varying recharge rates.

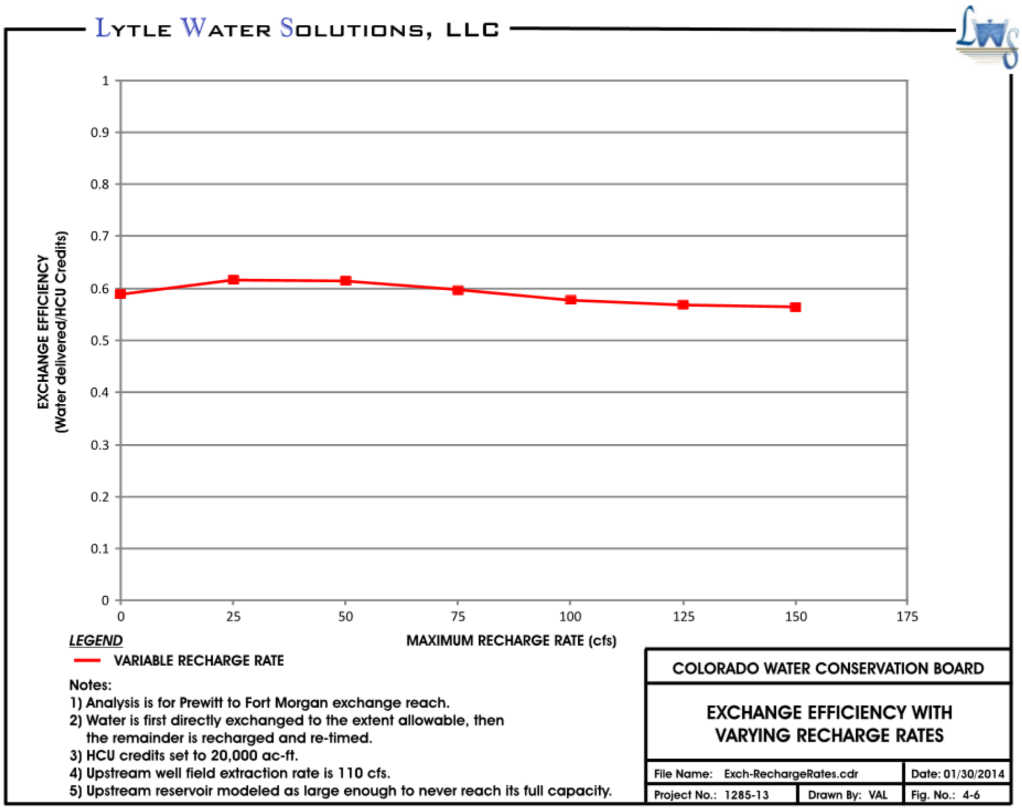


Figure 28. Exchange efficiencies using alluvial well fields.

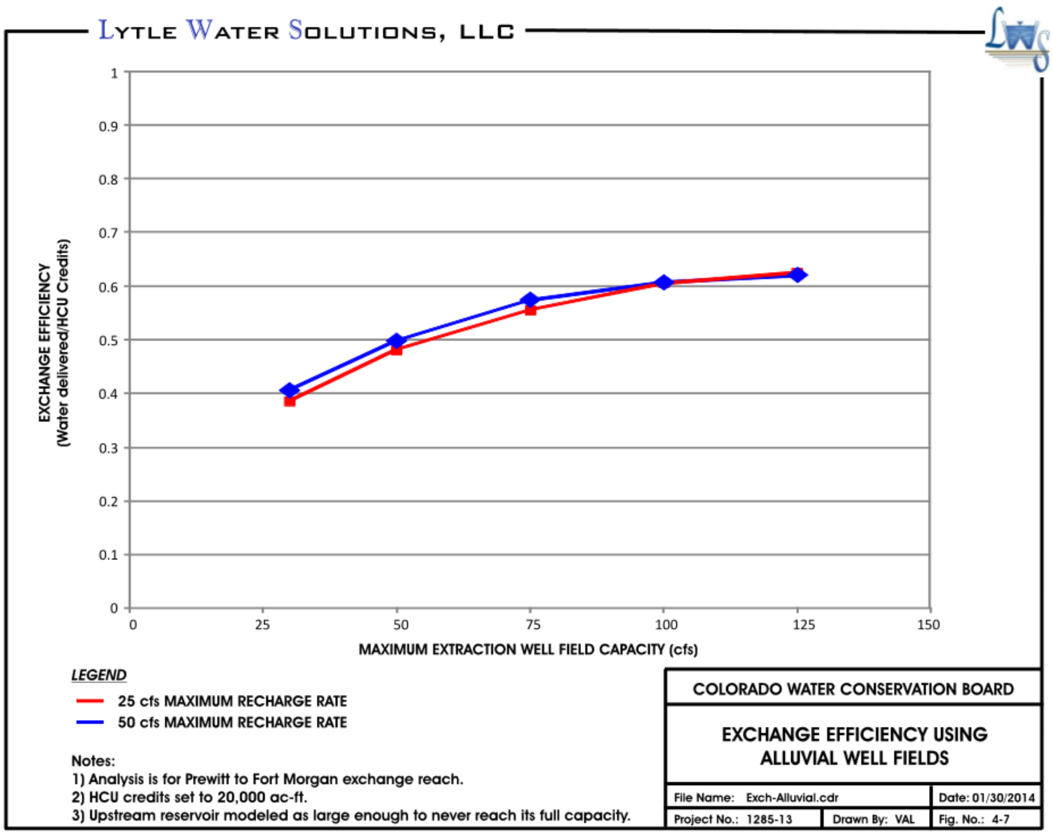


Figure 29. Exchange efficiencies using direct diversion and storage.

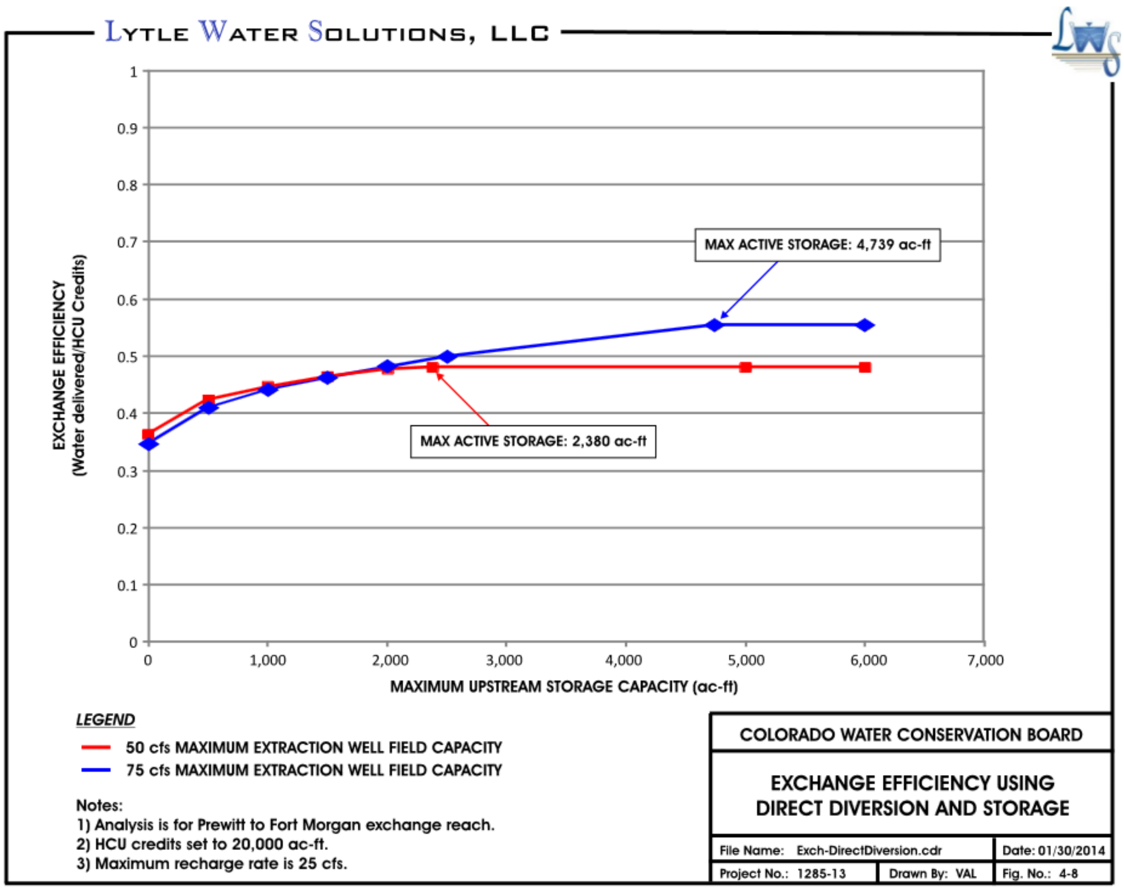


Figure 30. Iliff pipeline scenario recharge sensitivity.

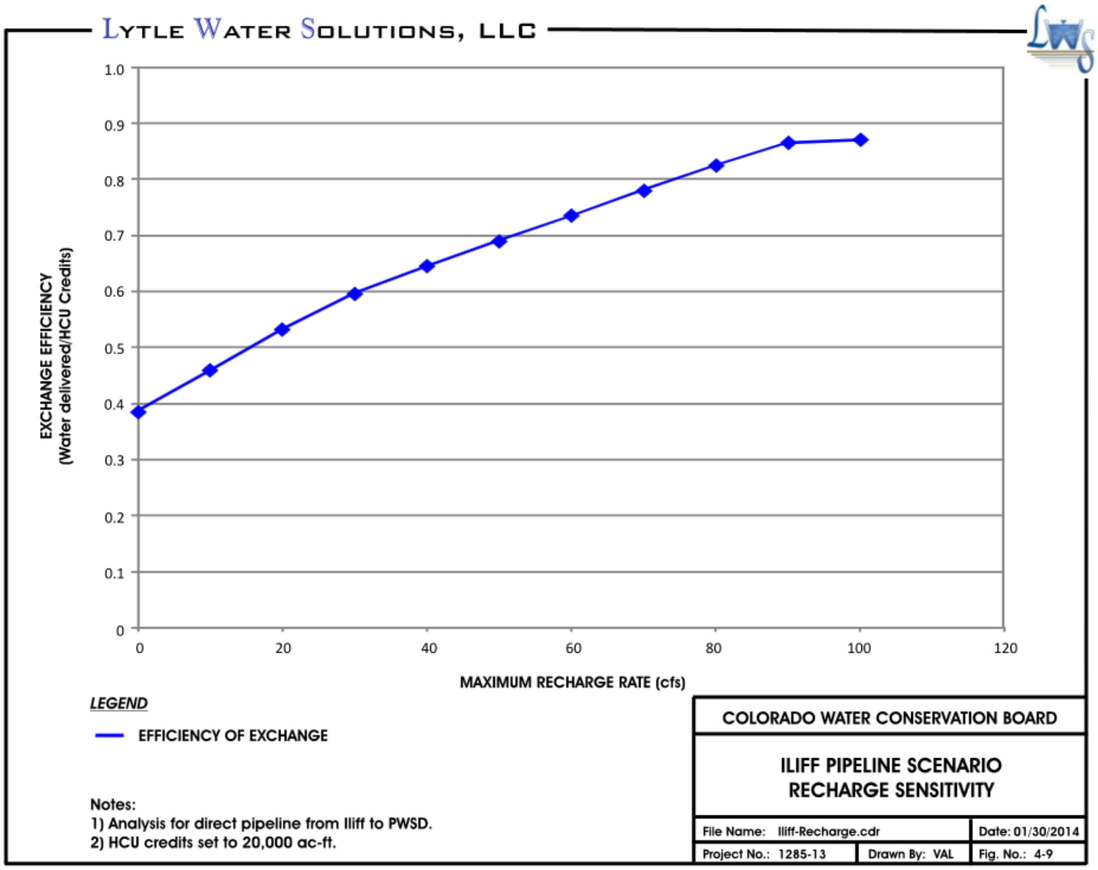


Figure 31. Average exchange flows during season.

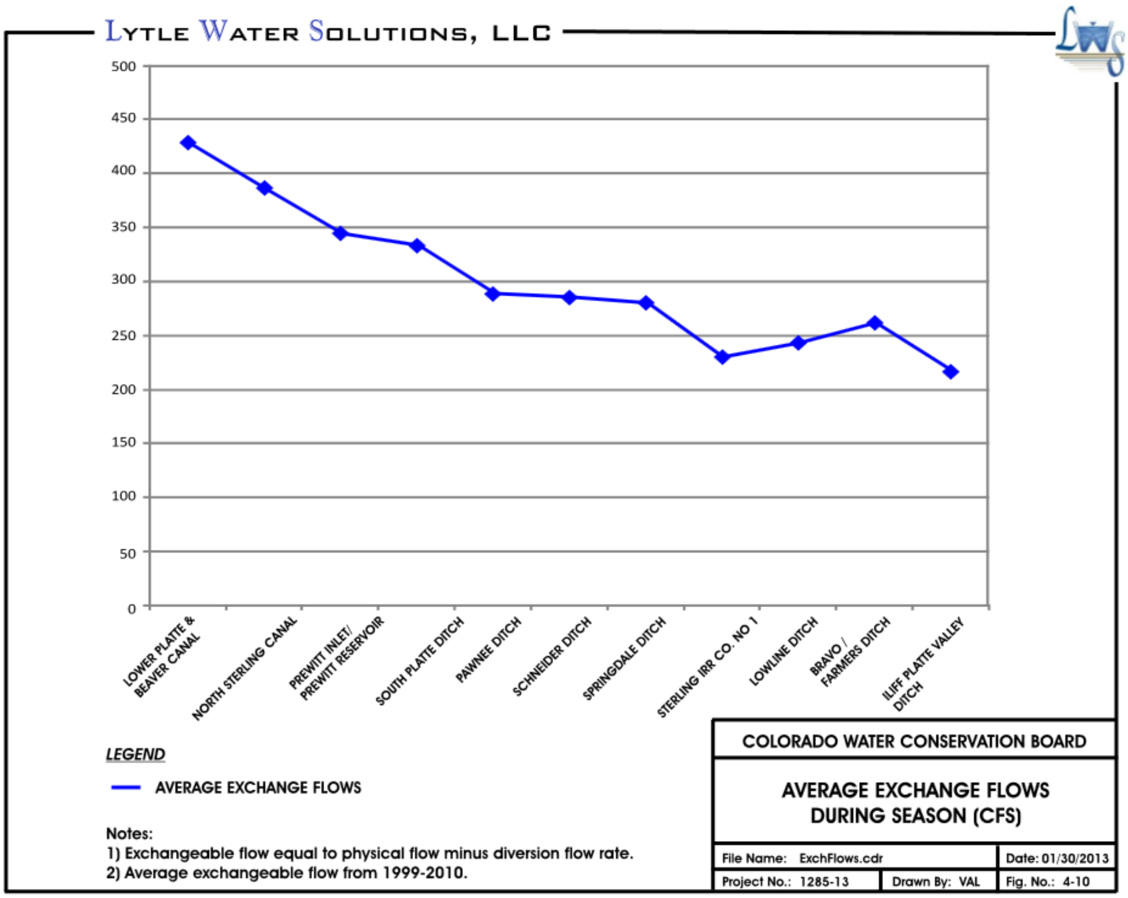
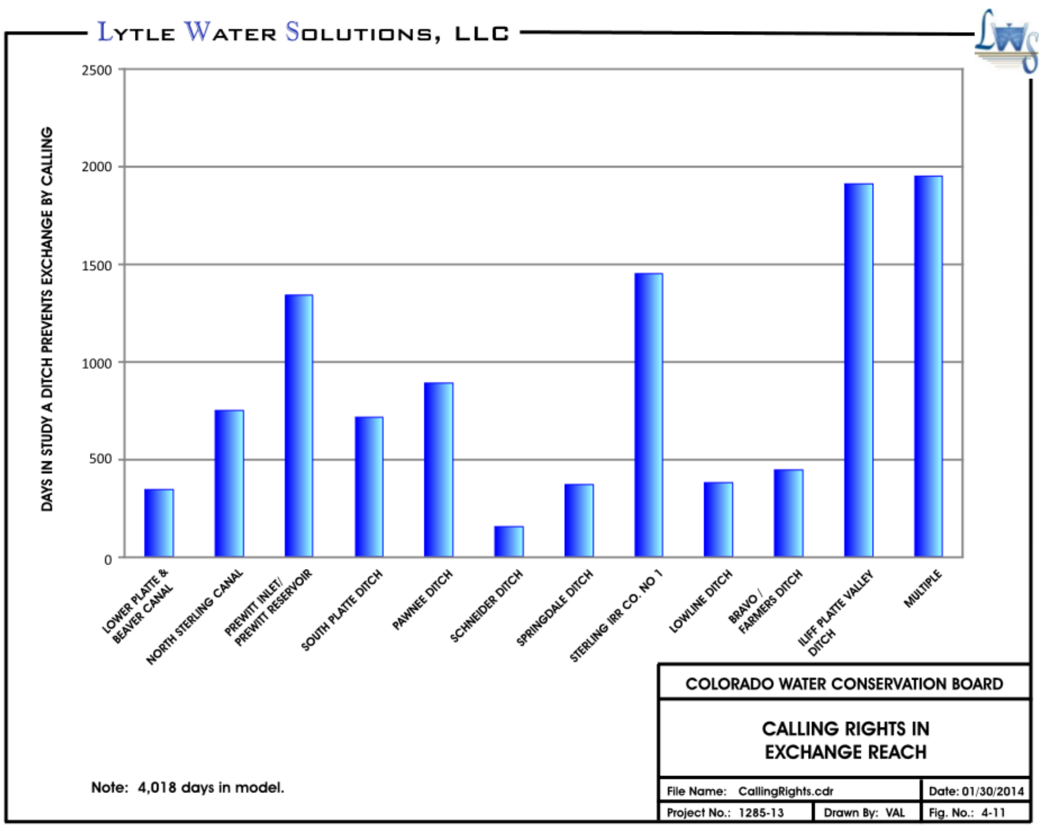


Figure 32. Calling rights in each exchange reach.



Conclusions

Task1: The first task in this Alternative Agricultural Water Transfer Grant evaluates approaches for quantifying consumptive savings of alternative cropping practices. Three approaches were evaluated and include a stress coefficient, the crop water stress index (CWSI), and satellite based remote sensing using the ReSET model. The intent of a stress coefficient is to apply the use of crop coefficients and standardized energy balance equations used for estimating reference ET to cropping systems that involve water stress. The stress coefficient estimates reductions in ET due to limitations from dry soil conditions. Stress coefficients were quantified for maize plots under well irrigated and deficit irrigated treatments at the Iliff research site during three growing seasons. The deficit irrigation treatment had a 20%-55% reduction in irrigation application and resulted in 10%-34% reductions in consumptive water use. The daily modeling approach outlined in the Irrigation and Drainage Paper No. 56, published by the Food and Agriculture Organization of the United Nations (FAO-56) underestimated maize water use, but the difference (8%-26%) was similar to typical errors reported for other data-intensive and complex water use estimation methods. In addition, seasonally averaged water use errors did not exceed 1.0 mm d^{-1} for any studied treatment and season, suggesting that the FAO-56 procedure can be used as an effective method for quantifying consumptive use and savings in limited irrigation systems. The practical application of this approach requires measurement of soil water content at the beginning of the growing season and site specific estimates of soil water retention properties.

The CWSI was a second method evaluated for quantifying consumptive use in deficit irrigated cropping systems. CWSI is a remote sensing approach based on the use of infrared thermometry to assess the temperature of the crop canopy. The canopy temperature is indexed against air temperature and humidity defined limits to calculate CWSI. As part of this project, upper and lower limits were established for corn in Eastern Colorado conditions. A remote sensing-based Crop Water Stress Index (CWSI) was estimated during a time with variable degrees of stress at the Iliff research farm in 2011. The CWSI was capable of differentiating among irrigation practices and is clearly a candidate method for assessing whether a crop is experiencing water stress. The CWSI values were also used to estimate corn transpiration rate. Applying an independent remotely sensed energy balance model showed that corn ET was 177 mm during the study period (29 days), 29% larger than CWSI-Ta (137 mm) during the same period. Thus the CWSI under-predicted ET. This method appears to have more application toward relative determination of crop water status than for quantification of saved consumptive use.

The third approach for quantifying consumptive use of limited irrigation systems uses a CSU developed model called Remote Sensing of Evapotranspiration (ReSET). The model utilizes thermal band satellite imagery, in combination with local weather observations to calculates evapotranspiration on the day the image was taken. The model can use multiple satellite images taken over the growing season to calculate the season crop consumptive water use and can express the spatial variation within fields. For this project, ReSET was tested against controlled conditions at the Iliff research site, and also on farmer's field. At the Iliff site, ReSET identified small differences in crop ET and produced good estimates of ET. To evaluate the model on farmer's fields, ReSET was tested for four fields. The temporal and spatial actual ET for each of these fields was calculated and documented using the ReSET model. The seasonal actual ET estimated by the ReSET model compared very well to reported irrigation records with an accuracy of up to 98% and not less than 92% for fields with normal growing conditions. ReSET was able to detect abnormal growing conditions on some fields such as late crop development, areas that do not have a good crop stand and the model results quantified the reduction in ET due to such conditions. The results of this research project show the potential for using the ReSET model to monitor and quantify the ET from agricultural fields with limited irrigation. The method does require some specialized technical knowledge, but there are good research publications that provide the details of how the method can be applied.

Each of the three methods evaluated have individual strengths and weaknesses, but any of them could be utilized in evaluating compliance with water transfers, while avoiding the need for complete dry-up of agricultural fields. One recommended approach would be that irrigators involved in water transfers associated with water conserving irrigation practices assume responsibility to track ET using a stress coefficient approach. Technical service providers, such as crop consultants, can support this effort. Farms in such an agreement would benefit from the use of flow meters and soil moisture sensors in their fields. Organizations overseeing water transfers could further utilize one of the remote sensing approach for verification of reported practices and ET rates.

Task 2: The second task for this project was to evaluate the potential of an allocation approach for administering the transfer of saved consumptive use from irrigated farms to municipalities. In an allocation approach, an irrigated farm would agree to a fixed, reduced allocation of water for irrigation. The approach makes an assumption of zero return flow from the applied irrigation, therefore the full obligation for maintaining historic return flows would be met through a separate diversion of water into an approved augmentation system. In this approach all of the monitoring and verification would occur at points of diversion or pumping and the need for in-field soil moisture sensors or remote sensing would be avoided. Only the saved consumptive use above the amount required for meeting return flow obligations would be transferred to municipal use. To illustrate the concept of the allocation approach, four hypothetical scenarios are outlined and discussed in the report. Further, in 2012 the Iliff field site was used for a demonstration of an allocation approach based on 5 years of baseline measured values. For a sprinkler irrigated corn crop with an allocation of 10 in., there were 4.3 in. of saved consumptive use available for transfer. Based on actual ET and drainage calculations, the amount of water that could be transferred was 4.6 in. The small amount of additional saved water does not well justify the high administrative burden of quantifying ET and return flows, illustrating the advantage of an allocation approach. The Iliff case study illustrates the potential of an allocation approach, event though the quantity of water available for transfer was small. The cost and benefits of a smaller allocation could be evaluated. A benefit from an allocation approach is that it creates an incentive for irrigation efficiency improvements, which is often lacking in water law governed by the prior appropriations doctrine. Another potential benefit is that the return flow assumptions are conservative and additional return flows may provide benefits to rivers and downstream users.

Task 3: LWS performed multiple model analyses to estimate the quantities of water that could potentially be delivered to PWSD for use in Parker and other local municipalities. The final determination of whether these scenarios are economically feasible will be determined by the price of the project versus the value of the water, but from our analysis, we can draw a number of conclusions and recommendations, which are presented below.

The exchange potential on the Lower South Platte River is generally low, but decreases as it nears the Nebraska State line. Figure 31 shows the average exchangeable flow from Iliff to

Fort Morgan during the irrigation season, and the trend is rather linear in its increasing flow moving upstream. While these flow values may seem high for each headgate, it is important to remember that the flows on the South Platte River are very episodic, coming in very large flow peaks of short duration. Figure 32 gives us another way of looking at this same restriction by graphically representing the number of days in the 10-year study period that each of the ditches in the exchange reach had placed a call which would prevent the exchange from operating. Looking upstream from Iliff, the Sterling Co. No. 1 Canal and the Prewitt Inlet are the most frequent individual callers, but it was even more common to have multiple calls that would keep the exchange from operating. These results show that moving further upstream would have a positive impact on the amount of exchangeable flow available to move HCU credits.

Given the lack of exchange potential shown by the model for the Iliff area, LWS recommends that the model be calibrated using real world observations and measurements to verify the lack of flows when the model estimates zero exchange potential. If the model estimates of flow are verified, LWS believes that the exchange from the Iliff area to Fort Morgan is too unreliable to be a municipal water supply for PWSD or other Front Range water users. From a reliability standpoint, a pipeline from the Iliff area to PWSD (i.e., Rueter-Hess Reservoir) produces the most efficient water delivery system. The second option to mitigate the lack of exchange flow in the Iliff area is to acquire HCU credits in the Prewitt area where the increased flows produce a more efficient exchange. Acquiring HCU credits in the Prewitt area could be accomplished by purchasing additional water rights or potentially by swapping HCU credits under the Northeast Colorado Water Cooperative group.

If it is determined that the pipeline from Iliff is the more viable method, retiming or storing the water in a reservoir is the next large factor to consider. The assessment of the efficiency of the reservoir storage will require a site to be selected so that a site-specific investigation can be performed to estimate seepage rates, develop an elevation-area-capacity curve, and refine the evaporation rate estimates. The LWS reservoir scenario modeling does provide a reasonable estimate of the maximum efficiency of 85 percent (Table 8), which could be achieved if the reservoir were to be built to the maximum storage value of roughly 10,000 ac-ft. In fact, the unit cost for storage, the pipeline, and treatment is approximately $20,000 per ac-ft, which is consistent with water prices in today’s market to develop the water resource and deliver it to its end use.

When using recharge to re-time irrigation season flows, the ideal recharged flows would begin to accrue to the South Platte River just as the irrigation season flows cease, and then end as the irrigation season flows begin again in the spring. The ideal URF curve is a 6-month peak that drops off quickly on either side. Glover URF curves in actuality are much flatter curves and, in this case, have rounded peaks which reach their maximum stream accruals in roughly 100 days and then slowly taper off for 500 days. When this type of URF is used for recharge year after year, the pattern of accruals is at its peak during the desired non-irrigation season, with a reduced flow in the peak irrigation season. But with the long "tail" of the URF curve, there will always be some level of accruals to the South Platte River if the recharge ponds have been operated in the last 600 days. Given the sporadic nature of the modeled flows at Iliff on the South Platte River, the constant return flows can be very advantageous if there are longer periods without native flow. The recharge system also has the advantage of not being subject to evaporation and being built in the highly prolific South Platte alluvium. Based on the sensitivity analysis curve presented in Figure 30, a recharge system could yield high efficiencies if it can be built economically to sustain a high level of recharge flows.

LWS believes there are significant amounts of water resources available in the Lower South Platte River basin that can be sustainably and responsibly used to benefit Front Range municipalities like PWSD without having a detrimental impact to irrigators on the South Platte River. While this analysis has solely used HCU credits as a measure of the water to be moved in a potential future water supply delivery system to the Front Range, the means to develop these credits has been the focal point of the CSU research into alternative agricultural transfer instead of the traditional "buy and dry" concept. As such, we believe that HCU credits can be a valuable part of the total waters diverted and transported back upstream for use, but do not have to be viewed as the sole source of water, to the detriment of rural economies.

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APPENDIX A1

StateCU Model Results

Table A1-1. Raw StateCU irrigation water requirement results for corn in the Iliff area.

Time Series Identifier = 7950
Description = STERLING
Data Source = C:\cdss\DATA\STATECUWIZARD\UseCurve\UseCurve.BD1
Data Type = Irrigation Water Reqt

Data Interval = Month
Data Units = ACFT
Period = 1912-01 to 2011-12
Orig./Avail. Period = 1912-01 to 2011-12

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1912	0	0	0	0	0.009	0.104	0.435	0.37	0.085	0	0	0	1.003
1913	0	0	0	0	0.01	0.437	0.557	0.017	0	0	0	0	1.021
1914	0	0	0	0	0.044	0.243	0.568	0.461	0.204	0	0	0	1.52
1915	0	0	0	0	0	0.046	0.326	0.3	0.327	0.037	0	0	1.036
1924	0	0	0	0	0	0.187	0.445	0.529	0.107	0	0	0	1.268
1928	0	0	0	0	0	0.033	0.383	0.468	0.279	0	0	0	1.164
1930	0	0	0	0	0	0.206	0.382	0.32	0.308	0.015	0	0	1.231
1931	0	0	0	0.006	0.035	0.313	0.618	0.539	0.2	0	0	0	1.711
1933	0	0	0	0	0	0.356	0.549	0.376	0.363	0	0	0	1.643
1934	0	0	0	0.012	0.083	0.234	0.673	0.65	0.148	0	0	0	1.802
1935	0	0	0	0	0	0.192	0.618	0.596	0.233	0	0	0	1.639
1936	0	0	0	0	0	0.27	0.543	0.403	0.264	0	0	0	1.479
1937	0	0	0	0	0.006	0.117	0.587	0.6	0.279	0	0	0	1.588
1938	0	0	0	0	0	0.188	0.484	0.591	0.249	0	0	0	1.512
1939	0	0	0	0	0.08	0.169	0.595	0.437	0.288	0	0	0	1.57
1940	0	0	0	0	0.088	0.111	0.585	0.522	0.276	0	0	0	1.582
1941	0	0	0	0	0.088	0.192	0.377	0.432	0.084	0	0	0	1.173
1945	0	0	0	0	0	0.025	0.476	0.348	0.131	0	0	0	0.98
1946	0	0	0	0	0	0.15	0.559	0.525	0.239	0	0	0	1.473
1948	0	0	0	0.011	0.051	0.155	0.505	0.432	0.195	0	0	0	1.35
1949	0	0	0	0	0	0.03	0.583	0.508	0.189	0	0	0	1.311
1950	0	0	0	0	0	0.196	0.399	0.48	0.267	0.041	0	0	1.383
1951	0	0	0	0	0.053	0.06	0.406	0.444	0.178	0	0	0	1.14
1952	0	0	0	0	0	0.31	0.646	0.431	0.329	0	0	0	1.716
1953	0	0	0	0	0.042	0.184	0.43	0.468	0.478	0.009	0	0	1.611
1954	0	0	0	0	0.018	0.266	0.527	0.574	0.407	0	0	0	1.792
1955	0	0	0	0	0	0.166	0.546	0.523	0.238	0	0	0	1.472
1956	0	0	0	0	0.061	0.216	0.401	0.477	0.015	0	0	0	1.169
1958	0	0	0	0	0.034	0.194	0.323	0.465	0.206	0	0	0	1.222
1959	0	0	0	0	0	0.225	0.551	0.537	0.263	0	0	0	1.576
1960	0	0	0	0	0.005	0.206	0.373	0.582	0.277	0	0	0	1.442
1961	0	0	0	0	0	0.242	0.295	0.591	0.134	0	0	0	1.262
1962	0	0	0	0.005	0	0.161	0.154	0.555	0.133	0	0	0	1.007
1963	0	0	0	0.012	0.08	0.316	0.44	0.33	0.149	0	0	0	1.327
1966	0	0	0	0	0.086	0.13	0.487	0.382	0.249	0	0	0	1.334
1967	0	0	0	0	0	0	0.391	0.544	0.34	0	0	0	1.275
1968	0	0	0	0	0	0.278	0.424	0.204	0.396	0.024	0	0	1.326
1969	0	0	0	0.011	0	0.165	0.569	0.486	0.151	0	0	0	1.383
1970	0	0	0	0	0	0.193	0.546	0.655	0.246	0	0	0	1.64
1971	0	0	0	0	0	0.197	0.559	0.583	0.171	0	0	0	1.509
1972	0	0	0	0	0.051	0.2	0.441	0.305	0.254	0	0	0	1.249
1973	0	0	0	0	0.002	0.179	0.411	0.631	0.154	0	0	0	1.377
1974	0	0	0	0	0.139	0.249	0.643	0.448	0.175	0	0	0	1.654
1976	0	0	0	0	0	0.304	0.59	0.513	0.275	0	0	0	1.682
1982	0	0	0	0	0	0	0.429	0.371	0.36	0	0	0	1.16
1983	0	0	0	0	0.015	0	0.443	0.558	0.303	0	0	0	1.318
1984	0	0	0	0	0.014	0.187	0.567	0.562	0.324	0	0	0	1.655
1986	0	0	0	0	0	0.185	0.557	0.55	0.328	0	0	0	1.62
1987	0	0	0	0.016	0	0.253	0.56	0.419	0.156	0	0	0	1.404
1988	0	0	0	0	0	0.353	0.522	0.626	0.231	0	0	0	1.733
1990	0	0	0	0	0.019	0.348	0.317	0.377	0.353	0	0	0	1.414
1991	0	0	0	0.005	0.008	0.296	0.59	0.489	0.176	0	0	0	1.565
1992	0	0	0	0.021	0.177	0	0.527	0.455	0.098	0	0	0	1.278
1993	0	0	0	0	0.065	0.234	0.513	0.458	0.167	0	0	0	1.437
1994	0	0	0	0.004	0.13	0.433	0.484	0.663	0.219	0	0	0	1.933
1998	0	0	0	0.001	0.021	0.196	0.053	0.547	0.275	0	0	0	1.094
1999	0	0	0	0	0	0.276	0.355	0.344	0.205	0	0	0	1.179
2000	0	0	0	0.003	0.116	0.398	0.628	0.627	0.19	0	0	0	1.963
2001	0	0	0	0	0	0.393	0.539	0.611	0.254	0	0	0	1.797
2002	0	0	0	0.003	0.082	0.391	0.705	0.524	0.269	0	0	0	1.974
2006	0	0	0	0.023	0.164	0.485	0.606	0.587	0.081	0	0	0	1.945
2007	0	0	0	0	0	0.298	0.623	0.53	0.289	0	0	0	1.739
2008	0	0	0	0	0.071	0.291	0.432	0.388	0.335	0	0	0	1.517
Average:	0.000	0.000	0.000	0.002	0.031	0.213	0.490	0.481	0.231	0.002	0.000	0.000	1.450

Missing years lacked the data to produce IWR results

Table A1-2. Raw StateCU potential consumptive use results for corn in the Iliff area.

Time Series Identifier = 7950
Description = STERLING
Data Source = C:\cdss\DATA\STATECUWIZARD\UseCurve\UseCurve.BD1
Data Type = Potential Crop ET

Data Interval = Month
Data Units = ACFT
Period = 1912-01 to 2011-12
Orig./Avail. Period = 1912-01 to 2011-12

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1912	0	0	0	0	0.082	0.274	0.587	0.547	0.176	0	0	0	1.665
1913	0	0	0	0	0.17	0.493	0.6	0.019	0	0	0	0	1.282
1914	0	0	0	0	0.096	0.332	0.607	0.572	0.223	0	0	0	1.829
1915	0	0	0	0	0.035	0.216	0.474	0.51	0.424	0.048	0	0	1.707
1924	0	0	0	0	0.022	0.225	0.492	0.579	0.283	0	0	0	1.602
1928	0	0	0	0	0.106	0.243	0.584	0.552	0.284	0	0	0	1.769
1930	0	0	0	0	0.056	0.285	0.596	0.616	0.44	0.019	0	0	2.012
1931	0	0	0	0.011	0.132	0.46	0.7	0.59	0.231	0	0	0	2.124
1933	0	0	0	0	0.079	0.366	0.663	0.592	0.465	0	0	0	2.164
1934	0	0	0	0.021	0.226	0.462	0.754	0.668	0.151	0	0	0	2.283
1935	0	0	0	0	0.033	0.256	0.623	0.641	0.396	0	0	0	1.949
1936	0	0	0	0	0.126	0.361	0.707	0.628	0.306	0	0	0	2.128
1937	0	0	0	0	0.128	0.302	0.677	0.669	0.314	0	0	0	2.091
1938	0	0	0	0	0.075	0.313	0.609	0.671	0.426	0	0	0	2.094
1939	0	0	0	0	0.126	0.325	0.668	0.558	0.296	0	0	0	1.971
1940	0	0	0	0	0.1	0.34	0.644	0.56	0.369	0	0	0	2.014
1941	0	0	0	0	0.155	0.352	0.623	0.588	0.134	0	0	0	1.852
1945	0	0	0	0	0.056	0.222	0.599	0.558	0.17	0	0	0	1.606
1946	0	0	0	0	0.037	0.269	0.613	0.579	0.328	0	0	0	1.826
1948	0	0	0	0.014	0.16	0.38	0.66	0.604	0.202	0	0	0	2.021
1949	0	0	0	0	0.117	0.323	0.635	0.579	0.189	0	0	0	1.844
1950	0	0	0	0	0.036	0.266	0.516	0.55	0.414	0.041	0	0	1.823
1951	0	0	0	0	0.09	0.258	0.553	0.588	0.226	0	0	0	1.714
1952	0	0	0	0	0.088	0.355	0.648	0.603	0.373	0	0	0	2.068
1953	0	0	0	0	0.061	0.315	0.619	0.624	0.478	0.011	0	0	2.108
1954	0	0	0	0	0.081	0.323	0.688	0.619	0.436	0	0	0	2.148
1955	0	0	0	0	0.129	0.302	0.681	0.658	0.295	0	0	0	2.066
1956	0	0	0	0	0.125	0.427	0.657	0.619	0.015	0	0	0	1.843
1958	0	0	0	0	0.138	0.34	0.57	0.61	0.302	0	0	0	1.959
1959	0	0	0	0	0.09	0.359	0.606	0.619	0.336	0	0	0	2.011
1960	0	0	0	0	0.103	0.321	0.618	0.595	0.306	0	0	0	1.943
1961	0	0	0	0	0.061	0.303	0.604	0.609	0.199	0	0	0	1.776
1962	0	0	0	0.006	0.158	0.373	0.637	0.592	0.133	0	0	0	1.899
1963	0	0	0	0.015	0.182	0.448	0.74	0.592	0.203	0	0	0	2.18
1966	0	0	0	0	0.102	0.314	0.686	0.54	0.331	0	0	0	1.972
1967	0	0	0	0	0.032	0.226	0.564	0.589	0.366	0	0	0	1.777
1968	0	0	0	0	0.053	0.301	0.575	0.562	0.4	0.027	0	0	1.919
1969	0	0	0	0.018	0.183	0.347	0.709	0.644	0.189	0	0	0	2.09
1970	0	0	0	0	0.121	0.328	0.658	0.655	0.288	0	0	0	2.05
1971	0	0	0	0	0.063	0.329	0.606	0.644	0.257	0	0	0	1.899
1972	0	0	0	0	0.109	0.357	0.583	0.578	0.295	0	0	0	1.923
1973	0	0	0	0	0.07	0.305	0.587	0.649	0.368	0	0	0	1.979
1974	0	0	0	0	0.152	0.396	0.728	0.555	0.178	0	0	0	2.009
1976	0	0	0	0	0.106	0.339	0.703	0.615	0.333	0	0	0	2.096
1982	0	0	0	0	0.057	0.238	0.593	0.638	0.424	0	0	0	1.95
1983	0	0	0	0	0.039	0.242	0.618	0.713	0.342	0	0	0	1.955
1984	0	0	0	0	0.09	0.296	0.644	0.669	0.347	0	0	0	2.045
1986	0	0	0	0	0.083	0.342	0.642	0.609	0.382	0	0	0	2.058
1987	0	0	0	0.021	0.202	0.471	0.729	0.616	0.162	0	0	0	2.2
1988	0	0	0	0	0.137	0.458	0.691	0.683	0.273	0	0	0	2.241
1990	0	0	0	0	0.097	0.408	0.623	0.611	0.406	0	0	0	2.146
1991	0	0	0	0.006	0.154	0.425	0.691	0.636	0.251	0	0	0	2.163
1992	0	0	0	0.027	0.205	0.419	0.648	0.602	0.132	0	0	0	2.033
1993	0	0	0	0	0.144	0.357	0.631	0.597	0.201	0	0	0	1.93
1994	0	0	0	0.012	0.181	0.485	0.682	0.693	0.237	0	0	0	2.29
1998	0	0	0	0.003	0.146	0.328	0.692	0.617	0.304	0	0	0	2.09
1999	0	0	0	0	0.1	0.331	0.686	0.623	0.319	0	0	0	2.059
2000	0	0	0	0.012	0.165	0.414	0.769	0.689	0.219	0	0	0	2.268
2001	0	0	0	0	0.131	0.397	0.748	0.657	0.294	0	0	0	2.227
2002	0	0	0	0.003	0.125	0.471	0.768	0.625	0.269	0	0	0	2.261
2006	0	0	0	0.034	0.211	0.555	0.808	0.729	0.092	0	0	0	2.429
2007	0	0	0	0	0.141	0.373	0.735	0.695	0.318	0	0	0	2.263
2008	0	0	0	0	0.095	0.327	0.709	0.605	0.373	0	0	0	2.109
Average:	0.000	0.000	0.000	0.003	0.110	0.346	0.647	0.605	0.284	0.002	0.000	0.000	1.997

Missing years lacked the data to produce PCU results

APPENDIX A2

Conceptual Pipeline
Delivery Alternatives

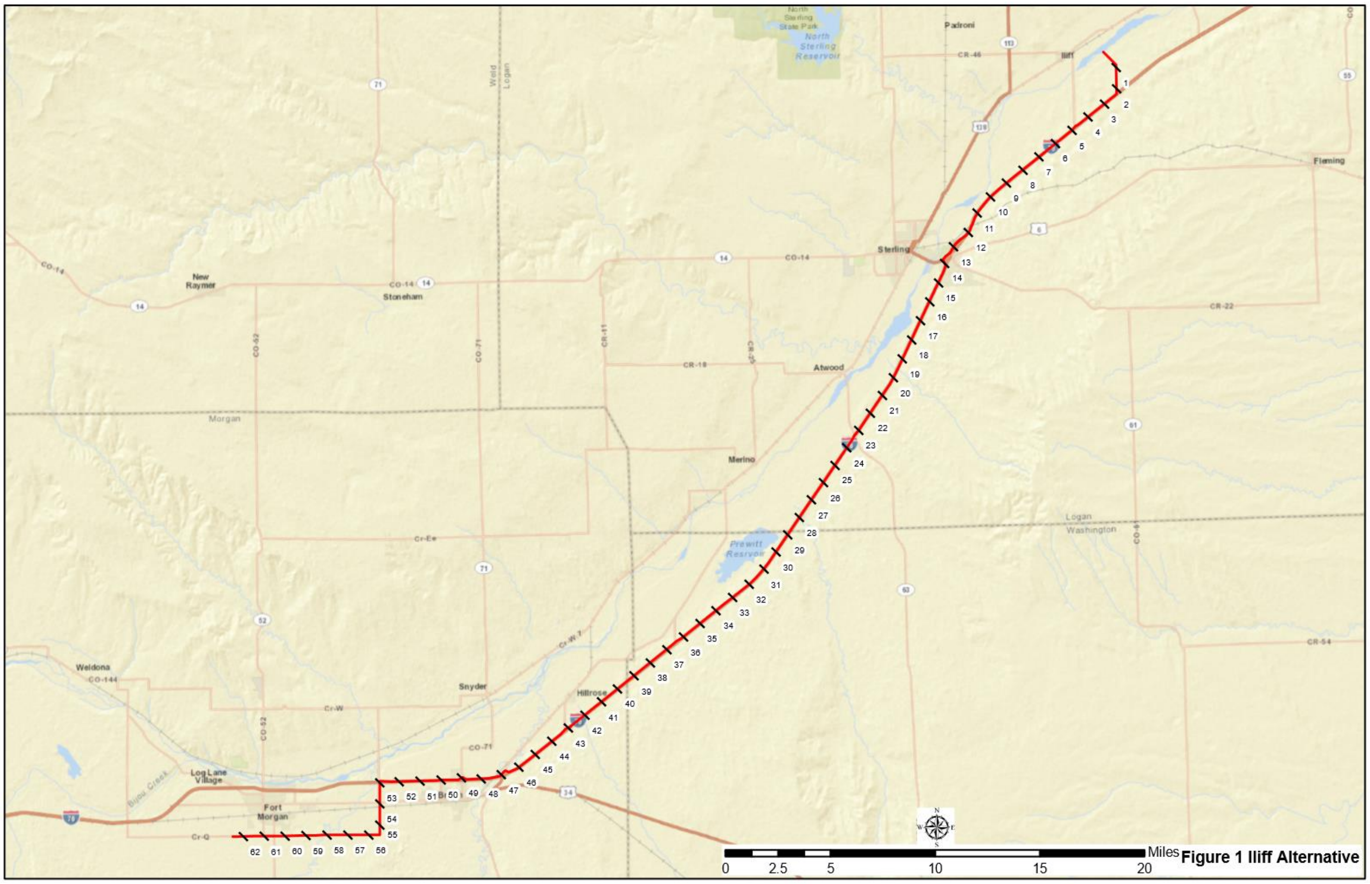


Figure 1 Iliff Alternative

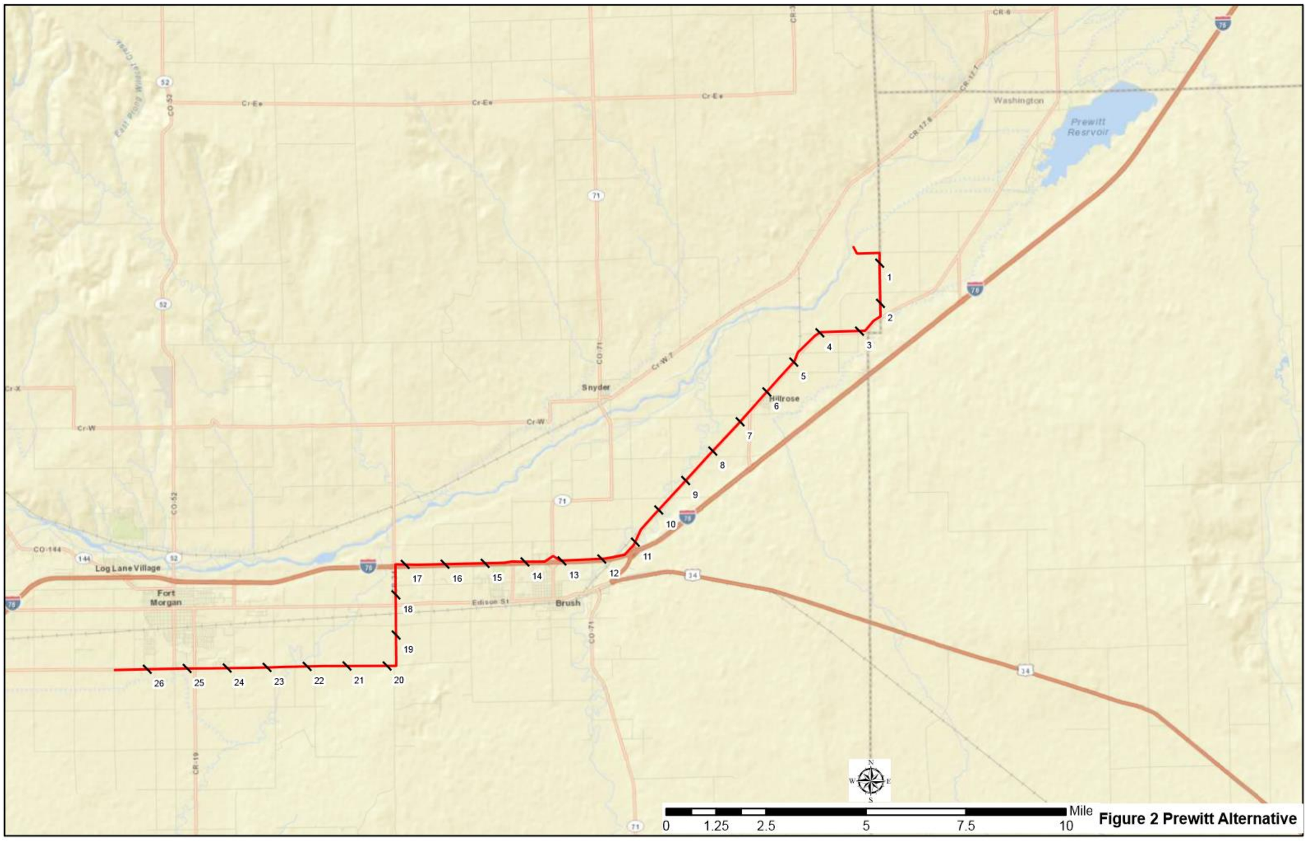
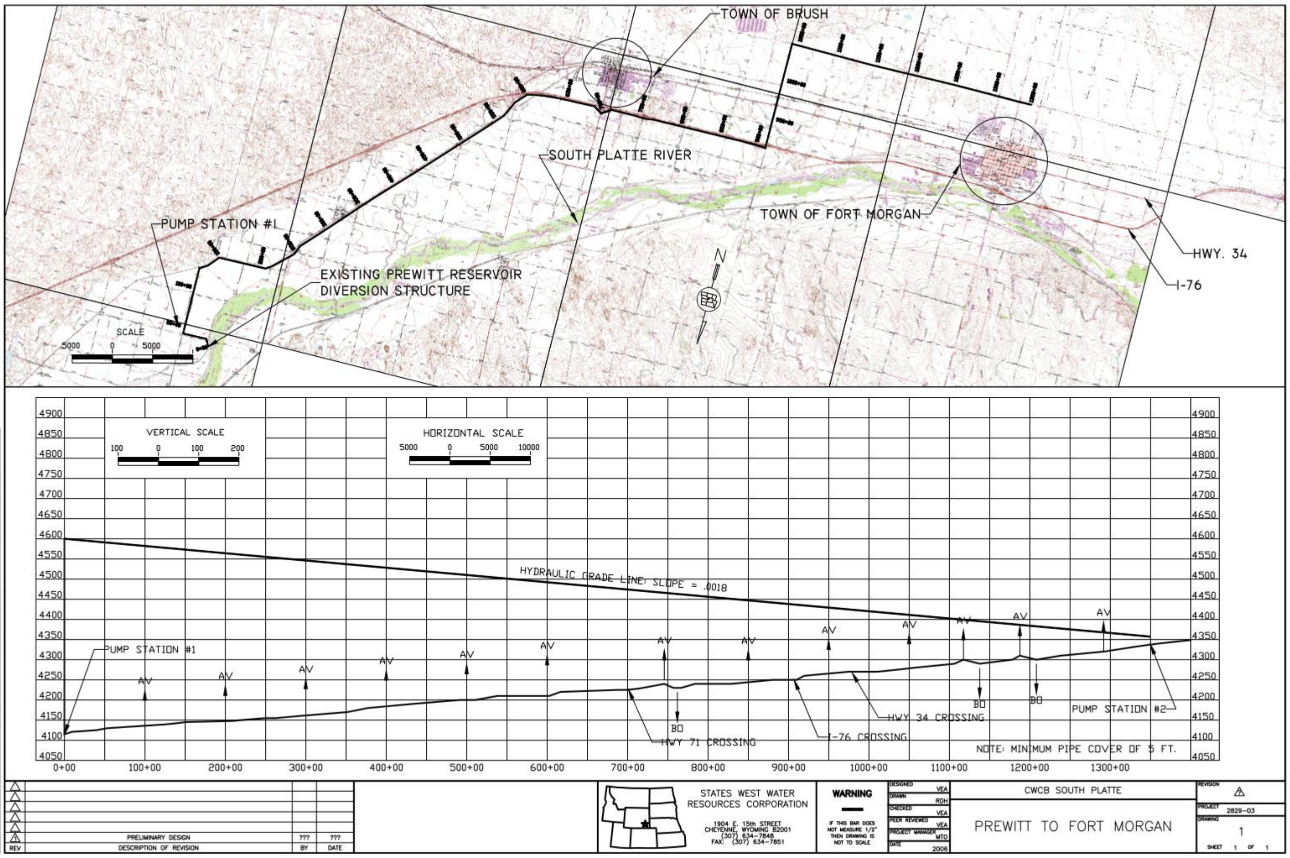
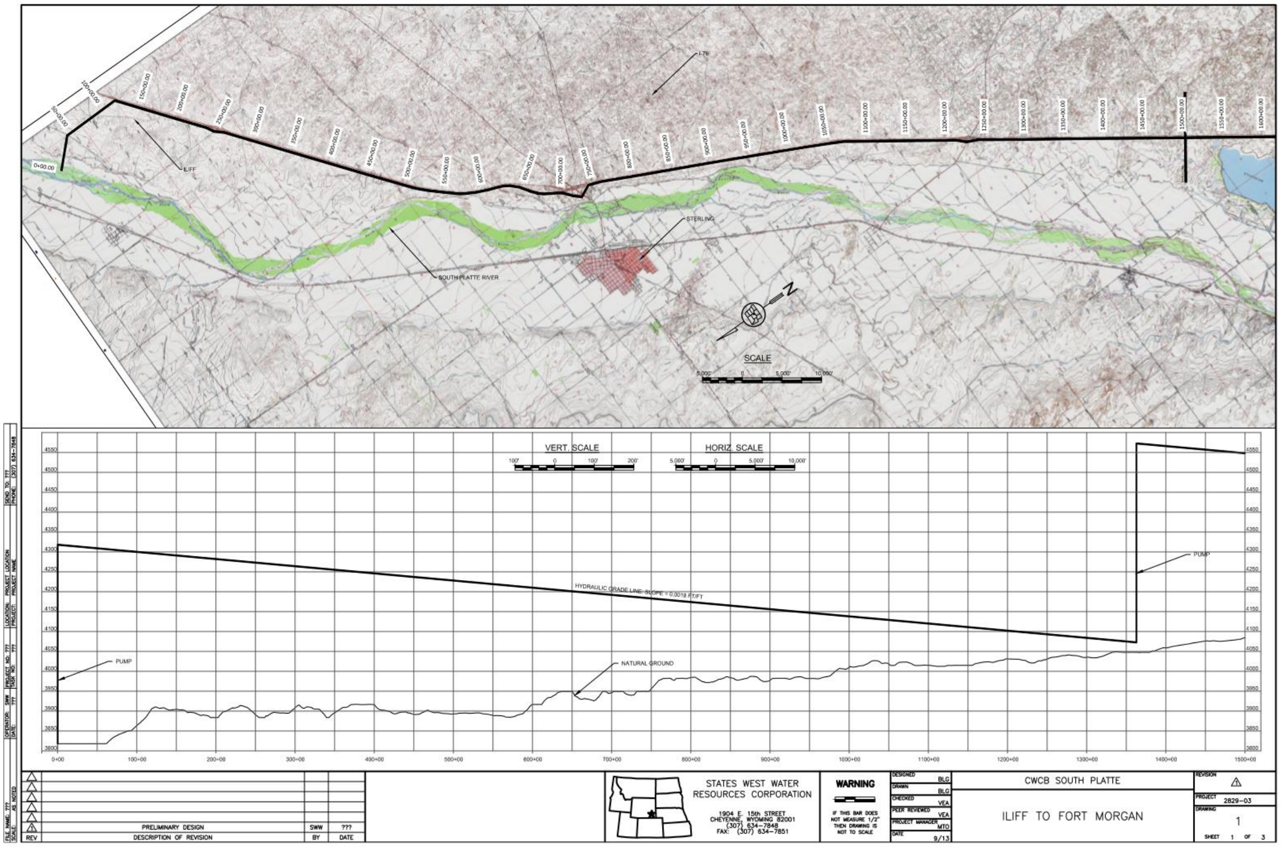
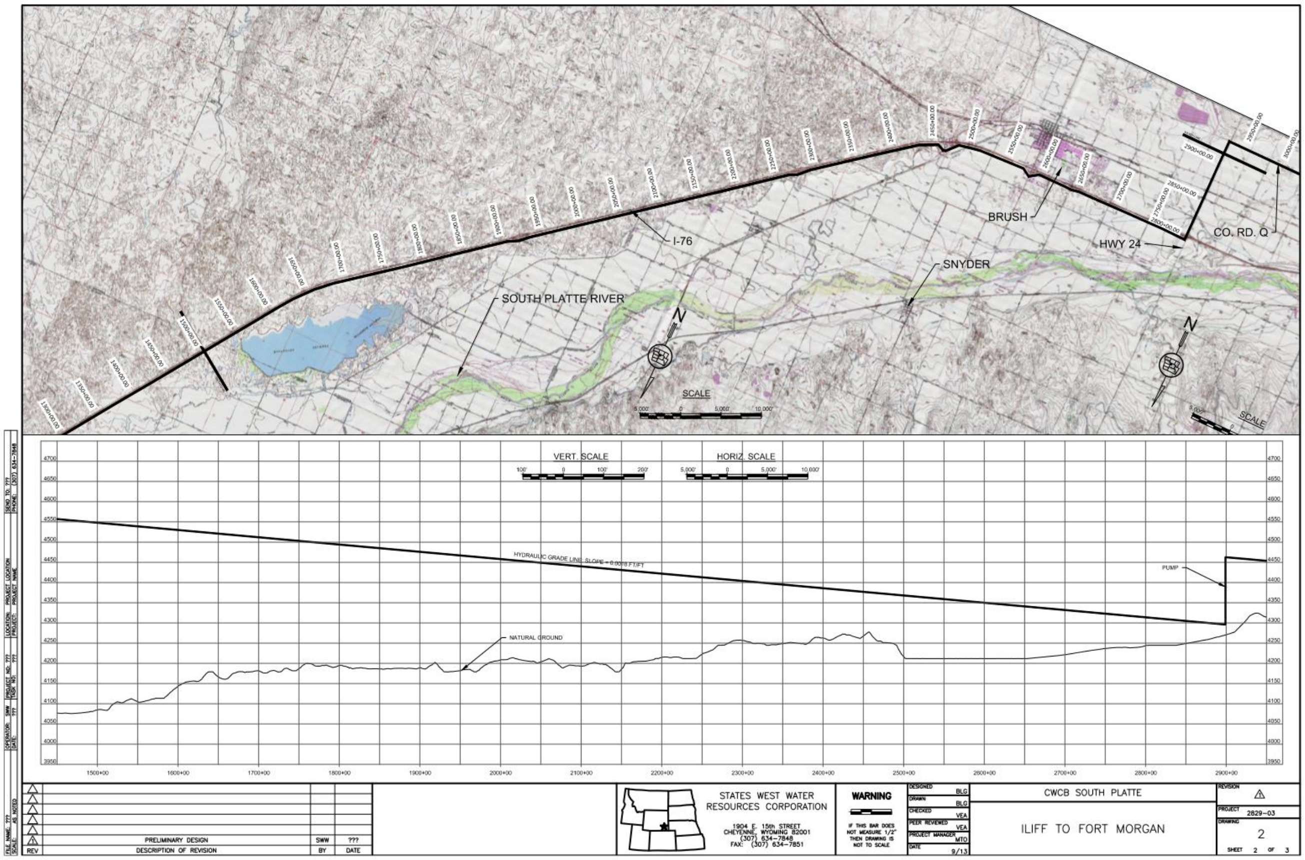


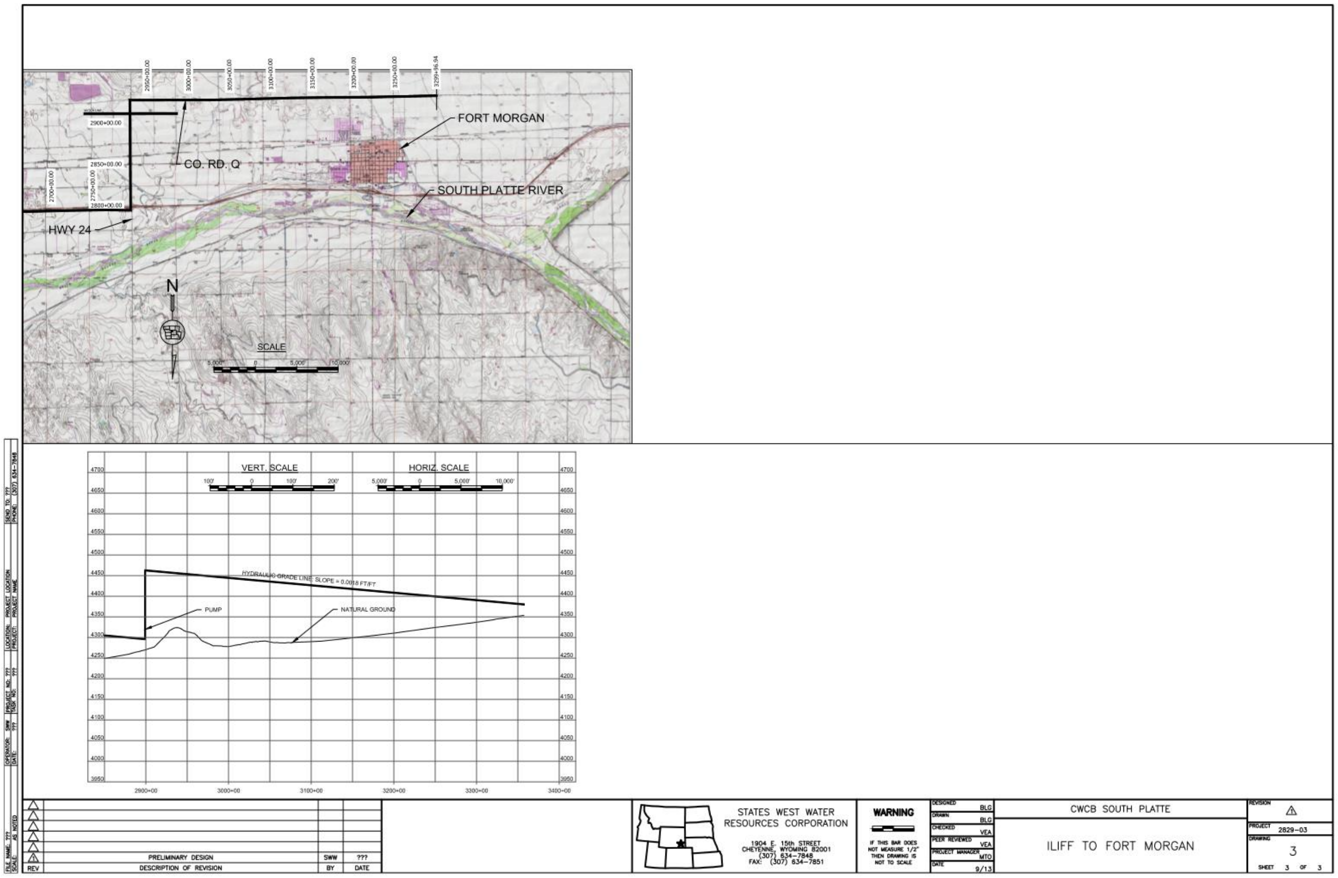
Figure 2 Prewitt Alternative


TOWN OF BRUSH
SOUTH PLATTE RIVER
PUMP STATION #1
EXISTING PREWITT RESERVOIR DIVERSION STRUCTURE
TOWN OF FORT MORGAN
HWY. 34
I-76
SCALE
5000 0 5000
N
VERTICAL SCALE
100 0 100 200
HORIZONTAL SCALE
5000 0 5000 10000
HYDRAULIC GRADE LINE: SLOPE = .0018
PUMP STATION #1
AV
BO
HWY 71 CROSSING
I-76 CROSSING
HWY 34 CROSSING
PUMP STATION #2
NOTE: MINIMUM PIPE COVER OF 5 FT.
4900
4850
4800
4750
4700
4650
4600
4550
4500
4450
4400
4350
4300
4250
4200
4150
4100
4050
0+00
100+00
200+00
300+00
400+00
500+00
600+00
700+00
800+00
900+00
1000+00
1100+00
1200+00
1300+00
PRELIMINARY DESIGN
??? ???
REV
DESCRIPTION OF REVISION
BY
DATE
STATES WEST WATER RESOURCES CORPORATION
1904 E. 15th STREET
CHEYENNE, WYOMING 82001
(307) 634-7848
FAX: (307) 634-7851
WARNING
IF THIS BAR DOES NOT MEASURE 1/2" THEN DRAWING IS NOT TO SCALE
DESIGNED VEA
DRAWN RDH
CHECKED VEA
PEER REVIEWED VEA
PROJECT MANAGER MTO
DATE 2006
CWCB SOUTH PLATTE
PREWITT TO FORT MORGAN
REVISION
PROJECT 2829-03
DRAWING 1
SHEET 1 OF 1



ILIFF
STERLING
SOUTH PLATTE RIVER
SCALE
VERT. SCALE
HORIZ. SCALE
PUMP
HYDRAULIC GRADE LINE SLOPE = 0.0018 FT/FT
NATURAL GROUND
PRELIMINARY DESIGN
SWW
???
REV
DESCRIPTION OF REVISION
BY
DATE
STATES WEST WATER
RESOURCES CORPORATION
1904 E. 15th STREET
CHEYENNE, WYOMING 82001
(307) 634-7848
FAX: (307) 634-7851
WARNING
IF THIS BAR DOES NOT MEASURE 1/2" THEN DRAWING IS NOT TO SCALE
DESIGNED BLG
DRAWN BLG
CHECKED VEA
PEER REVIEWED VEA
PROJECT MANAGER MTO
DATE 9/13
CWCB SOUTH PLATTE
ILIFF TO FORT MORGAN
REVISION
PROJECT 2829-03
DRAWING 1
SHEET 1 OF 3


I-76
BRUSH
HWY 24
CO. RD. Q
SNYDER
SOUTH PLATTE RIVER
SCALE
VERT. SCALE
HORIZ. SCALE
HYDRAULIC GRADE LINE
PUMP
NATURAL GROUND
PRELIMINARY DESIGN
SWW
REV
DESCRIPTION OF REVISION
BY
DATE
STATES WEST WATER RESOURCES CORPORATION
1904 E. 15th STREET
CHEYENNE, WYOMING 82001
(307) 634-7848
FAX: (307) 634-7851
WARNING
IF THIS BAR DOES NOT MEASURE 1/2" THEN DRAWING IS NOT TO SCALE
DESIGNED BLG
DRAWN BLG
CHECKED VEA
PEER REVIEWED VEA
PROJECT MANAGER MTO
DATE 9/13
CWCB SOUTH PLATTE
ILIFF TO FORT MORGAN
REVISION
PROJECT 2829-03
DRAWING 2
SHEET 2 OF 3



FORT MORGAN
CO. RD. Q
SOUTH PLATTE RIVER
HWY 24
N
SCALE
VERT. SCALE
HORIZ. SCALE
HYDRAULIC GRADE LINE SLOPE = 0.0018 FT/FT
PUMP
NATURAL GROUND
PRELIMINARY DESIGN
SWW
???
REV
DESCRIPTION OF REVISION
BY
DATE
STATES WEST WATER RESOURCES CORPORATION
1904 E. 15th STREET
CHEYENNE, WYOMING 82001
(307) 634-7848
FAX: (307) 634-7851
WARNING
IF THIS BAR DOES NOT MEASURE 1/2" THEN DRAWING IS NOT TO SCALE
DESIGNED BLG
DRAWN BLG
CHECKED VEA
PEER REVIEWED VEA
PROJECT MANAGER MTO
DATE 9/13
CWCB SOUTH PLATTE
ILIFF TO FORT MORGAN
REVISION
PROJECT 2829-03
DRAWING 3
SHEET 3 OF 3