Using Remote Sensing Assessments to Document Historical and Current Saved Consumptive Use (CU) on Alfalfa and Grass Hayfields Managed Under Full and Partial-Season Irrigation Regimes

Perry E. Cabot, Aman Vashisht and José L. Chávez

October 2016

Completion Report No. XXX

Acknowledgements

The authors would like to thank the Colorado Water Conservation Board for supporting the project. Additional support was provided by the Colorado River District, The Nature Conservancy, Trout Unlimited and The No Chico Brush Farmer-Led Focus Group, specifically pertaining to the field site in Delta, CO. We very much appreciate the willingness of cooperatives farmers Willy Frigetto, Jesse Kruthaupt, Nick McCracken and David Peterson for allowing us to access their fields during the course of the study. We would like to recognize the efforts of Sumit Gautam (graduate student), Kelsey Lindner (undergraduate student), Craig Moore (undergraduate student) and Carter Stoudt (undergraduate student).

This report was financed in part by the Colorado Water Conservation Board, through the Colorado Water Institute. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the State of Colorado.

Additional copies of this report can be obtained from the Colorado Water Institute, E102 Engineering Building, Colorado State University, Fort Collins, CO 80523-1033 970-491-6308 or email: cwi@colostate.edu, or downloaded as a PDF file from http://www.cwi.colostate.edu.

Using Remote Sensing Assessments to Document Historical and Current Saved Consumptive Use (CU) on Alfalfa and Grass Hayfields Managed Under Reduced and Full Irrigation Regimes

Perry E. Cabot
Aman Vashisht
José L. Chávez

Colorado State University

Completion Report to the Colorado Water Institute

December 2016

Table of Contents

Abstract

1 Background and Justification

1.1 Water Sharing Through Water Banking

1.2 Assessing Water Use by Alfalfa and Grass Hay under Water-Sharing Programs

1.3 Traditional Approaches for Assessing Actual Consumptive Use

1.4 Remote Sensing as a Method for Assessing Actual Consumptive Use

1.4.1 Estimates of AET with Remote Sensing

1.4.2 Remote Sensing Approaches for Assessing AET

1.4.2.1 Land Surface Energy Balance

1.4.2.2 Reflectance-based Crop Coefficient Approach

1.4.2.3 Other Energy Balance Models

1.4.3 Remote Sensing Models for Assessing AET using Energy-Balance Approaches

1.5 Data and Software Requirements

1.6 Challenges Using Remote Sensing on the Western Slope of Colorado

2 Project Objectives

2.1 Objective 1: Compare estimates of ACU derived from an energy-balance approach (using ReSET) against ACU derived from irrigation water balances and hand-held radiometer readings on alfalfa and grass fields in the Gunnison Basin

2.2 Objective 2: Apply an energy-balance approach (using ReSET) to archived multi-spectral observations (from Landsat) to estimate historical ACU on alfalfa and grass fields in Mesa, Delta, Montrose and Gunnison Counties.

2.3 Objective 3: Compare crop ACU derived an energy-balance approach (using ReSET) against the StateCU model, akin to methodology currently used in Coloradol

3 Methods

3.1 Study Period

3.2 Study Sites in the Gunnison Basin

3.3 Irrigation Water Balance Instrumentation

3.3.1 Site-Specific Characteristics and Measurements at Montrose Study Site

3.3.2 Site-Specific Characteristics and Measurements at Delta Study Site

3.3.3 Site-Specific Characteristics and Measurements at Gunnison Study Site

3.4 Estimating AET with ReSET

3.4.1 Satellite Data

3.4.2 Weather Data

3.4.3 Digital Elevation Data

3.4.4 Cover Crop Data

3.5 Determination of Daily AET using ReSET

3.6 Estimating AET with the MSR5 Hand-held Radiometer

3.6.1 Reflectance-based Crop Coefficient Approach

3.6.2 Estimating ET from the Crop Water Stress Index (CWSI)

4 Results
4.1 Objective 1 - Actual Consumptive Use derived from irrigation water balance, energy-balance, and a reflectance-based approach Monthly ET from 2015 and 2016 Seasons Derived from ReSET
4.1.1 Components of the Irrigation Water Balance
4.1.2 Results of the Irrigation Water Balance
4.1.3 Monthly ET from 2015 and 2016 Seasons Derived from Reflectance-Based Approach
4.1.4 Monthly ET from 2015 and 2016 Seasons Derived from Irrigation Water Balance
4.1.5 Discussion
4.2 Objective 2 - Apply an energy-balance approach to archived multi-spectral observations to estimate historical ACU on alfalfa and grass fields in Mesa, Delta, Montrose and Gunnison Counties.
4.2.1 Monthly ET 2011, 2013 and 2014 Seasons Derived from ReSET
4.2.2 Discussion
4.3 Objective 3 – Compare crop ACU derived an energy-balance approach against the StateCU model, akin to methodology currently used in Colorado
4.3.1 Monthly Historical ET Derived from StateCU Model
4.3.2 Discussion
5 Conclusion and Recommendations for Future Research

List of Tables

Table – Landsat information

Table – Dates of Landsat passes

Table – Site descriptions of Montrose Field, Delta Field, Gunnison Field (sites are in columns, descriptions are in rows) … WDID, water supply

Table – Irrigation data at Montrose Field, Delta Field, Gunnison Field

Table – Monthly ET rates at Montrose and Gunnison, based on ReSET and Irrigation Water Balance

Table – Snapshot ET rates at Montrose and Gunnison, comparing ReSET and Radiometer

Table – Historical CU rates at different sites

Table – Data from StateCU model run

List of Figures

Figure. Landsat passes.

Figure. Instrumentation diagram

Figure. Irrigation Water Balance Example (show screening out of irrigation dates)

Figure. Groundwater tables and measurements.

Figure. Example shot of 2-pixel Montrose field

Figure. Example shot of Delta field

Figure. Example shot of Gunnison field

List of abbreviations. List of simple formulas

PROJECT DELIVERABLES

1 Background and Justification

Evapotranspiration (ET) is the process by which water moves into the atmosphere by evaporation from the soil surface and transpiration from growing plants. Evaporation and transpiration are difficult to measure separately, so the two processes are usually quantified together (Taylor and Ashcroft, 1972). Crop consumptive use (CU) is a close analog to ET, emerging from the vernacular of agricultural water rights. Crop CU is a descriptive term for the amount or rate of water evaporated[1], transpired, incorporated into plant tissue and ultimately rendered unrecoverable for immediate reuse. The scientific literature is replete with explanations for distinguishing ET and CU, in regards to terminology and process (Burt et al., 1997; Allen and Jensen, 2016). Despite important differences, however, it is widely held that that both ET and CU describe the irrecoverable loss of water from irrigated agriculture. Because the main focus of this project was to quantify this form of water loss, irrespective of the underlying processes, the estimation of ET and CU was undertaken as a singular pursuit without consideration of technical distinctions.

Reliable estimates of the amount of water lost to the atmosphere by ET and CU through agricultural crop growth are critical to support two major premises on which water sharing arrangements rest. Firstly, a basic premise is that the transferable fraction of a water right[2] is its historical, beneficial[3] CU. This quantity is determined by the proportion of annual crop ET (less effective precipitation) that can be shown to have been met by the water right, for a representative period of years (Waskom et al, 2016). For both pricing and planning purposes, a reasonable degree of confidence is needed in the historical, beneficial CU estimate serving as a baseline in the sharing arrangement. Secondly, another premise is that foregone diversions and reduced irrigations will "conserve" water in the delivery system, since lower ET and CU is expected on the cropping system receiving less water, all other factors (e.g., crop type, field area) remaining the same. The term Conserved Consumptive Use (CCU) has been proposed to describe the proportion of historical, beneficial CU that originates from a water right as a result of diverting less than the historical rate to an irrigated cropping system (CAWA, 2008). If a water sharing arrangement relies on this conserved amount, estimation of CCU is important for "shepherding" the right amount of shared water elsewhere in the delivery system.

Among the most common approaches for estimating CCU are the Denver Water High Altitude Coefficients for high mountain meadows (Walter et al., 1990). These coefficients were produced from a 5-year lysimeter[4] study to develop estimations of the amount of transferrable CU made available by the purchase of water rights from approximately 40,000 acres of mountain meadows around South Park, CO at elevations greater than 6,500 feet. This method has been used on a basin-wide scale to estimate CU

[1] Crop CU is assumed to include evaporation, as evaporation rates directly affect transpiration rates.
[2] It is acknowledged that "water right" is different from a "water share" or "water contracts," as in the case of federal project water. Acknowledging these differences, the term "water right" will be used summarily for ease of discussion.
[3] Water rights in Colorado are usufructuary in nature, so water is lawful appropriated to be used with reasonably efficient practices for the benefit of the public.
[4] Lysimeter-derived crop coefficients, originating from actual field mass-balances in the region of interest, yield more accurate results than using a standardized crop coefficients.

and CCU for grasses with the Original Blaney-Criddle methodology in the Western Slope river basins. The Denver Water High Altitude Coefficients have been adapted at lower elevations, quantifying CCU by assigning a “Percent Reduction in CU Credit” for native grass and alfalfa, as a function of depth to groundwater at the field to which the water rights are appurtenant (CWCB and CDWR, 2013). Although these coefficients are used widely with some modification, there are noted inconsistencies and dissimilarities, even when applied to other high mountain areas, such as the Upper Gunnison (Smith, 2008).

This project was undertaken to address a recognized need for more geographically widespread data used for agreements under which agricultural water users forgo diversions, reduce irrigation and willingly impose plant stress in order to build CCU in the delivery system. One critique of using crop-coefficient approaches for estimating CU and CCU is that these methods are always to some degree localized and less applicable across larger regions. This is particularly problematic on the Western Slope, where the majority of irrigated grass hay fields and pastures are scattered over hundreds of thousands of acres. The need for reasonable accuracy in quantifying CU and CCU over such a large expanse is important for water resources planning, water sharing and water regulation (Allen et al., 2011). The successful operation of broad water-sharing programs involving agriculture requires an approach to cost-effectively monitor and track CU and CCU across an area as large and administratively decentralized as the Western Slope.

1.1 Water-Sharing through Water Banking

Water banking is a strategy to facilitate water sharing arrangements, whereupon water is “banked” in storage for commitment to a later use. A water bank is a guided market to address shortages by compensating agricultural water users for allowing their water to be temporarily used for another purpose. Water banking is intended to minimize the time, costs and impacts associated with temporary water transfers. There is not currently a water bank being implemented in Colorado, and ~~no process for transferring or leasing water under a water bank has been tested in Colorado water court or codified by the legislature~~.

What about CRS Title 37. Water and Irrigation §37-80.5-104.5? “The rules shall authorize, facilitate, and permit the lease, exchange, or loan of stored water within a water division.” “The banks shall operate within existing requirements of Colorado water law … including specifically the requirement that water transferred through the banks be put to a beneficial use.”

In the short term, a water bank could operate as part of the demand management component of the State’s contingency plan to prevent Lake Powell from going below minimum power levels. In the longer term, guided water markets or a water bank could operate to prevent shortages under the Colorado River Compact or to allow Colorado water users to weather regional shortages. A water bank would work with agricultural and other water users to implement voluntary, interruptible supply agreements, to make water available on a temporary basis to address either Lake Powell or Colorado River Compact issues.

1.2 Assessing Water Use by Alfalfa and Grass Hay under Water-Sharing Programs

As discussed earlier, crop ET and CU can be defined in several ways, generally starting with the concept of potential evapotranspiration (PET) or potential consumptive use (PCU). It is assumed the PET and PCU are achieved when ample water is available and crops experience no stress. Using PET or PCU as a baseline for historical CU, however, will overestimate the amount of sharable water expected under water conservation programs, since most crops in Colorado are likely to a have experienced crop stress at some point during a representative period of years. Of more practical use as a baseline for quantifying historical ET or CU at the field-scale is the concept of water supply-limited CU (WSLCU). The water actually available and actually used by the crop during the cropping season drives WSLCU. Because WSLCU occurs under actual conditions, it is also called actual consumptive use (ACU), similar to it agronomic analog, ET_a. A reasonable alternative theory for defining CCU, therefore, is proposed below:

$$(ACU_{base} - ACU_{trt}) - P_{eff} = (ET_{a,base} - ET_{a,trt}) - P_{eff} = CCU \quad (1.1)$$

where ACU_{base} and $ET_{a,base}$ are the ACU and ET_a of an accepted baseline or historical condition, ACU_{trt} and $ET_{a,trt}$ are the ACU and ET_a of the treatment condition required in the water sharing contract and P_{eff} is effective precipitation. The above formula could be used on a daily, weekly, monthly, seasonal or annual basis, depending on the criteria of the agreement.

Imprecise monitoring and measuring of CCU has led to difficulty in assessing the impacts and successes of water sharing programs. The Klamath Water Bank in Oregon, for example, could not quantify its true impact because the observed increases in river levels during the program were still within streamflow measurement error and could not be determined to have resulted from reduced irrigations (USGS, 2005; GAO, 2005). Water transfer proposals have also been prohibited or regulated for fields near canals that exhibit water seepage, fields with deep-rooted crops like alfalfa or fields with shallow groundwater (Colby et al., 2012; City of Aurora, 20XX). These prohibitions and regulations are imposed because, even if reliable diversion records are available, these records are unable to directly differentiate between the beneficial and non-beneficial CU that occurs after the diversions.

Reliable assessment of CCU is ever more crucial because of the temporary and intermittent nature of water sharing in a water bank where the net economic benefits of temporary transfers are small compared to the outright purchase of agricultural water rights. In other words, because CCU serves as the fundamental basis of compensation to agricultural water users who participate in water banks or other similar programs, a realistic baseline is needed against which to gauge the amount of water being conserved by reduced or partial-season irrigation. As the pressure to share water on the Colorado River increases, interest in accurately quantifying ACU rates by crop, parcel and region will increase.

Need to discuss Cuenca et al (2013) article.

Totals of irrigated land and water supply on the West Slope that could occasionally sustain deficit irrigation and potentially participate in a water bank have been evaluated previously (Natural Resources Consulting Engineers, 2012). A total of 92,510 acres of alfalfa and 623,295 acres of grass pasture on the Western Slope were identified as a baseline upon which to identify lands suitable for a water bank. The focus on alfalfa and grass pasture[5] evolved due to the fact that these crops constitute the majority of agricultural water use on the West Slope, and can withstand occasional fallowing or deficit irrigation without significant long-term effects. Recent studies on the Western Slope reported no significant differences in yields or stand density for alfalfa fields once they were returned to full irrigation after two seasons of partial-season irrigation (Jones, 2015). Reduced irrigation of grasses in particular could be significant to a water banking program because grass root systems are shallower than those of alfalfa crops, and thus less likely to tap groundwater and affect other return flows and water rights. From the above totals, lands were identified that had water rights with appropriation or adjudication date prior to 1929. Water supply limited consumptive use estimates were then ascertained for conditions in average hydrologic years. The maximum potential Water Bank Supply based on average year WSLCU was determined to be 110,164 AFY and 794,074 AFY for alfalfa and grass pastures, respectively. These amounts were revised downward to a total of 791,840 AFY for alfalfa hay and grass pastures, after adjustments for Tribal reserved water rights, Division 7 post-Compact stored water and transit loss of 10 percent to shepherd curtailed depletions to Lees Ferry (Paulson, 2012). Because the above amounts are highly variable, depending on the level of participation by qualifying irrigators, and level of deficit or partial-season irrigation on participating irrigated lands, further scenario analysis was performed and reported elsewhere (Paulson, 2012).

1.3 Traditional Approaches for Assessing Actual Consumptive Use

The methods described in this section, representing PCU or the upper envelopes of CU, are often used to assess CU "baselines."

Reference Crop Models. This approach is based on using one of the many reference CU models. The Blaney-Criddle equation (Blaney and Criddle, 1962) is used widely, for example, despite acknowledgement that it demonstrates variable adherence to AET and ACU of reference crops (Sammis et al., 2011). The use of Blaney-Criddle has gradually declined and been supplanted by updated models such as the Kimberly-Penman (Wright, 1982), Penman-Monteith FAO-56 (Allen et al., 1998) or ASCE Standardized Reference Evapotranspiration equations (ASCE-EWRI, 2005) equations. Adoption of these updated reference crop models is recommended because they are physically-based on climatic conditions and closely estimate ET and CU *for reference crops* (alfalfa and grass)[6]. Reference crop models estimate ET under disease-free, well-fertilized, extensive surface[7], unlimited water conditions to

[5] The report persistently refers only to a category of "grass pastures" and does not distinguish between grass pastures and "grass hayfields," which would refer to fields on which grasses are grown, baled and transported elsewhere.

[6] Grass reference ET (ETo) is defined as the ET of an actively growing, densely vegetated cool season grass of 0.12 m height that is spread over an extensive surface and is not short of water. Alfalfa reference ET (ETr) is defined as the ET of an actively growing, densely vegetated full cover crop of 0.50 m height that is spread over an extensive surface and is not short of water.

[7] The term "extensive surface" refers to expanse of same vegetation for at least 100 m.

achieve full production, and as such represent optimum conditions and not generally WSLCU. The State of Colorado's Consumptive Use Model (StateCU), for example, uses the reference crop model approach to determine PET.

Adjustments are made to the reference crop PET using crop coefficients (K_c) to estimate PET for other crops that exhibit different canopy, crop, albedo, stomatal and aerodynamic characteristics than alfalfa or grass. The accuracy of reference crop models depends upon the effectiveness of crop coefficients to correctly describe crop types, maturity stages, cutting schedules, regional meteorological effects and elevation effects. Output from these models is also bound to the generalized use of local weather station data. Using only temperature data, as in the Blaney-Criddle model for example, can result in significantly different predictions as compared with lysimeter measurements (Doorenbos and Pruitt, 1977). Although further modifications to reference crop models can be performed using coefficients to adjust for water stress (K_s) or dual coefficients to distinguish between basal transpiration (K_{cb}) and soil evaporation (K_e), these modifications are still subject to the same effect of generalization.

Pertinent to this study, tabulated values of these numerous conditions and associated coefficients, for instance, may not apply well to the agro-climatological conditions of Western Slope. Most importantly, reference crop models cannot capture the specific field-level impacts that affect crop water use during irrigation reductions, and are therefore a limited approach for tracking reduced ACU.

Water Delivery-Based Approach. This approach is based upon water delivery data collected by gauges installed at the headgates where agricultural water is diverted. The State of Colorado Division of Water Resources requires measurement of these diversions, which are subsequently modified based on assumed irrigation efficiencies to relate supply at the headgate to an irrigation water requirement (IWR) for parcels. This approach is used as an approximation of historical CU and is considered an acceptable measurement of WSLCU for business transaction purposes in "change cases," for example. If irrigation data is not available from a gauged diversion, historical water delivery records can be highly imprecise, thereby limiting the accuracy of historical CU estimates. As such, these records may also not be accurate to the degree expected in water-sharing transactions (McIntire, 1970; USGS, 2005). Diversion measurement systems are always undergoing improvement in terms of automated control and delivery management, but the contribution of seepage, tailwater, return flows and other incidental sources of irrigation to crops will always be difficult to account for on the basis of water deliveries at the headgate.

Irrigation Water Balance Monitoring. An irrigation water balance (IWB) approach can be used to derive point-based ET rates by monitoring water inputs and outputs to a soil root zone (Burt, 1999). Water balances can be applied to any scale, ranging from small fields to whole basins, with the key being that the balance depends on good measurements taken at the system boundaries. At the field scale, measurements are taken using meters, flumes, soil moisture sensors and other devices interfacing with data loggers to record the movement and storage of water in a soil root zone. The recorded measurements are then used in the following equation:

$$D_c = D_p + AET_c - P_{eff} - Irr - U + SRO + DP \quad (1.2)$$

where D_c and D_p are soil moisture deficits[8] for current and previous day, AET_c is crop evapotranspiration, P_{eff} is precipitation, Irr is irrigation, U is upflux groundwater contribution (capillary rise), SRO is surface runoff and DP is deep percolation. Limitations to the IWB approach include the inability to capture intra-field variability and the reliance on sensors that frequently require gravimetric calibration (Varble and Chávez, 2011). A significant limitation to the IWB approach is that some of the parameters are quite difficult to measure, such as ET_c, DP and U. In most cases, these parameters must be assumed or calculated as algebraic "closure terms." Nevertheless, because the IWB is an in-situ monitoring technique, it is useful a method for ground-truthing empirical models for estimating WSCLU.

1.4 Remote Sensing as a Method for Assessing Actual Consumptive Use

Remote sensing is performed by carriers on which remote sensing instruments are mounted. The most familiar carriers are earth observation satellites (EOSs) that have unrestricted ability to cover earth's surface repeatedly. Earth observation satellites range from low resolution (AVHRR, MODIS, ASTER, etc.) to moderate resolution (Landsat, Sentinel, SPOT etc.) to hyperspatial resolution (commercial satellites like Ikonos, Worldview, GeoEye, Quickbird etc.) and hyperspectral satellites (Hyperion etc.). While data from satellites like MODIS, Landsat, Sentinel 2a etc. can be obtained at no cost, high resolution (hyperspatial) data from commercial satellites like Ikonos, Quickbird, Worldview etc. is not free of charge. Some common EOSs that are utilized for earth observation, with their bands, resolutions and revisit periods, are given below in Table X.X.

Table X.X. Landsat Satellite Descriptions

Satellite Platform	*Operating Period*	*Revisit Time*	*Sensor*	*Band Number*	*Band*	*Bandwidth (µm)*	*GSD (m)*
Landsat 5	Mar 1984 - Nov 2011	16 days	MSS	1	Green	0.5 – 0.6	68 × 83*
				2	Red	0.6 – 0.7	68 × 83*
				3	NIR-1	0.7 – 0.8	68 × 83*
				4	NIR-2	0.8 – 1.1	68 × 83*
			TM	1	Blue	0.45 – 0.52	30
				2	Green	0.52 – 0.60	30
				3	Red	0.63 – 0.69	30
				4	NIR	0.76 – 0.90	30
				5	SWIR-1	1.55 – 1.75	30
				6	LWIR	10.4 – 12.5	120
				7	SWIR-2	2.08 – 2.35	30
Landsat 7	Apr 1999 - present	16 days	ETM	1	Blue	0.45 – 0.52	30
				2	Green	0.52 – 0.60	30

[8] As the crop grows and extracts water from the soil to satisfy its ET_c requirement, the stored soil water is gradually depleted. In general, the net irrigation requirement is the amount of water required to refill the root zone (R_z) soil water content back up to field capacity (FC). This amount, which is the difference between FC and current volumetric water content (VWC), corresponds to the soil water deficit (D) (Andales et al., 2011). It is determined by D= Rz (FC-VWC)

				3	Red	0.63 – 0.69	30
				4	NIR	0.76 – 0.90	30
				5	SWIR-1	1.55 – 1.75	30
				6	LWIR	10.4 – 12.5	60
				7	SWIR-2	2.08 – 2.35	30
				8	Pan	0.50 – 0.90	15
Landsat 8	Mar 2013 - present	16 days	OLI	1	Coastal	0.433 – 0.453	30
				2	Blue	0.450 – 0.515	30
				3	Green	0.525 – 0.600	30
				4	Red	0.630 – 0.680	30
				5	NIR	0.845 – 0.885	30
				6	SWIR-1	1.560 – 1.660	30
				7	SWIR-2	2.100 – 2.300	30
				8	Pan	0.500 – 0.680	15
				9	Cirrus	1.360 – 1.390	
			TIRS	10	LWIR-1	10.6 – 11.2	100
				11	LWIR-2	11.5 – 12.5	100

*Commonly resampled to 57 or 60 m

Ground Sample Distance (GSD) | Multispectral Scanner System (MSS) | Near Infrared (NIR) | Thematic Mapper (TM) | Short-wave Infrared (SWIR) | Enhanced Thematic Mapper Plus (ETM+) | Long-wave Infrared (LWIR) - Thermal Band | Operational Land Imager (OLI) – OLI Band 1 is Coastal/Aerosol |Thermal Infrared Sensor (TIRS) | Panchromatic (Pan)

Airborne platforms such manned or unmanned drones can be deployed to collect observations. Such technology is currently limited, but is beginning to be utilized more for agricultural purposes given that observations can be made more regularly than the schedule of satellite observations may permit.

1.4.1 Estimates of AET with Remote Sensing

Innovative and improved measurement of AET and ACU could reduce costs of monitoring and increase reliability of water-sharing programs such as a water bank (Colby et al., 2014). While historical full irrigation water use scenarios may be approximated by PCU (if crop coefficients and growth stage lengths for the climate, latitude, elevation, planting date etc. of the area are accurate), remote-sensing based assessments of CU can better represent ACU since they are much closer to real-time. Remote sensing data analysis methods have been advocated as an alternative method for estimating ACU where diversion records are too coarse to quantify ACU at parcel scales (URS, 2014), empirical models are not sufficiently specific for regional business transactions and program monitoring (citation) and point-based measurements are too costly to implement (citation). Monthly ACU estimates for side-by-side conditions could serve as the basis estimating CCU at the larger spatial sales of the Colorado River and its tributaries on the Western Slope.

1.4.2 Remote Sensing Approaches for Assessing AET

Estimating AET from remotely sensed spectral reflectance data and ground based meteorological data involves calculation of radiation and energy balances at for the land surfaces being evaluated.

Remote sensing techniques to estimate ET use two basic approaches described by Gowda et al. (2008):

1) land surface energy balance, and; 2) reflectance-based crop coefficient approach. More complex ET methods are not necessarily more accurate than empirical approaches (Kalma et al. 2008), but they are able to estimate ET on a geo-spatial basis over large and diverse coverage areas.

1.4.2.1 Land Surface Energy Balance

This approach is based on the law of conservation of energy which states that the total amount of energy in a system is conserved, although energy within the system can be changed from one form to another or transferred from one object to another. On land, the net energy, taking the form of net radiation (R_n) is converted to other forms of energy like sensible heat (H), ground heat (G), and latent energy (LE). The basic energy balance as a function of these variables is given below:

$$R_n = H + G + LE$$

The concept of using an energy balance to determine heat balance of the earth surface (Budyko et al., 1961), evaporation (Fritschen and Bavel, 1962), and evapotranspiration under non-water limiting conditions (McNaughton and Black, 1973) was originated several decades ago, but recent advances in estimating sensible heat flux (H) have enhanced the accuracy significantly (Taghvaeian et al., 2011). These advances have improved the use of the energy balance equation to determine LE, which can be used to derive ET based on a conversion utilizing the latent heat of vaporization (λ = 2.45 MJ/kg). Methods of estimating ET from spectral reflectance and emittance of radiation are described in detail by other published literature sources (Kustas and Norman, 1996).

1.4.2.2 Reflectance-based Crop Coefficient Approach

The reflectance-based crop coefficient approach is an empirical approach in which actual crop coefficients based on field conditions are empirically modelled by vegetation indices (VI). The reflectance-based crop coefficient approach first requires a spatially-distributed crop coefficient from reflectance data, which is the VI calculated from reflectance in specific bands. Since these crop coefficients are based on actual reflectance data they are considered to describe actual crop conditions in a field. These reflectance-based crop coefficients (K_{cr}) can then be multiplied by the ET_r from the nearest weather station to determine actual water use. Several previous studies have developed VI-Kc (or K_{cb}) functions for different crops over different areas. These include relations developed for alfalfa (Singh and Irmak, 2008). Modifications to NDVI have been performed to account for other background effects (Rondeaux et al. (1996; Huete, 1998; Jiang et al., 2006).

Vegetation indices distinguish vegetation biophysical properties (Vina et al., 2011). The NDVI uses near Infrared (NIR) and Red band measurements of the electromagnetic spectrum to quantify the greenness of vegetation, expected as a function of its density and health. It was developed by Deering (1978), and is given by the following equation:

$$\text{NDVI} = \frac{\text{NIR - Red}}{\text{NIR + Red}}$$

Reflectance based crop-coefficient approaches are simpler and have the potential of being utilized with remote sensing platforms that do not have a thermal band. A caveat for this approach is that since thermal band is not used, immediate and short-term stresses may not be captured. The reflectance based crop-coefficient approach also does not capture soil evaporation because it is modelled on the basis of VI that mostly captures vegetation and biomass changes. Remote sensing based crop coefficients can be accurately used for grain, non-grain and forage crops (Neale et al., 2003).

While the energy balance approach requires the coarser thermal band and follows a physically-based approach, the reflectance based crop coefficient approach is empirical but can afford higher resolution without the thermal band. This may be required for capturing intra-field variability, and is especially applicable for smaller pasture fields in the Western Slope where coarse thermal resolution is a limitation and energy balance method cannot be applied without some contamination of the thermal pixel from surrounding areas. A method needs to be developed and evaluated to be able to use this approach.

Empirical relationship for implementation on grass pastures and hayfields, especially for agro-climatological conditions of Western Slope has not been developed before. Either a previously-developed VI-Kc relation for a similar crop (Table 1.1) can be optimized for the study area and desired crop (grass pastures), or a new relation can be developed from the actual data from the study area. The feasibility and performance of this method relative to energy balance for both full and partial/slit-season irrigation regimes needs to be evaluated and quantified.

1.4.3 Remote Sensing Models for Assessing AET using Energy-Balance Approaches

Numerous remote sensing-based algorithms are available to estimate magnitudes and trends in crop ACU. Remote sensing techniques that employ data from earth-observation satellites have been proven reliable for assessing ACU at different spatio-temporal scales (Gowda et al., 2008; Jackson et al. 1984). Because these satellites have been operational since the latter half of the 20th century, archived imagery may also be used to do fair and equitable assessments of historical ACU for the establishment of water-sharing programs (Wulder et al., 2016). Remote sensing assessments of ACU can also be performed on side-by-side fully-irrigated and partially-irrigated fields, thereby replicating historical irrigation practices and reduced partial-season irrigation regimes at agricultural field sites.

The use of remotely sensed imagery to derive ACU involves the processing of measurements of the electromagnetic radiation emitted or reflected by the earth surface within the visible, near-infrared and thermal infrared bands of wavelengths. This radiation is measured by radiometers that are sensitive to radiation within narrow wavelength bands, and are thereby able to measure the strength of radiation within them. These measurements are then used to derive land surface temperatures, vegetation indices and other land based parameters like surface emissivity, long-wave radiation etc. These parameters, along with other ground-based meteorological measurements are then used as inputs to an algorithm that calculates surface fluxes and ultimately ET based on the energy balance equation. The various remote sensing platforms available are discussed later in this report.

1.4.3.1 Surface Energy Balance Algorithm for Land (SEBAL), Mapping Evapotranspiration with Internalized Calibration (METRIC) and Remote Sensing of Evapotranspiration (ReSET)

Use of the energy balance approach to estimate ET was pioneered with the Surface Energy Balance Algorithm for Land (SEBAL) model (Bastiaansen et al., 1998). Since remote sensing provides a snapshot at a particular time (hour) in the day, the instantaneous (hourly) estimates need to be extrapolated to daily values. The SEBAL model accomplishes this by assuming a constant evaporative fraction ratio (EF) of instantaneous ET to instantaneous available energy, especially for cloud-free sky conditions (Shuttleworth et al., 1989; Brutsaert and Sugita, 1992). Others have determined that EF rarely remains constant throughout the day (Gowda et al., 2008; Gentine et al., 2011) and as such the constant EF assumption might not hold on cloudy days (Nichols and Cuenca, 1993), or in arid and semi-arid regions where advection is common (citation?).

SEBAL has been utilized worldwide and its typical accuracy, on an average is 85% for daily and 95% for seasonal ET estimations. Applications of SEBAL in Idaho by Trezza et al. (2002) documented accuracies ranging from 65% to 97.3%, with an average accuracy of 81.8%. SEBAL may not be able to capture advection and thus may underestimate ET. In this case, a modified SEBAL model called SEBAL-A (Mkhwanazi et al., 2015a) can be used in areas of limiting weather data and advective conditions. For irrigated surfaces with advective conditions where SEBAL errors were significantly higher, SEBAL-A performed better with a daily accuracy higher than 85% (Mkhwanazi et al., 2015b). The innovative component of the SEBAL model is that it uses anchor pixels at two extremes of ET range, a "cold pixel" for maximum ET and "hot pixel" for negligible ET. The hot and cold pixels are used to calibrate the image and the rest of the calculations for the other pixel values are done relative to these two anchor points.

An improved modification of the SEBAL model is the Mapping Evapotranspiration with Internalized Calibration (METRIC) model, which is based upon the same principles as SEBAL, with the main difference lying in its calibration[9] (Allen et al., 2007, Trezza et al., 2002). For extrapolating from hourly to daily ET, METRIC uses an ET reference (alfalfa) fraction (ETrF) which is the ratio of remotely sensed instantaneous ET to reference ET at that instant. This ratio is essentially equal to actual crop coefficient that does not vary from instantaneous to daily time scale, and thus can be used for estimating daily ET from remote sensing (Trezza et al., 2002). Alternatively, ET reference fraction for grass (EToF) can be utilized. METRIC has been validated in Idaho for different crop conditions, reporting daily ET estimation errors in the range of 10-20%, and error over a 4-month period reduced to 4% (Allen at al., 2005; Allen et al., 2007; Gowda et al., 2008).

[9] Instead of assuming all available energy consumed for ET at the cold pixel, it assumes cold pixel ET equal to 1.05 times of alfalfa reference ET calculated from nearest weather station; and for the hot pixel, instead of assuming ET to be negligible, it suggests doing a daily surface soil water balance to confirm if ET equals zero or to supply a non-zero value for ET if there is residual evaporation from antecedent precipitation or wetting event.

A further modification of SEBAL and METRIC is the Remote Sensing of Evapotranspiration (ReSET) model that explicitly takes into account the spatial variability in weather data (Elhaddad and Garcia, 2008; Elhaddad and Garcia, 2011). ReSET can be run in either calibrated mode, or in uncalibrated mode, depending upon the weather data available. The calibrated mode is similar to METRIC in which the reference ET from weather stations is used to set the maximum ET of the cold pixel in the image, and the uncalibrated mode is similar to SEBAL where no maximum ET value is imposed (Elhaddad et al., 2011). In both of these modes, the internal calculations are rasterized such that each pixel is modeled on the basis of its spatial location.

ReSET is a land surface energy balance model built on the same theoretical bases of its two predecessors METRIC (Allen et al., 2007) and SEBAL (Bastiaanssen, 1998) with the additional ability to handle data from multi weather stations, which enhances local to regional crop evapotranspiration (ET_c) estimates by taking into consideration the spatial variability of weather conditions through data acquired from different weather stations (across the area covered by the remote sensing system/imagery). Thus, instead of scaling surface radiometric (thermal) temperature based on two extreme pixels found in the entire satellite scene, ReSET parses the image into pixels around the location of agricultural weather stations and identifies the cold pixel near the station. The uniqueness of this algorithm makes it possible to incorporate micro-climate conditions in the procedure to optimize the estimation of sensible heat fluxes and through the energy balance the latent heat flux or ET.

From URS report … the RESET procedure was used by David Eckhardt, Bureau of Reclamation, for estimation of actual crop water use following the procedure of Luis Garcia and Aymn Elhaddad of CSU. This procedure was successfully used on a trial basis but is not an operational Reclamationprogram. It has been applied by Eckhardt to two study areas: one in the Sacramento Valley of California for the 2008 and 2009 growing seasons, and one in western Colorado for the 2006 growing season. Eckhardt automated the sensible heat flux model and substituted some of the METRIC algorithms where it made sense. He also modified some data inputs, like using MODIS precipitable water vapor images to calculate band-specific atmospheric transmittance values, using NLDAS-2 wind speed data for the sensible heat flux model, and using NLDAS-2 DSRF (downward shortwave radiation flux), specific humidity, and atmospheric pressure data to improve 24-hour net radiation estimates. It should be noted that one objective was to minimize need for local meteorological data. Refer to Eckhardt (2013) for a full description of this method.

The estimation of ET for periods longer than daily requires interpolation between consecutive overpass daily ET estimates. While originally SEBAL did a linear interpolation, METRIC prefers interpolation for ETrF for non-overpass days, using curvilinear interpolation functions like cubic spline that better fit typical curvilinearity of crop coefficients in a growing season (Allen et al., 2011). ReSET interpolation between two consecutive overpass dates includes a linear interpolation while taking into account spatio-temporal variability in weather data (Elhaddad and Garcia, 2008).

The ReSET model was found to exhibit errors of 13.6% for the uncalibrated mode and 11.6% for the calibrated mode, on a daily basis relative to a local lysimeter in Bushland, Texas was (Elhaddad et al., 2011).

A new iteration of METRIC, to be called METRIC EFFLUX will soon be operational and will utilize bias-corrected spatial weather data with the original METRIC (Kilic and Allen, 2015). With METRIC EFFLUX, ET estimations will be performed on the Google Earth Engine at the website: http://eeflux-level1.appspot.com.

1.4.3.2 Other Energy Balance Models

Besides the one-source models discussed above, other energy balance models include two-source or two-layer models which consider canopy and soil fluxes separately, and multi-layer models that divide the canopy into many layers. Among these, the Two-Source Model (TSM) developed by Norman et al. (1995) and Kustas and Norman (1999) has been applied in several studies. This approach in addition to weather and remote sensing data (thermal and multispectral bands) requires some knowledge of crop and requires assumptions such as partitioning of composite radiometric surface temperature into soil and vegetation components, turbulent energy and mass exchange at soil level and coupling/decoupling of soil and canopy (parallel or series network) (Gowda et al., 2008). Gonzalez-Dugo et al. (2006) compared ET obtained from TSM with eddy covariance ET estimates and found the regression between them equal to 0.94. According to French et al. (2015), implementation of TSM involves many assumptions, is sensitive to land surface temperature observation errors, and is recommended when crop biophysical surface conditions are known.

1.5 Data and Software Requirements

There are certain data requirements that exist for the implementation of the energy balance method. Calculation of the radiation and energy balances requires access to satellites that remotely sense surface temperature and visible and Near InfaRed (NIR) band data necessary to compute NDVI.

1.6 Challenges Using Remote Sensing on the Western Slope of Colorado

There is still a gap, however, between research studies and practical application of remote sensing techniques for water management (Ambast et al., 2002). This is particularly true on the Western Slope of Colorado because of the complex agro-environmental conditions, including the prevalent surface irrigation methods, small to medium field sizes, complex topography, limited spatial coverage of ground weather data(especially at higher elevations in Gunnison), higher relief and higher elevation decreasing the probability of cloud-free imagery in a growing season.

From URS (2013) – "*Application of the atmospheric lapse rate is required to account for the effects of elevation on both the radiation and energy balance. This is accounted for in the standard implementation of the METRIC procedure by use of a DEM of the Landsat scene. The "cold" pixel surface temperature is adjusted as a function of elevation and the atmospheric lapse rate (Eckhardt, 2013). The standard atmospheric lapse rate of the International Civil Aviation Organization (ICAO) is 0.0065˚C/m.*

Eckhardt (2013) indicated potential problems using the standard ICAO lapse rate and recommended developing unique lapse rates for each Landsat image using the surface temperatures of small lakes or reservoirs to define the relationship. Allen and Snyder (2011) indicate use of a "flat" lapse rate of 0.0065˚C/m for elevations less than 1,750 meters and a "mountain" lapse rate of 0.010˚C/m for elevations above 1,750 meters as part of routine processing of Landsat data using METRIC. This of course requires an additional data processing step, which must be set up as either a rule-based decision or requiring input of a human data analyst."

2 Project Objectives

One strategy that is proposed to build CCU within the river system is to reduce the number of irrigations on perennial alfalfa and grass hay fields. This practice, referred to as "partial-season irrigation," entails a farmer beginning irrigation only after a certain point in the season (e.g., after the first cutting of hay, on specific date) or cutting off irrigation water at a certain point (e.g., after a specific hay cutting, after a specific date, etc.). Partial-season irrigation is a fairly low-risk and easy-to-implement alternative to fallowing. Irrigators have also stated preferences for partial-season leases, rather than full-season leases (Cook and Rabotyagov, 2014).

The following objectives were undertaken to estimate CCU under partial-season irrigation regimes and to assess historical CU at broad spatial scales. These objectives are deemed integral to water banking, which needs methods to assess and monitor water that builds in the system as an effect of foregone diversion and reduced irrigation.

2.1 Compare estimates of ACU derived from an energy-balance approach (using ReSET) against ACU derived from irrigation water balances and hand-held radiometer readings on alfalfa and grass fields in the Gunnison Basin

The ReSET model was developed on the Eastern Front Range of Colorado and has been applied for crops like corn, alfalfa etc. An energy-balance approach, such as the one employed by ReSET, could potentially be applied to the geographically diffuse agricultural areas of the Western Slope, specifically for grasses. In the past, ReSET evaluations where conducted for energy-limiting conditions of crop growth, rather than soil water-limiting conditions where the canopy is not homogenous and the "big-leaf" assumption may not hold. Thus, the performance of ReSET and the energy-balance approach is valuable for ACU estimations under partial irrigation regimes. Performance can be evaluated by comparing model results with other methods, such as irrigation water balancing or hand-held radiometric measurements.

2.2 Apply an energy-balance approach (using ReSET) to archived multi-spectral observations (from Landsat) to estimate historical ACU on alfalfa and grass fields in Mesa, Delta, Montrose and Gunnison Counties.

Landsat has been operational since the latter half of the 20th century, so multi-year ReSET modeling of archived multi-spectral observations is possible. The purpose of this modeling was to assess historical

ACU using another method not typically employed for Western Slope agriculture.

2.3 Compare crop ACU derived an energy-balance approach (using ReSET) against the StateCU model, akin to methodology currently used in Colorado

Historical crop CU analysis can be performed using StateCU, which uses specific crop water requirements combined with climate and temperature data from weather stations in the Basin to estimate CU for irrigated parcels. The StateCU Documentation provides a complete description of the model and its capabilities (CDWR, 2008). The StateCU model and CRDSS input files can be downloaded at http://cdss.state.co.us/Modeling/Pages/ConsumptiveUseStateCU.aspx (CDWR, 2011).

3 Methods

3.1 Study Period

3.2 Study Sites in the Gunnison Basin

The study sites are situated in the Uncompaghre Valley and Upper Gunnison areas of the Western Slope of Colorado. The elevation of the region varies from about X,XXX feet to about 10,000 feet. Precipitation in the area ranges from 8 to 14 inches (citation needed). Precipitation and temperature vary with elevation resulting in differences in crop ET, effective precipitation, and consumptive water requirements. The crops of focus for this study are alfalfa fields and grass hay/pasture fields because they occupy a major part of irrigated agriculture in the region, and are economically attractive for a water bank (MWH Americas, Inc., 2012).

Two grass pasture sites and one alfalfa site were selected at geographically different locations on the Western Slope to achieve the objective of comparing CU derived from ReSET against CU derived from irrigation water balances and hand-held radiometer readings.

[*Figure 3.1: Uncompaghre Valley irrigation area with Montrose and Delta field sites highlig*hted]

[*Figure 3.2: Upper Gunnison area with Gunnison field site highlighted*]

Grass Hay/Pasture Site (Montrose, CO). One of the grass hay/pasture sites is in Montrose, CO at approximately 38.509˚ N and -107.874˚ W, elevation ~5792 FAMSL. This site is historically furrow-irrigated using gated pipe along the south side of the property, using water from the Loutzenheiser Canal. The site (Figure X.X) is 14.50 ac (5.87 ha), was divided into two treatments: 1) full irrigation (reference) replicating irrigation conditions under typical management, under the terms of the water diversion, and; 2) reduced (partial-season; treatment) irrigation replicating a potential water bank scenario where irrigation is applied up until a certain date. The areas of the full and reduced irrigation field were 6.30 ac (2.55 ha) and 8.20 ac (3.32 ha), respectively. The reference plot was irrigated throughout the season, while the reduced (partial-season) irrigation plot received no water after August

14 in 2015[10] and after May 12 in 2016. Irrigation timing, along with cutting dates and animal pasturing are depicted in Figure X.X for the Montrose, CO field site.

Table X.X. Full and partial irrigation plot irrigation dates at the Montrose (grass hay) field site

Reference Irrigation Field (6.3 ac)	*Reduced (Partial-Season) Irrigation Field (8.2 ac)*
July 5, 2015	July 7, 2015
July 28, 2015	July 10-11, 2015
August 15, 2015	August 7, 2015
September 30, 2015	August 13, 2015 (land owner was called)

Grass coverage is dominantly (~40%) fescue (*Festuca arundinace*), with other minor coverage of smooth bromegrass (*Bromus inermis*) and bluegrass (*Poa pratensis*). Interspersed coverage (<10%) of plantago (*Plantago lanceolate*) and some volunteer alfalfa (*Medicago sativa*) was also noted. Plant species composition and cover data was collected using a modified step-point method (Owensby, 1973). The results of the soils analysis conducted by Midwest Laboratories (Omaha, NE) are tabulated in Table X.X.

Table X.X. Soil Characteristics at the Montrose (grass hay/pasture) field site

Irrigation	*Abbrev*	*Area*	*Field Capacity*	*Wilting Point*	*Available Moisture*	*Textural Class*
Full	REF	6.3 ac	31.29 %	17.47 %	13.82 %	Clay
Partial-Season	TRT	8.2 ac	33.33 %	12.44 %	20.89 %	Clay Loam

[*Figure X.X: Montrose field site layout with instrumentation*]
[*Figure X.X: Montrose irrigation, cutting data, pasture chart chronology*]

Grass Hay/Pasture Site (Gunnison, CO). The other grass hay/pasture site is located east of Gunnison, CO at approximately 38.458˚ N and -106.634˚ W, elevation ~8030 FAMSL. This site is historically wild-flood irrigated from a shared metal diversion structure, along grass swales with temporary dams arranged from polypropylene tarps. Irrigation water is suppled from the Coats Brothers Ditch.

The Gunnison hay/pasture site (Figure X.X) is 178 ac (72 ha). No treatments were imposed on this site in 2015. In 2016, the entire 178 ac entered into a short-term lease with the Colorado Water Conservation Board, to use decreed water as an instream flow. A smaller 30 ac (12 ha) field to the north did continue to receive water in 2016. Even for the 2015 growing season, however, the undulating topography and underlying hydrology of the field and surrounding area suggested that certain portions of the field would receive much less surface and sub irrigation than others, allowing a diversity of remote-sensing

[10] Simulating a water banking scenario required the treatment field to have irrigation curtailed no later than July 1 during these years, but a miscommunication between the participating farmer and his irrigator resulted in irrigations being applied to the treatment field on July 11, July 20, August 7 and August 13 in 2015.

derived CU estimates.

[*Figure X.X: Gunnison field site layout with instrumentation*]

Grass coverage a mix of meadow foxtail (*Alopecurus pratensis*), timothy-grass (P*hleum pratense*), smooth bromegrass (*Bromus inermis*), and orchard grass (*Dactylis glomerata* L.). Plant species composition and cover data was gathered from the producer. The field is spatially heterogeneous with soil types mixed across the site as sandy loam (42%), silty clay (31%), loam (21%) and clay loam (2%), as characterized by the NRCS. Soils and root zone on these fields are extremely shallow, underlain by cobble. Available moisture in these soils is held dominantly near the surface with an estimated available moisture of 30%, 11%, 6% and 2% in the profiles 0-3", 3-7", 7-15" and 15"-60" respectively (NRCS, 20XX). The irrigation, cutting and pasturing data for the Gunnison field site is summarized in Figure X.X.

[Figure X.X: Gunnison irrigation, cutting data, pasture chart chronology]

Alfalfa Site (Delta, CO). The original project scope was designed to include a site in Loma, CO where the instrumentation installed for calculating the IWB was similar to the Montrose and Gunnison sites. However, the scope was modified because Landsat Path 35 (which covers all of the Uncompahgre and most of the Grand Valley) does not happen to include Loma, CO. There would have been considerable extra time involved in processing the additional Landsat path. Therefore, a substitute location was used in Delta, CO. The site used is at approximately 38.664° N and -108.062° W, elevation ~5275 FAMSL. This site is was historically furrow-irrigated using gated pipe until 2014 when an overhead sprinkler-pivot system was installed. The site receives water from the Ironstone Canal. The site (Figure X.X) is 70 ac (28 ha), was irrigate fully in 2016 using an irrigation plan entirely determined by the producer. The results of the soils analysis conducted by the CSU Soils Testing Lab (Ft. Collins, CO) and Midwest Laboratories (Omaha, NE) are tabulated in Table X.X.

Table X.X. Soil Characteristics at the Delta (alfalfa) field site

Irrigation	*Tested*	*Field*	*Field Capacity*	*Wilting Point*	*Available Moisture*	*Textural Class*	%C	%S
Full	2014	East	17.90 %	8.10 %	9.80 %	Sandy Loam	21	61
Full	2014	East	17.40 %	8.90 %	8.50 %	Sandy Clay Loam	24	52
Full	2016	West	23.13 %	9.28 %	13.85 %	Clay Loam	21	60
Average			**19.48 %**	**8.76 %**	**10.72 %**		**22**	**58**

The irrigation management and alfalfa cutting chronology is summarized in Figure X.X for the Delta, CO field site.

[*Figure X.X: Delta field site layout with instrument locations*]

3.3 Irrigation Water Balance Instrumentation

Irrigation, Precipitation and Tailwater. The irrigation water volume diverted to each surface irrigated field were measured in-line SeaMetrics® EX800, SeaMetrics® AG2000, or McCrometer® McPropeller® flow meters depending on the irrigation water delivery system. Flow meters were equipped with instantaneous flow rate indicator to totalize flow volumes, after which data was delivered to Campbell Scientific CR206 data loggers and reported telemetrically. Examples of flow metering installations are shown below in Figure X.X. Tailwater was recorded using EZ Flow Ramp™ flumes equipped with stilling wells and automatic Campbell Scientific CS451 pressure transducers. Flumes in these types of applications are estimated to have measurement accuracy of about ±15 percent. Precipitation was monitored with direct-read raingages and checked for timing against the daily record from the nearest CoAgMet station (www.coagmet.edu).

Soil Moisture and Electrical Conductivity. Campbell Scientific CS655 soil water content reflectometers were installed in 2015 at 6 inches (150 mm) and 18 inches (450 mm) at each sensing station at the Montrose and Gunnison sites. These reflectometers measures soil water content, temperature and electrical conductivity. Data was collected from these sensors every 30 minutes and stored in a CR206X datalogger with 900 MHz spread-spectrum radio. The radios from each sensor station interfaced with a CR800 datalogger, equipped to transmit data telemetrically with a Raven XT cellular modem. Periodic measurements of soil water content were also taken using a CPN 503DR Neutron Probe. Access tubes for taking neutron probe measurements were installed with a Giddings rig to varying depths, depending on the penetrability of soil layers at each site. The access tubes were 1.5 inch Schedule 40 PVC, requiring a correction equation made available from the neutron probe manufacturer: $M = 3.611 \times CR - 0.094$, where M = soil water content (in/ft) and CR = count ratio from the neutron probe.

The Montrose site is equipped with two (2) soil moisture sensing stations each in the fully irrigated and partial-season irrigated fields, located in the middle of the fields, at distances of 25% and 75% along the distance of the furrows. The Gunnison site is equipped with six (6) sensing stations at locations representing low, middle and high points in the field where flood waters would be more or less likely to collect. The Delta site is equipped with soil water potential sensors installed in 2016 at 12 inches (300 mm) and 24 inches (600 mm). Data from these sensors is transmitted telemetrically using Zigbee wireless system that interfaces with a cellular gateway designed by Irrometer. The Delta site is equipped with five (5) sensing stations at locations representing the inner, middle, and outer rings of the pivot coverage area. Irrometer?

Groundwater. Subsurface movement of water is difficult to monitor in the field. Nevertheless, instrumentation was installed to assess the potential contribution of capillary rise (upflux) and loss of water to deep percolation. Because a 1-dimentional IWB model was to be applied at the sites, lateral flow of water was not measured. Capillary rise and deep percolation were assessed relative to the dynamic elevation of the groundwater table, which was measured using 1.0" PVC observation wells and Solinst® Level Logger Junior pressure transducers. Capillary rise and deep percolation were also assessed relative to the changes in electrical conductivity that were evident in the deeper profile.

The instrumentation used for measuring these variables is summarized in Table X.X.

Table X.X. Instrumentation for IWB monitoring

Variable	*Instrument*	*Vendor*	*Product*
Soil Moisture	soil water content reflectometer	Campbell Scientific	CS655
	neutron probe	CPN	503DR
	soil water potential sensor	Irrometer	Watermark®
Evapotranspiration	atmometer	ETGage	Model A/Model E
Precipitation	direct read raingage	Productive Alternatives	Stratus™
Irrigation	electromagnetic flowmeter	SeaMetrics	EX800/AG2000
Capillary Rise		*no direct measurement*	
Surface Runoff	ramp flume with transducer	Welfelt Fabrication	Nu-Way flume (3.5 cfs)
		Campbell Scientific	CS451
Deep Percolation	observation well with transducer	Solinst	Levelogger® Junior Edge M5
	barometric correction transducer	Solnist	Barologger® Edge

3.3.1 Site-Specific Characteristics and Measurements at Montrose Study Site

At periodic times during the field season, gravimetric samples were taken from the soil using a Madera Probe, to develop a calibration curve for the clay loam soils at the Montrose site. After they were oven-dried at 105 ◦C for 24 h, volumetric water content (θ_v) was computed for the samples by multiplying the gravimetric water content by the soil bulk density obtained from the field and divided by the density of water. The Montrose site is characterized by a fairly shallow groundwater table. Pressure transducers were installed in observation wells in 2016 to determine the extent of deep percolation and capillary rise.

Large Aperture Scintillometer. On the partial irrigation treatment plot, a Kip and Zonen Large Aperture Scintillometer (LAS) was installed to measure sensible heat flux (H). Also installed was a net radiometer to measure net radiation (Rn) and soil heat flux plates to measure ground heat flux (G). These sensors were installed from August June-October in 2015 growing season.

Large Aperture Scintillometer (LAS) functions by transmitting an electromagnetic beam between a source unit, that is, a transmitter and a receiver. It operates at a near-infrared wavelength of 880 nm, and detects turbulence caused due to temperature fluctuations. Thus, it can be used to describe fluxes of heat (H) (e.g., Moene et al. 2005).

3.3.2 Site-Specific Characteristics and Measurements at Delta Study Site

The Delta site uses an overhead center pivot sprinkler for irrigation. Observation wells were installed in 2015, in order to monitor groundwater and potential capillary rise.

3.3.3 Site-Specific Characteristics and Measurements at Gunnison Study Site

Gravimetric samples were not obtained from the Gunnison site, therefore, a generic calibration was developed using factory recommendations. The Gunnison study site experiences regular flooding during irrigation events. The practice of wild flooding makes the calculation of ET and CU from remote sensing complicated due to the prevalence of standing water. Additional errors in the energy-balance may have been introduced by the presence of animals on the field. The following table is a list of groundwater well locations and depths. Transducers were installed at the observation wells at K3, K4, K5, K6, K7 and K8.

Table 3.3.

ID	Longitude	Latitude	Longitude DMS		Latitude DMS		Elevation		Depth	
K1*	-106.63683542666982	38.4621987270425	-106° 38' 12.6060"	W	38° 27' 43.9158"	N	2442.5	m	---	In
K2	-106.63683542666982	38.4603841143088	-106° 38' 12.6060"	W	38° 27' 37.3818"	N	2443.5	m	37.00	In
K3	-106.63683542666982	38.4586870740551	-106° 38' 12.6060"	W	38° 27' 31.2726"	N	2444.3	m	45.00	In
K4	-106.63449654042319	38.4586870740551	-106° 38' 4.18500"	W	38° 27' 31.2726"	N	2443.7	m	37.50	In
K5	-106.63383135257986	38.4558305795152	-106° 38' 1.79160"	W	38° 27' 20.9916"	N	2445.5	m	40.25	In
K6	-106.63071999012634	38.4586870740551	-106° 37' 50.5878"	W	38° 27' 31.2726"	N	2443.6	m	41.00	In
K7†	-106.6290892070379	38.4558305795152	-106° 37' 44.7198"	W	38° 27' 20.9916"	N	2445.7	m	52.00	In
K8	-106.62685760914582	38.4558305795152	-106° 37' 36.6852"	W	38° 27' 20.9916"	N	2446.1	m	37.00	In
K9	-106.62743696628749	38.4541502357754	-106° 37' 38.7696"	W	38° 27' 14.9394"	N	2446.1	m	46.00	In
K10	-106.62486204563383	38.4517976887909	-106° 37' 29.5026"	W	38° 27' 6.47220"	N	2450.5	m	64.00	In

3.4 Estimating AET with ReSET

The ReSET model (Elhaddad and Garcia, 2011) was chosen for our study because the expertise for running its applications already existed at the time of development for this project. One of the major advantages of ReSET is its ability to use spatially referenced ET_r and wind speed data as a data grid, by incorporating the CoAgMet (www.coagmet.com) weather station network. In doing so, the model uses the weather stations as site-specific anchor points for calibration. Each pixel of model output therefore has geographical coordinates relative to weather station data.

3.4.1 Satellite Data

Data from Landsat 7 and Landsat 8 satellites was used, as it is free and offers the reasonably fine thermal resolution needed to perform energy balance calculations. Two Landsat path/row combinations were selected: 1) Path 35/Row 33 covering most of the Grand Valley and all of the Uncompahgre and North Fork areas, and; 2) Path 34/Row33 covering the Upper Gunnison area. The coverage areas are shown in Figures X.X and X.X. Each of these images is 160 km × 160 km. Some striping was noted in the Landsat 7 images, but the Montrose study site fortunately lies at the center of the scene and is free of stripes. The Gunnison study site lies in the striped part of the image, but the field is large enough to obviate the loss of imagery due to striping. Cloud-free images for the 2015 and 2016 growing season were used to for the portion of the project concerning comparisons between energy balance, irrigation water balance and reflectance-based approaches, given that the data for the latter two approaches was only available from June 2015 through 2016. These are given in Table X.X for Path 35/Row 33 (Delta, Montrose) and in Table X.X for Path 34/Row 33 (Gunnison).

Table X.X: Growing season cloud-free imagery for Landsat 7 overpass dates

Path 35/Row 33 (Delta, Montrose)				**Path 34/Row 33 (Gunnison)**			
2015		2016		2015		2016	
Date	Cloud Cover	Date	Cloud Cover	Date	Cloud Cover	Date	Cloud Cover
Mar 30	2%	Apr 1		Apr 8		Apr 10	
Apr 15	65%	Apr 17		Apr 24		Apr 26	
May 1	41%	May 3		May 10		May 12	
May 17	---	May 19		May 26		May 28	
Jun 2	0%	Jun 4		Jun 11		Jun 13	
Jun 18	11%	Jun 20		Jun 27		Jun 29	
Jul 4	39%	Jul 6		Jul 13		Jul 15	
Jul 20	46%	Jul 22		Jul 29		Jul 31	
Aug 5	4%	Aug 7		Aug 14		Aug 16	
Aug 21	1%	Aug 23		Aug 30		Sep 1	
Sep 6	34%	Sep 8		Sep 15		Sep 17	
Sep 22	---	Sep 24		Oct 1		Oct 3	
Oct 8	0%	Oct 10		Oct 17		Oct 19	

Table X.X: Growing season cloud-free imagery for Landsat 8 overpass dates

Path 35/Row 33 (Delta, Montrose)				**Path 34/Row 33 (Gunnison)**			
2015		2016		2015		2016	
Date	Cloud Cover	Date	Cloud Cover	Date	Cloud Cover	Date	Cloud Cover
Apr 7	3%	Apr 9		Mar 31		Apr 2	
Apr 23	37%	Apr 25		Apr 16		Apr 18	
May 9	59%	May 11		May 2		May 4	
May 25	62%	May 27		May 18		May 20	
Jun 10	---	Jun 12		Jun 3		Jun 5	
Jun 26	1%	Jun 28		Jun 19		Jun 21	
Jul 12	9%	Jul 14		Jul 5		Jul 7	
Jul 28	1%	Jul 30		Jul 21		Jul 23	
Aug 13	15%	Aug 15		Aug 6		Aug 8	
Aug 29	9%	Aug 31		Aug 22		Aug 24	
Sep 14	80%	Sep 16		Sep 7		Sep 9	
Sep 30	64%	Oct 2		Sep 23		Sep 25	
Oct 16	7%	Oct 18		Oct 9		Oct 11	

For the assessment of actual historical CU from 2011, 2013 and 2014[11], Landsat 7 and 8 were used for 2013 and 2014 growing seasons, while Landsat 7 and Landsat 5 were used for the 2011 growing season.

[11] 2012 was excluded since it was a very dry year and only Landsat 7 was operational during 2012. Landsat 8 was launched in 2013 and Landsat 5 operation ended at the end of 2011.

Table X.X: **Table X.X**: Growing season cloud-free imagery for Landsat 7 overpass dates

Path 35/Row 33 (Delta, Montrose)				Path 34/Row 33 (Gunnison)			
2013		2014		2013		2014	
Date	Cloud Cover	Date	Cloud Cover	Date	Cloud Cover	Date	Cloud Cover

Table X.X: Growing season cloud-free imagery for Landsat 8 overpass dates

Path 35/Row 33 (Delta, Montrose)				Path 34/Row 33 (Gunnison)			
2013		2014		2013		2014	
Date	Cloud Cover	Date	Cloud Cover	Date	Cloud Cover	Date	Cloud Cover

Table X.X: Growing season cloud-free imagery for Landsat 5 and 7 overpass dates in 2011

Path 35/Row 33 (Delta, Montrose)				Path 34/Row 33 (Gunnison)			
Landsat 5		Landsat 7		Landsat 5		Landsat 7	
Date	Cloud Cover	Date	Cloud Cover	Date	Cloud Cover	Date	Cloud Cover

3.4.2 Weather Data

Weather data was downloaded from Colorado Agricultural Meteorological (CoAgMet) network of weather stations (http://www.coagmet.com/). These weather stations provide weather variables like air temperature, relative humidity vapor pressure, solar radiation, wind speed and precipitation. Throughout 2015 growing season, there were 9 functional point weather stations, while from 2011-2014, there were 4 functional weather stations. While most of these weather stations are in Uncompaghre and Grand Valley, the Gunnison area had one weather station installed in 2015. Because the Western Slope is located in a valley-like geographical area, wind speed in the area is generally low (at times less than 0.5 m/s), which essentially means no data [12] for those measurement and the need to make certain assumptions. Also at other times, wind speed is lower than 1 m/s. If there is little or no wind speed, the surface aerodynamic resistance (rah) term in the sensible heat flux equation (Equation X.X) breaks apart of numerical instability because it is based on turbulence (good mixing) created by the interaction of wind with surface elements. Therefore, for missing all wind speed below 1m/s (no data or otherwise), an assumption of wind speed equivalent to 1 m/s is made before spatially interpolating wind speed and utilizing wind speed map in the model. Because an assumption of wind speed is being made, a wind sensitivity analysis was done for all 2015 growing season images for Montrose overpass to check if increasing the wind speed has a significant difference on daily ET estimations. Also, it is noteworthy to mention that since wind speed in the area is quite low, advection effects on energy balance would be minimal.

3.4.3 Digital Elevation Data

Elevation on the Western Slope varies widely, so short-wave radiation reaching the surface of earth also varies widely and an atmospheric lapse rate correction is needed to take into account the net cooling of temperature aloft with elevation. Thus, a digital elevation model (DEM) over the area is needed. The National Elevation Dataset (NED) of ⅓ arc-second, about equal to 10 meters in the study area, was used.

The DEM was used in slope and aspect calculations to adjust for solar elevation away from nadir and determine short-wave radiation reaching the surface of the earth. Also, it was used for correcting the

[12] The threshold wind speed for the CoAgMet weather station anemometers is 0.5 m/s (1.12 miles/hour or 26.84 miles/day) and values below this are dropped to 0.

surface temperature. Since locations with higher elevations are at a lower temperature than lower elevation areas, the model may detect higher locations as having higher ET values. To correct this error, temperature was adjusted to compensate for the change in elevation. This correction is called atmospheric lapse rate correction, (sometimes referred to as "elevation correction") given by the following equation:

$$T_{corr\_s} = (DEM - x) \times 0.0065 + T_s$$

Where, T_{corr_s} is the corrected surface temperature, T_s is the original surface temperature, DEM is the digital elevation data at any pixel and x is the average elevation of the area of interest in the image.

3.4.4 Crop Cover Data

Crop cover data for alfalfa and grass pasture crops was collected in the Uncompaghre and Grand Valley during field visits. The crop cover map for 2015 was downloaded from USDA NASS Cropscape (http://nassgeodata.gmu.edu/CropScape/). Some grass pasture sites in Uncompaghre and Grand Valley are classified as "other pastures" in the Cropscape map, therefore, for Uncompaghre and Grand Valley, ground-truthed data was used. Ground data for crop type was not collected in Gunnison since majority of the crops are grass pastures, and Cropscape also identifies most of the fields in Gunnison as grass pastures.

The crop coefficients derived from physically-based energy balance models are considered practical and accurate (Taghvaeian 2011). Thus, crop coefficients derived from full-irrigation regimes can potentially represent crop coefficients of the agro-climatological conditions of the area and can be compared to generic FAO-56 tabulated coefficients to check tabulated coefficients' accuracy for application in the Western Slope of Colorado. Also, lengths of growth stages of a crop may vary substantially from region to region places because the rate at which vegetation develops depends on climate, latitude, elevation and planting date (FAO-56). Using remote sensing data, local growth stage lengths of different cutting cycles (first cutting cycle is usually longer than the rest because of lower temperatures) can be obtained, which can be used beneficially for future water management.

3.5 Determination of Daily AET using ReSET

The approach used to determine daily ET using Landsat data followed the ReSET Manual (citation) with ERDAS IMAGINE software.

ReSET calibrated mode involving inputs of spatially-distributed reference ET (instantaneous as well as daily) and wind speed maps was utilized for both Montrose (Path 35/Row 33) imagery and Gunnison (Path 34/Row 33) imagery because the spatial coverage of 9 weather stations in the area was sufficient. These spatially distributed maps were created by determining both hourly and daily (24-hour) alfalfa reference ET from Penman-Monteith method at each weather station, utilizing wind speed data from each weather station, and spatially interpolating these using Inverse Distance Weighted (IDW) function. Daily reference ET at each weather station was calculated by summing up the hourly reference ET (calculated for each hour from equation 1.2) for the whole day rather than using daily time-step in equation 1.2, because substantial changes in wind speed, humidity, cloudiness etc. during the day can affect average daily estimates of the parameters of equation 1.2. The ReSET model was largely automated, including selection of calibration/anchor (hot and cold) pixels. The automatic selection of hot and cold pixels was done by creating NDVI and albedo masks, selecting top candidates of pixels from image histogram, conditioning top candidate pixels to be in a cluster of 8 similar surrounding pixels and by constraining cold pixel selection to be within 10-20 km radius around the weather station. The automatic selection of hot and cold pixels was checked manually for every image before further running the energy balance. This automated selection of anchor pixels worked well enough for most of the Montrose imagery, but not for Gunnison imagery because of the complex topography (mountainous), soil-mineral depositions, lots of narrow water bodies and shallow groundwater cooling down the ground surface. Because of this, it was determined to best select anchor pixels manually for Gunnison imagery.

After determining instantaneous (hourly) ET at the time of the Landsat overpass, the grass reference evapotranspiration fraction (EToF) mechanism was used to extrapolate instantaneous (hourly) ET to daily. EToF is the ratio of remotely sensed instantaneous ET (ET_i) to the grass reference ET (ET_{ref}) computed from weather station data at the time of satellite overpass.

$$\mathrm{EToF} = \frac{\mathrm{ET_i}}{\mathrm{ET_{ref}}} \tag{3.13}$$

This ratio is essentially the actual grass-based crop coefficient, which does not vary from instantaneous to daily time scale, and was used to estimate daily ET_d by using the following equation:

$$\mathrm{ET_d} = \mathrm{EToF} \, . \, \mathrm{ET_{d\_ref}} \tag{3.14}$$

where ET_{d_ref} is the daily grass reference ET calculated from weather station. These calculations are done in raster form, on a pixel-by-pixel basis. For interpolation between two consecutive overpass days to get weekly or monthly ET, correction ratio (γ) method, as mentioned in Elhaddad and Garcia (2008) and given below, was implemented.

$$\gamma = [(\mathrm{EToF_i} - \mathrm{EToF_{i+1}})/\mathrm{N}] \tag{3.15}$$

$$\mathrm{ET_{d\_i}} = [\, \mathrm{EToF_i} - (\gamma * \mathrm{T})] * \mathrm{ET_{d\_ref}} \tag{3.16}$$

where $EToF_i$ and $EToF_{i+1}$ are the EToF grids of two consecutive overpass days between which interpolation is being done, N is the number of days between the overpass images for which the data is being interpolated, ET_{d_i} is the interpolated daily ET between two consecutive overpass dates and ET_{d_ref} is the daily reference ET for that particular date. The ET_{d_i} changes for each day, depending on where that day falls between the beginning and end of the interpolation period (T). For determining the weekly or monthly ET, the daily ETs obtained on the days with and without satellite overpass were added cumulatively over a desired time period.

Since Gunnison overpass imagery (Path 34/Row 33) lies in a complex mountainous hydro-geographical area with a lots of meandering water bodies, and soils deposited with minerals - selection of hot and cold pixels, even manually may not be highly accurate. Since the ReSET model depends heavily on selection of right anchor points, it is essential to cross-check ET estimations for this imagery. This was done using the adjacent Montrose (Path 34/Row 33) imagery, which has an overlap with Gunnison imagery. Montrose overpass is always one day after Gunnison overpass, and the overlap area is north Gunnison (near Gunnison weather station). Because crop coefficients estimated over an area do not change significantly over a day, crop coefficients determined over Gunnison and Montrose imagery on consecutive days can be compared for evaluating the estimation of ET over Gunnison area, and to check the anchor points' selection.

Evaluation of ReSET ET assessments was done using three separate methods.

The first evaluation criteria selected involves choosing fully- irrigated alfalfa field(s) in the study area (with specifically checking that it's not used as calibration/anchor points) and comparing ReSET estimates at that field(s) with reference alfalfa ET calculated from weather station. This was done for both Montrose and Gunnison imagery, on day(s) when crop was yet to reach full over and the crop height was close to 50 cm height. It was evaluated whether the ReSET- estimated ET at the chosen fully-irrigated alfalfa field(s) was reasonably close to alfalfa reference ET.

The second evaluation criterion involves comparing the ET estimated from the soil water balance with ReSET-estimated ET. An incoming and outgoing balance will be implemented given as shown in Equation 1.4 (as described in Hoffman et al 2007).

The third evaluation using measured estimates of H, Rn and G were carried out only for the partial irrigation treatment plot at Montrose site because water-stressed vegetation has lower vegetation cover that leads to heterogeneity of surface, which creates discrepancy between actual and ET estimated from models like ReSET that are based on big-leaf approach.

Rn and G were measured by net radiometer and ground heat flux plats respectively. These separate measured estimates of energy balance components were compared to ReSET-derived components.

3.6 Estimating AET with the MSR5 Hand-held Radiometer

A ground-based level, a hand-held, multi-spectral radiometer (Model MSR5, CROPSCAN, Inc., Rochester, MN) was used to measure surface reflectance in five spectral wavebands similar to those of the sensors onboard the Landsat 5 Thematic Mapper (TM) satellite. This device was used to monitor grass water stress and AET for different stress regimes designed by the Northern Colorado Water Conservancy District in 2011 (Chávez and Taghvaeian, 2012). The wavelength bands were in the blue (TM1), green (TM2), red (TM3), NIR (TM4) and short-wave infra-red (SWIR, TM5) parts of the electromagnetic spectrum. The MSR5 sensor has two sets of optics with 28° field of view. What is the footprint? One set of optics is placed looking downward to detect the radiance reflected from the surface and the other is placed looking upward, through an opal glass cosine diffuser, to estimate the incoming radiance in the same bands. Target reflectance in each of the five bands is estimated by dividing the reflected radiance by the incoming radiance, using an internal program on the data logging controller attached to the MSR5. An infra-red thermometer or IRT (model IRt/c.2, Exergen Corp., Watertown, MA) with a 35° field of view is also attached to the MSR5 to measure canopy temperature.

The estimation of AET using the MSR5 is done using a reflectance-based crop coefficient approach. This calculation is done in post-processing step, using a PET reference condition (ET_r), multiplied by a crop coefficient (K_c) for the surface vegetation. A major advantage of using the multi-spectral sensor is that K_c can be developed on the basis of a Normalized Difference Vegetation Index (NDVI) unique to the location being measured.

3.6.1 Reflectance-based Crop Coefficient Approach

Singh and Irmak (2009) developed a regression model to relate NDVI and the K_c for corn, soybeans, sorghum, and alfalfa. A model for irrigated alfalfa, developed from 1,260 pixel values in southeastern Nebraska is shown below:

$K_c = a \times \text{NDVI} + b$ where a = 0.981 and b = 0.113

The above equation was used as such for the alfalfa site at Delta. Since this project deals with grasses at two of the sites, the above equation was used to derive K_c as a function of NDVI developed from the MSR5 data. Because a correction was needed to estimate grass *ET*, the software program RefET (version 3) developed at the University of Idaho (Allen, 2008) was used to calculate ET_r for both alfalfa and grass, and subsequently a ratio of alfalfa to grass *ET*. The K_c derived from the Singh and Irmak (2009) equation was then divided by the alfalfa to grass ET ratio, to obtain a modified K_c for grass. This modified K_c was subsequently used to calculate ET_a from the ET_r obtained from the nearest CoAgMet weather station.

The limitation of this approach is that since the physiology of grass pastures is closer to alfalfa than the reference grass, it is not always expected to give results as accurate as an empirical equation derived for grass pastures itself. Also, since the equation above was developed in agro-climatological conditions of Nebraska, it may not perform as well in Western slope of Colorado. Since this reflectance based approach does not use a thermal band, it may not be able to capture immediate crop stresses, but will only capture them when the stresses start to affect vegetation conditions(that is , decrease in NDVI due to leaf rolling, stunted growth etc.).

3.6.2 Estimating ET from the Crop Water Stress Index (CWSI)

Though not used in this study, an alternative method worth mentioning is the Crop Water Stress Index (CWSI) approach was developed in 1981, when Idso et al. (1981) and Jackson et al. (1981) proposed the empirical and theoretical methods of estimating CWSI, respectively. For our study, the CWSI was the intended original approach, but due to a malfunction in the cold junction compensator on the MSR5, this data is still being evaluated for later use. Idso et al. (1981) proposed the equation below:

$$\text{CWSI} = \frac{dT_m - dT_{LL}}{dT_{UL} - dT_{LL}}$$

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. Since all variables have the same units, CWSI is a dimensionless ratio. The lower limit of *dT* occurs under non-water-stressed conditions when *ET* is only limited by atmospheric demand. On the other hand, the upper limit of *dT* is reached under non-transpiring conditions when *ET* is stopped due to the lack of water. Idso et al. (1981) proposed that under non-water-stressed conditions the lower *dT* limit is a linear function of the air vapor pressure deficit (VPD, kPa):

$dT_{LL} = a + b \times \text{VPD}$ where “a” is the intercept and “b” is the slope of the linear relationship.

Similarly, the upper limit can be expressed as a linear function of vapor pressure gradient (VPG, kPa):

$dT_{UL} = a + b \times \text{VPG}$ where “a” and “b” are the same coefficients as above.

Jackson et al. (1981) showed that there is a unique mathematical relationship between CWSI and the ET of the studied vegetative surface. The equation derived by Jackson et al. (1981) can be rearranged into the following format:

$ET_a = (1 - \text{CWSI}) \times ET_p$ where ET_a is AET, and ET_p is PET.

While this approach has been utilized on several crops like corn, alfalfa, turfgrass etc., “a” and “b” coefficients in above equations have not been developed before for grass pastures. Also, since these coefficients can be local (depending on agro-environmental conditions), they need to be developed for study area/Western Slope.

4 Results and Discussion

4.1 Objective 1 - Actual Consumptive Use derived from irrigation water balance, energy-balance,

and a reflectance-based approach

Objective 1 was to compare the results of three methods for estimating ACU on alfalfa and grass hayfields at the study sites. The three methods evaluated were: 1) irrigation water balance (calculated using data from in-situ Campbell Scientific CS655 water content reflectometers); 2) energy-balance approach (calculated using satellite observations with ReSET model), and; 3) reflectance-based approach (calculated using measurements taken with a Cropscan® MSR5hand-held radiometer). Both ACU and AET were quantified identically in terms of their effect on system loss.

For the three approaches, monthly ACU was the basis for comparison, given that different methods encounter inaccuracies in the estimation of daily ACU. These methods are under resolution by other research efforts. For example, a method combining SEBAL with a reference ET fraction to extrapolate daily AET rates for irrigated crops yielded prediction errors averaging -18.2% (under-prediction) when compared to measurements from a standardized ground control lysimeter (Trezza, 2002). Although the accuracy of ACU estimation by remote sensing continually improves, the 8-day schedule and cloud-free requirement for Landsat passes is a major hindrance to accurate daily estimates (Chávez et al., 2008). Additionally, the accuracy of daily IWB calculations can be governed by selection of root zone depth, which can be seasonally variable, depending on the plant growth stage. Finally, hand-held radiometer measurements were only taken on the days of Landsat passes and not taken daily, given the travel distance involved. Given the likely errors in all three methods for estimating daily ACU, therefore, the monthly basis for comparison was used. An additional rationale for using a monthly basis is that most water sharing contracts are also structured on monthly ACU rates.

Before the results discussion, a modification of the original scope for Objective 1 is noted below:

Originally, Objective 1 was planned to include sites in both the Grand Valley and the Gunnison basin. The geographic extent of this objective was reduced, however, to include only the Gunnison basin. The reason for this modification entailed workload and timeline constraints. More specifically, Landsat Path 35 (which covers all of the Uncompahgre and most of the Grand Valley) does not include Loma, CO, where the proposed Grand Valley ground-truth site is located. This exclusion of the Loma site in the Landsat imagery was not considered when the proposal was written, and this field site had already been established under a separate project. Considerable time and effort would have been required to process the additional Landsat Path 36 to incorporate the Loma, CO field site. Therefore, a substitute location in Delta, CO instead, using field observations from a different project. The inclusion of the Delta, CO introduced dissimilarity in soil moisture sensing approaches, given that the Montrose and Gunnison sites were equipped with Campbell CS655 sensors, whereas the Delta site had already been equipped with Irrometer Watermark sensors. Appropriate approaches to determining soil water content from each sensor were used. As such the project was confined to using field sites in Montrose, CO and Delta, CO (Landsat Path 35) and Gunnison, CO (Landsat Path 34).

4.1.1 Monthly AET for 2015-2016 Time Period Using the Irrigation Water Balance Approach

Calculation of monthly AET for 2015-2016 was performed by: 1) estimating *daily* AET_c for the crop at the study site (alfalfa or grass), then; 2), correcting *daily* AET_c for days when the IWB results were clearly in error, and finally; 3) estimating *monthly* AET_c by summing the daily AET_c estimates. For step one, a daily timestep[13] was used with AET_c as the closure term. Monthly AET_c was estimated in 2015 and 2016, respectively, for June - August and April - August.

The *field-scale monthly* AET_c was obtained by averaging the results between the two sensing stations each on the fully- and partially-irrigated fields in Montrose, and the five sensing stations for the sprinkler irrigated field in Delta. On the other hand, because of its larger size, AET_c for each sensing station at the Gunnison site was compared individually to AET_c from remote-sensing and radiometer observations.

4.1.1.1 Components of the Irrigation Water Balance

For much of the season the IWB could be simplified, given that: 1) irrigations were infrequent, and; 2) upflux was negligible (as will be discussed below).

Rooting Depth. For alfalfa at the Delta site, rooting depth was estimated at no greater than 60 inches, based on field examinations where drilling depths were 82, 77, 62, 40 and 38 inches when installing the observation wells. Drilling depth and consequently plant rooting depth was likely impacted by resistant gravel deposits characteristic of the mesa where the site is located. Additionally, the alfalfa stand at the study site had been planted recently (July 2015), so a fully mature and deep root system was not expected. For grass pastures, typical rooting depths are 24-36 inches (Jensen et al., 2006; Orloff et al., 2016). The rooting depth of grasses at the Montrose site was estimated to be approximately 30 inches, based on Giddings core sampling. Rooting depth of grasses at the Gunnison site was estimated at 18 inches, based on previous studies (Coupland and Johnson, 1965; Moore and Rhoades, 1966; Manning et al., 1989, along with field evaluations and well drilling. Prior studies suggest that a sharp restriction in root matter is expected at the interface of rocky layers found close to the surface and approximately 6 inches above the high-water table (Walter et al, 1990). Data from the observation wells at the Gunnison site exhibited groundwater levels at approximately 24 inches, except during irrigation inundation.

Soil Moisture Deficit (D_c - D_p). Components D_c and D_p were calculated from calibrated sensor data and determined relative to the field capacity of the soils provided in Table X.X in Section 2. Calculations of soil moisture at the Montrose and Gunnison sites were derived using measurements from field and laboratory calibration curves shown in Figure X.X. Soil moisture at the Delta site was derived from a derived soil-water characteristic equation for clay loam soils (Saxton et al., 1986), shown in Equation 4.1.

$$\Psi = A \times \Theta^B \qquad (\text{for } 1500 \text{ Kpa} < \Psi < 10 \text{ Kpa}) \qquad (4.1)$$

[13] Because the stations were equipped with solar panels, using a daylight hour ensured that a reliable VWC reading would have been recorded, even if data logger power happened to fail at night due to low battery voltage. Such failures were rare, however, and soil VWC also varied insubstantially during each 24 hour period (except immediately following irrigations). Data loggers were programmed to record at every 30 minutes. The VWC at 6:00 AM was used to calculate D_c and D_p.

where Ψ = soil tension (kPa or Cb), Θ = soil moisture (ft^3/ft^3), $A = \exp[a + b(\%C) + c(\%S)^2 + d(\%S)^2(\%C)] \times 100.0$, $B = e + f(\%C)^2 + g(\%S)^2(\%C)$, %C = percent clay, %S = percent sand, a = -4.396, b = -0.0715, c = -4.880×10^{-4}, d = -4.285×10^{-5}, e = -3.140, f = -2.22×10^{-3}, g = -3.484×10^{-5}.

%S = 22
%C = 58

[Figure. CS655 vs VWC calibration curve]

Effective Precipitation (P_{eff}). Maximum and median precipitation events are summarized in Table X.X for the sites in 2015 and 2016. None of these precipitation events were associated with tailwater runoff from the fields, based on flume water levels. Soil water content sensors were not shallow enough to detect the wetting of the immediate surface from the precipitation events. Nevertheless, P_{eff} was an input to the IWB and assumed to contribute to AET_c, therefore, P_{eff} was set to 100%. Similar rationale was employed in the development of the Denver Water High Altitude Coefficients (Walter et al., 1990).

Table X.X. Precipitation (2015-2016 study period)

	Delta, CO		*Montrose, CO*		*Gunnison, CO*	
	2015	2016	2015	2016	2015	2016
Median		0.07		0.05		0.05
Maximum		0.65		0.88		0.74

Irrigation (Irr). Because irrigation was measured only at the field scale, irrigation data was not precise enough to calculate irrigation rates at each individual sensing station. Soil moisture measurements did, however, increase rapidly to the point of oversaturation when irrigation events occurred. Therefore, the irrigation (Irr) rate was assumed as the increase in soil water content. At the Delta site, irrigation rates were cross-checked with recorded flows on the sprinkler system. At the Montrose site, field-scale recorded flows in both the irrigation pipe flow meter and tailwater were cross-checked for amount and timing of the Irr component in the IWB. At the Gunnison site, due to the system using wild-flood, swales and check-structures was not possible to monitor reliably for irrigation input.

Surface Runoff (SRO) and Deep Percolation (DP). The SRO and DP components of the IWB could not be measured independently, but both are considered losses in the IWB. Therefore, SRO and DP were accounted for in a simple way by setting D_c to zero whenever water additions (P_{eff} and Irr) caused D_c to be negative. A negative D_c meant that water added to the root zone exceeded soil field capacity within the plant root zone. Any excess water in the root zone can be assumed lost through SRO or DP (Andales et al., 2011). Since SRO and DP are both losses, the approach of deriving AET_c as the algebraic closure term was unaffected by combining SRO and DP.

[Figure. Irrigation, Cutting and Tailwater]

Upflux (U). In the equation above, U = 0 for each site, based on the effect of groundwater which was nonexistent (Delta), negligible (Montrose) or [explain] (Gunnison). The upflux contribution was inferred from measured groundwater levels and electrical conductivity measured by the CS655 sensors (Montrose, Gunnison). At the Delta site, U was considered nonexistent, given the lack of groundwater in all 5 observation wells for the entire season. The 5 wells drilled at this site were 82, 77, 62, 40 and 38 inches deep. Additionally, the Delta site received irrigation water entirely from an overhead sprinkler system. At the Montrose site, U was considered negligible, given the depth to groundwater and the dry conditions (near wilting point) and trend of decreasing EC at the deep sensor position. Had capillary rise occurred, EC levels would be expected to increase as wetting fronts pushed water salts higher into the root zone. At the Gunnison site, prior studies of intermountain meadows suggest that rocky layers as observed in this study pose significant restrictions in the rise of adequate capillary water into the zone of heaviest rooting (Walter et al., 1990).

[Figure. Groundwater levels in Gunnison and Montrose]

4.1.1.2 Results of the Irrigation Water Balance

Based on the approaches and assumptions described above, the IWB equation for daily AET_c was simplified as follows, based on the study site conditions and caveats:

$$AET_c = D_c - D_p \quad \text{(when Irr = 0.0, } P_{eff} = 0.0\text{, SRO + DP = 0.0, and U = 0.0)} \tag{4.2}$$

$$AET_c = P_{eff} + Irr - D_p \quad \text{(for } D_c < 0.0 \text{ when } P_{eff} + Irr \text{ are large enough to exceed soil field capacity)} \tag{4.3}$$

The results of Equations 4.2 and 4.3 produced four outcomes.

1. The most typical was the outcome in which daily AET_c fell within an expected range of ET rates between 0.05 to 0.50 inches per day for well-irrigated grasses and alfalfa in the study region. All estimations for this outcome were accepted in the summation of monthly AET.
2. The second outcome occurred when AET_c rates were greater than zero but less than 0.05 inches per day. Given the lower frequency and higher variability of irrigation at these sites, especially when fields received no irrigation, these lower AET_c rates were deemed reasonable and were also accepted in the summation of monthly AET.
3. The third outcome occurred when IWB-derived daily AET_c rates were calculated to be negative. Negative AET values have been noted to manifest occasionally in AET evaluations, due to actual processes, such as condensation, or data quality issues, in assumed precipitation for instance (Wang et al., 2015). Negative AET values were extremely small in this evaluation, averaging a total of -0.59 and -0.22, respectively, for the fully and partially-irrigated fields in 2016, meaning that the seasonal total could be underestimated by these amounts.
4. The fourth outcome occurred in the instances when the estimated AET_c rates was affected by large changes in D_c - D_p, due to a process that could not be modeled in this study, such as

drainage from the lower root zone only. This outcome was highly infrequent, occurring in less than 3% of the daily estimates.

Monthly estimated AET results are shown in Table X.X for the study sites during periods of assessment June -August (2015) and April – August (2016).

Table X.X. Monthly estimated AET (2015-2016) using Irrigation Water Balance Method (inches)

	Delta (alfalfa)		*Montrose (grass)*				*Gunnison (grass)*	
	2015	2016	2015		2016		2015	2016
Month	sprinkler		full	partial†	full	partial	flood	
April					1.98	2.54		
May					6.94	5.47		
June					2.67	3.99		
July					1.72	0.94§		
August					6.37	1.52		
Sept								
October								

* Data have not been evaluated yet.
** IWB stations were not installed.
†Irrigation was suspended on August 13, 2015
§ Irrigation was suspended on July 7, 2016 after the first cutting of grass hay.

Table X.X. Monthly estimated AET at individual well locations at Gunnison, CO (2016) using Irrigation Water Balance Approach (inches)

	Observation Well ID and Description								
	K1	K2	K3	K4	K5	K6	K7	K8	K9
Month			middle	low	low	middle	high	middle	
May			0.55	0.50	0.58	2.06	1.45	2.57	
June			0.06	0.00	0.73	1.65	1.44	3.64	
July			0.71	0.61		2.90	3.83	6.24	
August									
September									
October									

† Data have not been evaluated yet.
‡ No equipment installed at this location for soil water balance evaluation
** Data is partially evaluated

4.1.2 Monthly ET from 2015 and 2016 Seasons Derived from Energy-Balance Approach

The fine resolution helped greatly not only to accommodate the size of the small site in this study (Montrose, CO), but also allowed this project to operate at a field area size in the range of those typical to the Uncompahgre and Grand Valley area that might participate in water-sharing programs. Talk about how the data were fit into fields/pixels.

Table X.X. Monthly estimated AET (2015-2016) using Energy Balance Method (inches)

	Delta (alfalfa)	*Montrose (grass)*	*Gunnison (grass)*

	2015	2016	2015		2016		2015	2016
Month	sprinkler		full	partial	full	partial	flood	
April		3.23			1.85	1.09		
May		5.27			4.59	4.10		6.10
June		5.95	6.19	5.88	4.11	4.30		7.27
July		5.28	4.29	4.91	3.15	2.39[§]		5.15
August	5.39		4.81	4.77[‡]				
Sept			4.01	3.40				
October			2.56	2.12				

[†] Data have not been evaluated yet.
[‡] Irrigation was suspended on August 13, 2015.
[§] Irrigation was suspended on July 7, 2016 after the first cutting of grass hay.

Table X.X. Monthly estimated AET at individual well locations at Gunnison, CO (2016) using Irrigation Water Balance Approach (inches)

	Observation Well ID and Description								
	K1	K2	K3	K4	K5	K6	K7	K8	K9
Month			middle	low	low	middle	high	middle	
May	5.90	6.97	6.68	6.91	6.58	6.19	4.83	5.90	5.77
June	8.30	8.48	7.15	7.75	6.75	8.14	7.43	5.98	6.18
July	5.15	5.44	6.56	6.30	4.78	3.95	5.32	3.80	4.76
August									
September									
October									

4.1.3 Monthly ET from 2015 and 2016 Seasons Derived from Reflectance-Based Approach

Table X.X. Monthly estimated AET (2015-2016) overpass dates) comparing IWB, EB, MSR5 (in/day)

	Delta (alfalfa)			*Montrose (grass hay)*						*Gunnison (grass hay)*			
	sprinkler			full			partial			partial			full
Date	IWB	EB	MSR5	IWB	EB	MSR5	IWB	EB	MSR5	IWB	EB	MSR5	EB
8/13/2015					**0.153**			**0.173**	**0.160**				
9/23/2015												0.05	
10/1/2015					**0.139**			**0.097**	**0.067**				
6/21/2016											0.25	0.11	
6/28/2016		0.22	0.22	**0.025**	**0.032**	**0.076**	**0.025**	**0.054**	**0.088**				
7/7/2016											0.29	0.14	
7/14/2016		0.12	0.13	**0.008**	**0.088**	**0.107**	**0.019**	**0.070**	**0.123**				
7/22/2016		0.13	0.18	**0.135**	**0.119**	**0.104**	**0.010**	**0.075**	**0.096**				
7/23/2016											0.11	0.11	
7/30/2016		0.09	0.13	**0.185**	**0.128**	**0.105**	**0.002**	**0.072**	**0.064**				

4.1.4 Using a Reflectance-Based Approach to Develop Grass Pasture Crop Coefficients

Remote sensing techniques to estimate ET use two basic approaches described by Gowda et al. (2008):

1) land surface energy balance, and; 2) reflectance-based crop coefficient approach. Although this project utilized the energy balance approach for the LANDSAT data, both methods are discussed in the upcoming sections.

Discuss Aman's thesis work – NDVI reflectance-based method.

4.1.5 Discussion

August data is forthcoming but not possible due time limitations. Landsat data only becomes available 10 days after each overpass. Hourly weather data must be downloaded to compute reference ET. Processing the rasterized RefET and then running ReSet for August would take another 2 weeks. Therefore, August 2016 data will be provided at a later date.

Possible explanations for overestimation using ReSET:

1. 60-100m pixel sizes for TIRS governs (Landsat 7= 60, Landsat 8 = 100) the daily AET estimation, and consequently the extrapolation. May have picked up heterogeneity in green at larger than IWB scale.
2. Cannot use ReSET with MSR5. MSR5 would require Norman 2-source energy balancen model, but advantage is more fine scale and more densely sampled field.

4.2 Objective 2 - Apply an energy-balance approach to archived multi-spectral observations to estimate historical ACU on alfalfa and grass fields in Mesa, Delta, Montrose and Gunnison Counties.

The second objective of this project was to apply the energy balance method (through ReSET) to archived Landsat data, for the purpose of estimating historical rates of ET on alfalfa and grass hay field sites. Again, the geographical extent of this objective was also modified to include only the Gunnison basin, not also the Grand Valley as indicated in the original proposal, for the reasons specified in Section 4.1. The purpose of this objective was to approach the estimation of historical CU using a different method than current models based largely on PET or other rudimentary approaches.

4.2.1 Monthly ET 2011, 2013 and 2014 Seasons Derived from ReSET

There were 7 weather stations in these years, all in Montrose overpass imagery with none in Gunnison overpass imagery. Because of this reason, uncalibrated version of ReSET for Gunnison imagery was utilized, while calibrated version of ReSET with spatially-distributed instantaneous ET, daily ET and wind speed (same as described in last section) was utilized for Montrose overpass imagery. Uncalibrated version is a rasterized version of SEBAL model, that does assumes H=0 at cold points and LE=0 at hot points, but models each area on the basis of its local hot and cold pixels. Rest of the procedure for processing Gunnison imagery was mostly similar, except extrapolation from hourly to daily was done on the basis of Evaporative Fraction (EF) as in SEBAL, and interpolation between consecutive overpass days was done on the basis of linear interpolation between two overpass image results. The overlap part of

Gunnison in both Gunnison and Montrose imagery was cross-checked for consecutive crop coefficient for year 2014, just like described before in section 2.6.1. The monthly ET estimates of all these years at both Montrose and Gunnison sites were compared with 2015 monthly estimates to check variability from year-to-year. And using all these monthly estimates (2011-2015, except 2012), upper and lower monthly limits of ET at each site were determined. Also, cumulative monthly PCU, which should theoretically be the upper bound of ET was compared to the Historical Monthly ACU for 2011-2015 to determine if there is a practically significant difference.

Landsat 7 was the only satellite operational in 2012 as Landsat 5 mission was ended in 2011 and Landsat mission started in 2013. With only one satellite, the temporal resolution was reduced was reduced by 50%- with August having no cloud-free imagery; and June and July months had only 1 cloud-free imagery- with which it is not accurate to calculate monthly ET in the growing season.

4.2.2 Discussion

4.3 Objective 3 – Compare crop ACU derived an energy-balance approach against the StateCU model, akin to methodology currently used in Colorado

The third project objective was to compare crop CU derived from ReSET against StateCU model, akin to methodology currently used in Colorado.

4.3.1 Monthly Historical ET Derived from StateCU Model

This section needs further elucidation of the determination of supply-limited consumptive use, or actual consumptive use, which requires estimates the crop irrigation requirement (CIR). Depending on the extent of measured diversion records, the states and Reclamation take different approaches to estimate ACU. Scenarios were created using HydroBase Wizard. Need to discuss the concept of IWR in StateCU.

This section needs a discussion of the fact that the State of Colorado Division of Water Resources requires that river diversions are measured; therefore, Colorado performs an analysis that compares supply at the ditch level to CIR to estimate ACU.

Table X.X. Field site characteristics

Site Name	*Location*	*WDID*	*Water Source*	*Irrigation Type*	*Crop Type (2015)*	*Diversion*
RN	Delta	4100534	Ironstone Canal	Furrow	Alfalfa	
FG	Montrose	4100537	Loutsenhizer Canal	Furrow	Grass Pasture	
KR	Gunnison	2800532 2800513	Coats Bros Ditch	Flood	Grass Pasture	

Table X.X. Monthly estimated ETp (?) using StateCU (in/mo)

	Delta, CO (alfalfa)			*Montrose, CO (grass hay)*			*Gunnison, CO (grass hay)*		
Month	Start	End	ETp (in)	Start	End	ETp (in)	Start	End	ETp (in)
April	---	---	---	1998	2015	2.25	---	---	---

May	1998	2015	5.14	1998	2015	4.00	---	---	---
June	1998	2015	7.49	1998	2015	6.11	1999	2015	3.83
July	1998	2015	9.26	1998	2015	7.50	1999	2015	5.16
August	1998	2015	7.65	1998	2015	6.18	1999	2015	4.33
September	1998	2015	4.62	1998	2015	3.98	1999	2015	2.62
October	---	---	---	1998	2015	2.01	---	---	---

Table X.X. Monthly estimated IWR using StateCU (in/mo)

	Delta, CO (alfalfa)			*Montrose, CO (grass hay)*			*Gunnison, CO (grass hay)*		
Month	Start	End	IWR (in)	Start	End	IWR (in)	Start	End	IWR (in)
April	---	---	---	1998	2015	1.90	---	---	---
May	1998	2015	4.80	1998	2015	3.28	---	---	---
June	1998	2015	7.07	1998	2015	5.83	1999	2015	3.29
July	1998	2015	7.47	1998	2015	6.32	1999	2015	4.06
August	1998	2015	6.21	1998	2015	5.13	1999	2015	2.98
September	1998	2015	3.55	1998	2015	3.12	1999	2015	1.63
October	---	---	---	1998	2015	1.46	---	---	---

4.3.2 Discussion

5 Conclusion and Recommendations for Future Research

Richard Allen's new version of METRIC? CWSI approach with new baselines? Use Sentinel data in addition to Landsat to increase temporal frequency?

Large spikes in ET will confound baseline ET measurement.

REFERENCES

Allen, R.G., L.S. Pereira, D. Raes and M. Smith. (1998). Crop evapotranspiration —Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. Food and Agriculture Organization, Rome.

Allen, R.G. and M.E. Jensen. (2016). Evaporation, evapotranspiration, and irrigation water requirements. ASCE MOP 70 (2nd ed). American Society of Civil Engineers, Reston, VA.

Allen, R. G., I.A. Walter, R. Elliott, B. Mecham, M.E. Jensen, D. Itenfisu, T.A. Howell, R. Snyder, P. Brown, S. Echings, T. Spofford, M. Hattendorf, R.H. Cuenca, J.L. Wright and D. Martin, (2000). Issues, requirements and challenges in selecting and specifying a standardized ET equation. National Irrigation Symposium Proceedings of the 4th Decennial Symposium, Phoenix, Arizona, USA, November 14-16, 2000: 201-208.

Allen R, A Irmak, R Trezza, JMH Hendrickx, W Bastiaanssen and JvKjaersgaard. 2011. Satellite-based ET estimation in agriculture using SEBAL and METRIC. Hydrological Processes 25: 4011–4027

Allen, R. G.,M. Tasumi, and R. Trezza. (2007). Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) - Model. *Journal of Irrigation and Drainage Engineering*, 133(4): 380-394.

Allen, R.G., 2008. REF-ET: Reference Evapotranspiration Calculation Software for FAO and ASCE Standardized Equations. University of Idaho, 82 pp. [http://www.kimberly.uidaho.edu/ref-et/index.html

Ambast, S.K., A.K. Keshari, and A.K. Gosain. (2002). Satellite remote sensing to support management of irrigation systems: Concepts and approaches, Irrigration & Drainage, 51:25–39

Andales, A.A., J.L. Chávez, and T.L. Bauder. (2011). Irrigation Scheduling: The Water Balance Approach. Fact Sheet No. 4.707. Colorado State University Extension, Fort Collins, CO. Retrieved November 7, 2016, from CSU Extension.
(http://extension.colostate.edu/topic-areas/agriculture/irrigation-scheduling-the-water-balance-approach-4-707/)

ASCE-EWRI (2005) The ASCE standardized reference evapotranspiration equation. In: Allen RG, Walter IA, Elliot RL, et al. (eds.) Environmental and Water Resources Institute (EWRI) of the American Society of Civil. Engineers, ASCE, Standardization of Reference Evapotranspiration Task Committee Final Report, 213pp. Reston, VA: American Society of Civil Engineers (ASCE).

American Society of Civil Engineers (ASCE). (2002). The ASCE standardized equation for calculating reference evapotranspiration, Environment and Water Resources Institute of ASCE, New York.

Burt, C. M. (1999). Irrigation water balance fundamentals. Conference on Benchmarking Irrigation System Performance Using Water Measurement and Water Balance. Denver, CO. March 10, 1999.

Blaney, H.F. and W.D. Criddle. (1962). Determining consumptive use and irrigation water requirements. USDA Technical Bulletin 1275, US Department of Agriculture, Beltsville, MD.

Campbell Scientific. (2016). CS650 and CS655 Water Content Reflectometers. Revision: 6/16.

Chávez, J.L., C.M.U. Neale, J.H. Prueger and W.P. Kustas. (2008). Daily evapotranspiration estimates from extrapolating instantaneous airborne remote sensing ET values. Irrigation Science. 27(1): 67-81.

Chávez, J.L. and S. Taghvaeian. (2012). Grass Water Stress and ET Monitoring Using Ground- and Airborne-based Remote Sensing. Report for the Northern Colorado Water Conservancy District. 21 pp.

Colorado Agricultural Water Alliance (CAWA). (2008). Meeting Colorado's Future Water Supply Needs: Opportunities and Challenges Associated with Potential Agricultural Water Conservation Measures [White Paper]. Retrieved August 29, 2016, from Colorado Agricultural Water Alliance: http://coagwater.colostate.edu/docs/Meeting_CO_Future_Water_Supply_Needs_September_2008.pdf.

Colorado Division of Water Resources. (2008). State of Colorado's CDSS Consumptive Use Model. StateCU. s.l., Colorado, United States : Colorado's Decision Support Systems, September 2008.

Colorado Division of Water Resources. (2011) Colorado Division of Water Resources – Estimating Consumptive Use. http://cdss.state.co.us/Modeling/Pages/ConsumptiveUseStateCU.aspx. Retrieved October 19, 2016.

Colorado Water Conservation Board (CWCB) and Colorado Division of Water Resources (CDWR). (2013). Criteria and Guidelines for Fallowing-Leasing Pilot Projects [White Paper]. Retrieved October 5, 2016 from Colorado Water Conservation Board: http://cwcb.state.co.us/water-management/water-projects-programs/Documents/FallowLease/FINALFallowing-LeasingCriteriaAndGuidelines2016.pdf

Colby, B. (2014). Innovative Water Transactions to Meet Urban and Environmental Demands in the Face of Climate Change. In K. W. Easter (Ed.), Water Markets for the 21st Century: What Have We Learned? (pp. XX-XX). New York, NY: Springer.

Colby, B., L. Jones and M. O'Donnell. (2014). Supply Reliability under Climate Change: Forbearance Agreements and Measurement of Water Conserved. K. W.Easter and Q. Huang (Ed.), Water Markets for the 21st Century: What Have We Learned? (pp. 57-82). New York, NY: Springer.

Cook, J., & Rabotyagov, S. S. (2014). Assessing irrigators' preferences for water market lease attributes with a stated preferences approach. Water Resources and Economics, 7, 19-38.

Coupland, R.T. and R.E. Johnson. (1965). Rooting characteristics of native grassland species in Saskatchewan. J Ecol 53:475-507.

Eckhardt, D. 2013. Mapping Evapotranspiration in the Upper Colorado River Basin using the ReSET Energy-Balance Model. Technical Memorandum 86-68260-13-01, Bureau of Reclamation.

Idso, S. B., R.D. Jackson, P.J. Pinter Jr., R.J. Reginato and J.L. Hatfield. (1981). Normalizing the stress-degree-day parameter for environmental variability. *Agricultural Meteorology*, 24(1), 45-55. Page 21

Jackson, R. D.,S.B. Idso, and R.J. Reginato. (1981). Canopy temperature as a crop water stress indicator. *Water Resources Research*, 17(4), 1133-1138.

Jensen, M.E., R.D. Burman, and R.G. Allen. 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practice No. 70, Am. Soc. Civil Engr., New York, NY. 332 pp.

Jensen, K.B., J.G. Waldron and B.L. Robins. 2006. Cool Season Perennial Grasses for Hay. In: Proceedings, 2006 Western Alfalfa & Forage Conference, December 11-13, 2006, Reno, NV.

Jones, L. P. (2015). Agronomic Responses of Grass and Alfalfa Hayfields To No and Partial Season Irrigation as Part of a Western Slope Water Bank. M.S. Thesis. Colorado State University, Fort Collins, Colorado.

Kalma, J., McVicar, T., and McCabe, M.: Estimating land surface evaporation: a review of methods using remotely sensed surface temperature data, Surv. Geophys., 29, 421–469,

Keplinger, K.O. and B. McCarl. (1998). The 1997 Irrigation Suspension Program for the Edwards Aquifer: Evaluation and Alternatives. Texas Water Resources Institute. Technical Report No. 178.

Kilic, A. and R. Allen, 2015. Google Earth Engine Evapotranspiration Flux – EEFlux. INOVAGRI, Fortaleza, Brazil, Sept. 1, 2015 . Retrieved September 28, 2016, from Brazilian National Water Agency (ANA): http://arquivos.ana.gov.br/imprensa/eventosprojetos/20150904_Kilic_Allen_EEFlux_ANA_Brasilia_2015a.pdf

Kustas, W.P. and J.M. Norman. (1996). Use of remote sensing for evapotranspiration monitoring over land surfaces. J. of Hydrological Sciences 41 (4): 495–516.

Leonard Rice Engineers, Inc. (2009). Historic Crop Consumptive Use Analysis – Yampa River Basin. Retrieved October 4, 2016 from http://cwcbweblink.state.co.us/WebLink/ElectronicFile.aspx?docid=146456&&dbid=0

Manning, M. E., S.R. Swanson, T. Svejcar and J. Trent (1989). Rooting characteristics of four intermountain meadow community types. Journal of Range Managemen. 42(4): 309-312.

Moore, A.W. and HF. Rhoades. (1966). Soil conditions and root distribution in two wet meadows of the Nebraska sandhills. *Agronomy Journal*. 58:563-566

MWH Americas, Inc. (2012). Colorado River Water Bank Feasibility Study: Phase 1. Final Report. June 2012. 155 pp.

Natural Resources Consulting Engineers. (2012). Colorado River Compact Colorado Water Bank Feasibility Study Water Supply Technical Memorandum.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database for [Survey Area, State]. Available online. Accessed [month/day/year]

Nichols, W. E. and R. H. Cuenca. (1993). The Evaporative Fraction as a Measure of Surface Energy Partitioning. Water Resources Research, Vol. 29 (11), pp. 3681 - 3690.

Orloff, S.B., E.C. Brummer, A. Shrestha and D.H. Putnam. 2016. Cool-Season Perennial Grasses Differ in Tolerance to Partial-Season Irrigation Deficits. Agronomy Journal 108:692–700

Owensby, C. E. 1973. Using a Step-point Method for Botanical Composition and Basal Cover Estimates. J. of Range Management. 26 (4):302-303.

Paulson, C. (2012). Basic Supply and Water Use Comparison Scenarios for the Colorado River Compact Water Bank Feasibility Study Technical Memorandum.

Sammis T. W., J. Wang, and D. R. Miller. 2011. The Transition of the Blaney-Criddle formula to the Penman-Monteith equation in the Western United States. Journal of Service Climatology. 5 (1): 1-11.

Saxton, K. E., W.J. Rawls, J.S. Romberger, and R. I. Papendick. (1986). Estimating Generalized Soil-water Characteristics from Texture. Soil Sci. Soc. Amer. J. 50(4):1031-1036.

Shuttleworth, W. J., R. J. Gurney, A. Y. Hsu, and J.P. Ormsby. 1989. FIFE: The variation in energy partition at surface flux sites, in Remote Sensing and Large-Scale Global Processes (Proceedings of the IAHS Third International Assembly, Baltimore, MD, May 1989), edited by A. Rango, IAHS Publ., 186, 67-74.

Singh, R. and A. Irmak. (2009). Estimation of Crop Coefficients Using Satellite Remote Sensing. Journal of Irrigation and Drainage Engineering. 135(5): 597-608.

Smith, D. H., J. E. Brummer and D. E. Temple. (2006). Consumptive Irrigation Water Use in the Upper Gunnison River Basin. Upper Gunnison River Water Conservancy District.

Smith, D. H. (2004). Special Report to: Statewide Water Supply Initiative (on Upper Gunnison River Basin Irrigation Water Consumptive Use Studies). May 19, 2004.

Smith, D. H. (2008). Consumptive Irrigation Water Use Intermountain Meadows of Colorado. Colorado Water. Newsletter of the Water Center of Colorado State University. January/February 2008.

Taghvaeian, S., J.L. Chávez and N. C. Hansen. (2012). Infrared thermometry to estimate crop water stress index and water use of irrigated maize in Northeastern Colorado. *Remote Sensing*. 4(11): 3619-3637.

Trezza, R. (2002) Evapotranspiration using a satellite-based surface energy balance with standardized ground control. Ph.D. dissertation, USU, Logan, UT, 339 pp.

URS. (2013). Assessing Agricultural Consumptive Uses in the upper Colorado River Basin. November 2013.

Walter, I.A., E.G. Siemer, J.P. Quinlan and R.D. Burman. (1990). Evapotranspiration and Agronomic Responses in Formerly Irrigated Mountain Meadows, South Park, Colorado. Report for the Denver Board of Water Commissioners, City and County of Denver, CO. March 1, 1990. 216 pp.

Wang, S., M. Pan, Q. Mu, X. Shi, J. Mao, C. Brummer, S. Jassal, P. Krishnan, J. Li and A. Black A. (2015). Comparing Evapotranspiration from Eddy Covariance Measurements, Water Budgets, Remote Sensing, and Land Surface Models over Canada. Journal of Hydrometeorology 16(4):1540—1560.

Waskom, R. K. Rein, D. Wolfe and M. Smith. (2016). How Diversion and Beneficial Use of Water Affect the Value and Measure of a Water Right: Is “Use It or Lose It” an Absolute? (Special Report No. 25). Retrieved August 29, 2016, from Colorado Water Institute: http://cwi.colostate.edu/publications/SR/25.pdf.

Wright, J.L. (1982). New Evapotranspiration Crop Coefficients. Journal of Irrigation and Drainage Division, ASCE, 108:57-74.