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

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

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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 have been historically difficult to measure separately, so the two processes are quantified together to measure agricultural water use in common practice (Taylor and Ashcroft, 1972). Crop consumptive use (CU) is a close analog to ET, emerging from the vernacular of agricultural water rights. The term CU describes the amount or rate of water that is put to beneficial use through evapotranspiration and incorporation into plant tissue. As the term implies, CU is water that is consumed and ultimately rendered unrecoverable for immediate reuse. The scientific literature is replete with explanations distinguishing ET and CU, in regards to both terminology and process (Burt et al., 1997; Allen and Jensen, 2016).

Because the main focus of this project was to quantify water consumed by agriculture, irrespective of underlying processes, estimation of ET and CU was undertaken as an identical pursuit without consideration of legal and technical distinctions. Therefore, the terms ET and CU are used interchangeably, with some exceptions for describing specific processes.

Reliable estimates of the amount of water transferred to the atmosphere by ET and CU are critical to support two major premises on which water sharing arrangements rest. The first basic premise is that the transferable fraction of a water right[1] is its historical, beneficial[2] CU. This quantity is determined by the proportion of annual crop[3] ET (less effective precipitation) that can be shown to have been met by the water right, for a representative period of years, using a representative period of hydrologic years. (Waskom et al., 2016). Secondly, another premise is that foregone diversions and reduced irrigations will "conserve" water and it will remain elsewhere in the delivery system, since lower ET is expected for 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 therefore been proposed to describe the proportion of historical, beneficial CU, originating from a water right because of diverting less than the historical rate to an irrigated cropping system (CAWA, 2008). Water sharing arrangements require reasonably accurate estimation of CCU to "shepherd" shared water and assure equitable negotiations.

For both pricing and planning purposes, a reasonable degree of confidence is needed in the baseline CU used for water sharing arrangements. The modified Blaney-Criddle method (1962) is used to quantify transferrable CU in water court (Walter, 2004; Montgomery, 2005). The primary crop CU determination method used in the Colorado Division of Water Resources (DWR) Decision Support System (http://cdss.state.co.us/Pages/CDSSHome.aspx) StateCU model is the modified Blaney-Criddle method (Colorado DWR, 2011), but the original Blaney-Criddle is also used in StateCU for high mountain meadows

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[1] 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.

[2] 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. Similar evaluation of water rights may be applied to other administrative structures that may use shares or contracts.

[3] Multi-year crop sequences are often used to characterize historical CU because most farmers will have rotated through multiple crops, such as alfalfa and corn or wheat.

(CDWR, 2010). Another common approach for estimating CU and CCU uses is 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 conducted to estimate the amount of transferrable CU made available by the purchase of water rights from approximately 40,000 acres near South Park, Colorado. These results have been extrapolated to other locations and scales to estimate CU and CCU for grasses with the original Blaney-Criddle methodology in the Western Slope river basins. Although the Denver Water High Altitude coefficients were developed at elevations greater than 6,500 ft, they have also been adapted at lower elevations under substitute water supply plans. Using these coefficients, CCU is quantified 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). There are noted inconsistencies and dissimilarities, however, when characterizing CU in other regions, such as the Upper Gunnison (Smith, 2008; Juday et al., 2011), which was one region of study for this project.

The Colorado Water Institute (CWI) undertook this project to address a recognized need for methods that acquire data at geographically large scales characterized by spatial variability. The need for greater accuracy in quantifying CU and CCU over large expanses is important for water resources planning, water sharing, and water regulation (Allen et al., 2011). This data is also needed to build equitable agreements under which agricultural water users forgo diversions, reduce irrigation, and transfer water. One critique of using crop-coefficient approaches for estimating CU and CCU is that these methods are always to some degree tied to local hydrometeorological conditions, making their applicability limited across larger regions. This is particularly problematic on the Western Slope, where most irrigated grass hay fields and pastures are scattered over hundreds of thousands of acres and weather stations are not abundant. Even in localized conditions, significant variation in CU has been observed. For instance, in the Upper Gunnison River Basin, which is a relatively small region of irrigated agriculture relative to the overall irrigated acreage of the Western Slope, a 5-year lysimeter study reported May, June, and July rates ranging from 3.79-8.22, 5.33-9.63 and 4.43-9.33, respectively, from nine lysimeters (Juday et al., 2011). Imprecise monitoring and measuring of CCU has also 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; CDWR, 2005). 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.

Due partly to the lack of other verified methods, the shortcomings of current CU estimation methods have been accepted. Nevertheless, a growing chorus of proponents argue that the successful operation of broad water-sharing programs involving agriculture will require a better approach to cost-effectively

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[4] Lysimeter-derived crop coefficients, originating from actual field mass-balances in the region of interest, yield more accurate results than using standardized crop coefficients.

manage and monitor CU and CCU across large and administratively decentralized areas (Jones and Colby, 2012; URS, 2014). Reliable assessment of CCU is also crucial because of the nature of temporary arrangements where the net economic benefits 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 sharing programs, a fair baseline is needed to measure the amount of water being conserved by fallowing, reduced, or partial-season irrigation. As the pressure to share water on the Colorado River increases, interest in accurately quantifying CU rates by crop, parcel, and region will increase.

1.1 Water Sharing Through Water Banking

This project incorporated sites that are currently under study for the Water Bank Workgroup[5]. 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, although CRS Title 37 under “Water and Irrigation” (§37-80.5-104.5) contain provisions stating “[u]pon request by a water conservancy district or water conservation district, the state engineer shall promulgate program rules necessary or convenient for the operation of a *water bank* within the division in which such district is located.” The statute contains a notable limitation that “[t]he rules shall authorize, facilitate, and permit the lease, exchange, or loan of ***stored water*** within a water division.” and that “[t]he ***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” (emphasis added).

The Water Bank Workgroup holds the position that the water bank approach could be adopted in targeted locations on the Western Slope as part of the demand management component of a contingency plan to prevent Lake Powell from declining below minimum power levels. In the long term, guided water markets or water banking could operate to prevent shortages under the Colorado River Compact or to allow Colorado water users to weather regional shortages. A water banking approach 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 Water Use by Alfalfa and Grass Hay Under Water-Sharing Programs

The total amount of irrigated land and water supply on the West Slope that could occasionally sustain limited irrigation (and therefore potentially participate in water banking) has been assessed previously as part of the Colorado River Water Bank Phase I Feasibility Study (Natural Resources Consulting Engineers, 2012). This assessment, suggested a focus on irrigated alfalfa fields, grass hay fields, and pastures. A total

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[5] The Water Bank Workgroup includes the Colorado River District, The Nature Conservancy, Front Range Water Council and the Southwestern Water Conservation District

of 92,510 acres of alfalfa and 623,295 acres of grass pasture on the Western Slope were reported as a baseline for irrigated lands potentially suitable for participation in water-sharing programs. The focus on alfalfa and grass pasture[6] is explained by the fact that these crops constitute most of the agricultural water use on the West Slope, and can withstand occasional limited irrigation in some areas without significant long-term effects. Recent studies of alfalfa fields 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). It is important to note that these studies were conducted in locations where soil types were favorable to strong root structure development.

Table 1.1. Characteristics of alfalfa sites used to evaluate impact of limited irrigation on forage yield on the western slope of Colorado under Phase II-B of the Colorado River Water Bank Feasibility Study (Jones, 2015).

Location	*County*	*Elevation (ft)*	*Annual Rainfall (in)*	*Soil Texture*	*Growing Season (days)**
Fruita	Mesa	4,527	8.8	Silty clay loam	173
Eckert	Delta	5,567	12.5	Loam	166
Yellow Jacket	Montezuma	6,900	16.0	Loam	136

*Growing season length estimated using the *Western Regional Climate Center* freeze-free (-2.2˚C) season probabilities.

Reduced irrigation of grass fields, was identified as a possible component of a water banking program because grass root systems in some regions are shallower than those of alfalfa crops, and thus less likely to tap groundwater and affect other return flows and water rights. On the other hands, shallower root systems make it more difficult for plants to recover from periods of stress, and there are large differences in drought tolerance between grass species and varieties (Orloff et al., 2014).

From the above total acreage, lands were identified that had water rights with appropriation or adjudication dates prior to 1929. Water supply limited consumptive use (WSCLU; see next section for definition) estimates were then made for conditions during a representative period of hydrologic years. The maximum potential water 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 Lake Powell (Paulson, 2012). Because the above amounts will vary depending on the level of participation by qualifying irrigators, and implementation of deficit or partial-season irrigation on participating irrigated lands, further scenario analysis was performed and reported elsewhere (Paulson, 2012).

1.3 Potential Consumptive Use, Actual Consumptive Use, Irrigation Water Requirement and Water Supply Limited Consumptive Use

The concepts of *potential* evapotranspiration (PET) and *potential* consumptive use (PCU) are useful starting points for “baseline” quantifications of CU. It must be understood that both PET and PCU are *potentially* achievable when ample water is available and crops experience no stress. Moreover, these

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[6] 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.

rates are often developed through lysimeter studies and are therefore designed to describe idealized irrigation conditions. Another closely related concept is the Irrigation Water Requirement (IWR), which in the StateCU model describes the amount of water required from surface or groundwater diversions to meet crop consumptive needs, and is calculated as PET or PCU less effective precipitation and stored winter precipitation. Obviously, using PET, PCU, or IWR as a baseline for historical CU under actual conditions will overestimate the amount of sharable water expected under water conservation programs, since most crops in Colorado are not irrigated in accordance with the rigorously scheduled conditions that characterize lysimeter studies. The operative question is: How significant is the difference between *potential* and *actual* CU when it comes to developing water sharing arrangements?

Of more practical use as a baseline for quantifying actual historical ET or CU at the field-scale, limited by water availability, is *water supply-limited* CU (WSLCU), based on water *actually* available and *actually* used by crops during the growing season. Because WSLCU is intended to reflect *actual* conditions, it is comparable to *actual* CU (ACU) or an agronomic analog, *actual* ET (AET). A reasonable alternative means of defining CCU, therefore, is proposed below:

$$CCU = (ACU_{ref} – ACU_{trt}) – P_{eff} = (AET_{,\,ref} – AET_{,\,trt}) – P_{eff} \qquad (1.1)$$

where ACU_{ref} and AET_{ref} are the ACU and AET of an accepted historical reference (ref) condition, ACU_{trt} and AET_{trt} are the ACU and AET of the treatment (trt) condition required in the water sharing contract and P_{eff} is effective precipitation[7]. The above formula could be used on a daily, weekly, monthly, seasonal or annual basis, depending on the criteria of the agreement.

1.4 Traditional Approaches for Assessing Actual Consumptive Use

The methods described in this section are often used to develop baseline assessments of CU, but may have limited applicability as the spatial areas they are intended to represent gets larger.

Reference Crop Models. This approach is based on using one of the many reference CU models, generally the upper range of CU. 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 while updated models such as the Kimberly-Penman (Wright, 1982), Penman-Monteith FAO-56 (Allen et al., 1998) or ASCE Standardized Reference Evapotranspiration (ASCE-EWRI, 2005) equations have been adopted more widely. These updated reference crop models are based on a greater number of hydrometeorologic variables, the inclusion of which is expected to provide closer estimates of ET and CU for reference crops (alfalfa and

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[7] Effective precipitation must be subtracted because it is understood that any CU or ET attributable to natural rainfall cannot be transferred, since natural precipitation occurs irrespective of irrigation. The StateCU model, for example, calculates the crop potential evapotranspiration and then subtracts effective precipitation using historical precipitation records to estimate the consumptive irrigation water requirement. The method used by StateCU for estimating effective precipitation is the SCS TR-21 Method.

grass)[8]. These estimates, however, are still calibrated to disease-free, well-fertilized, extensive surface[9], and unlimited water conditions. As such, they achieve near-full crop production rates, under optimum conditions and not generally WSLCU. The State of Colorado's Consumptive Use Model (StateCU), for example, uses reference crop models.

Reference crop models then use adjustments called crop coefficients (K_c) to estimate PET for other crops that exhibit canopy, crop, albedo, stomatal and aerodynamic characteristics different than alfalfa or grass. A simple reference crop formula is: $PET_{ref} = K_c(PET_{crop})$. The accuracy of reference crop models depends upon the crop coefficient to correct represent crop types and maturity stages. Output from these models is also bound to the extent that local weather station data can be extrapolated to other locations (Engman, 1995). Using only temperature data, as the Blaney-Criddle model does, for example, has been demonstrated to give significantly different predictions as compared with ideal lysimeter measurements (Doorenbos and Pruitt, 1977), let alone actual conditions. 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 bound to the same effect of extrapolation.

Pertinent to this study, tabulated values of numerous coefficients may not apply well to the agro-climatological conditions of Western Slope. Most importantly, reference crop models cannot capture the specific field-level impacts, such as reduced production under less irrigation reductions, that would affect ACU during real water sharing arrangements.

Water Delivery-Based Approach. This approach is based upon water delivery data (diversion records) collected by gauges installed at headgates where agricultural water is diverted. The State of Colorado Division of Water Resources requires measurement of these diversions, which are subsequently used to determine historical beneficial CU and irrigation water requirement (IWR) by examining diversion records, conveyance efficiencies, application efficiencies, and soil moisture interactions (Waskom et al., 2016) for appurtenant parcels. This approach is used in quantifications 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. Additionally, considerations of conveyance and irrigation efficiency are subject to basic assumptions.

For instance, furrow and flood irrigation is regarded as 45% efficient while canal efficiency is assumed to be 80% efficient in the StateCU model. As such, these records may also not be accurate to the degree expected in future water-sharing transactions (McIntire, 1970; USGS, 2005). Diversion measurement systems are always undergoing improvement in terms of automated control and delivery management,

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[8] 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.

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

but the contribution of seepage, tailwater, return flows and other incidental sources of irrigation to crops will always be difficult to account for based on water deliveries at the headgate.

Irrigation Water Balance Monitoring. An irrigation water balance (IWB) approach can be used to derive point-based AET rates by monitoring water inputs and outputs to a soil root zone (Burt, 1999; Andales et al., 2011). 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 an equation akin to the following:

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

where D_c and D_p are soil moisture deficits[10] 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.*

1.5 Remote Sensing as a Method for Assessing Actual Consumptive Use

Given the limited spatial accuracy inherent to traditional methods of baselining CU, a reliable method of describing ACU is interest to water sharing program participants. Satellite observations and remote sensing have now made possible the ability to map ACU across expansive regions where hydrometeorologic data is limited, thus reducing or even eliminating the need for detailed irrigation water balances (Tang et al., 2009; Peel and McMahon, 2014). Application of higher resolution satellite data to evaluate ACU rates for irrigated agriculture in the western states is possible with improving algorithms, and reduced errors are associated with models that use land surface temperature (Anderson et al., 2012; Cuenca et al., 2013).

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 scan the earth

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[10] 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)

surface repeatedly. Earth observation satellites range from low resolution (e.g., AVHRR, MODIS, ASTER) to moderate resolution (e.g., Landsat, Sentinel, SPOT etc.) to higher resolutions available with commercial hyperspatial satellites (e.g., Ikonos, Worldview, GeoEye, Quickbird) and hyperspectral satellites (Hyperion). While data from satellites like MODIS, Landsat, and Sentinel 2a can be obtained at no cost, higher resolution data and imagery must be purchased. The common free-of-charge Landsat EOS bands, resolutions and revisit periods, are described below in Table 1.2.

Table 1.2. Landsat satellite descriptions.

Satellite Platform	*Operating Period*	*Revisit Time*	*Sensor*	*Band Number*	*Band*	*Bandwidth (nm)*	*GSD (m)*
Landsat 5	Mar 1984 - Nov 2011	16 days	MSS	1	Green	500 – 600	68 × 83*
				2	Red	600 – 700	68 × 83*
				3	NIR-1	700 – 800	68 × 83*
				4	NIR-2	800 – 1100	68 × 83*
			TM	1	Blue	450 – 520	30
				2	Green	520 – 600	30
				3	Red	630 – 690	30
				4	NIR	760 – 900	30
				5	SWIR-1	1550 – 1750	30
				6	LWIR	10400 – 12500	120
				7	SWIR-2	2080 – 2350	30
Landsat 7	Apr 1999 - present	16 days	ETM	1	Blue	450 – 520	30
				2	Green	520 – 600	30
				3	Red	630 – 690	30
				4	NIR	760 – 900	30
				5	SWIR-1	1550 – 1750	30
				6	LWIR	10400 – 12500	60
				7	SWIR-2	2080 – 2350	30
				8	Pan	500 – 900	15
Landsat 8	Mar 2013 - present	16 days	OLI	1	Coastal	433 – 453	30
				2	Blue	450 – 515	30
				3	Green	525 – 600	30
				4	Red	630 – 680	30
				5	NIR	845 – 885	30
				6	SWIR-1	1560 – 1660	30
				7	SWIR-2	2100 – 2300	30
				8	Pan	500 – 680	15
				9	Cirrus	1360 – 1390	
			TIRS	10	LWIR-1	10600 – 11200	100
				11	LWIR-2	11500 – 12500	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 also be deployed to collect remotely sensed observations. Such technology is currently limited, but is being utilized more for agriculture given that observations can be made more regularly and at finer scales than satellite observations offer.

1.5.1 Estimates of Actual Consumptive Use with Remote Sensing

Innovative and improved measurement of 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 can better represent ACU since they are much closer to actual conditions in 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 (Cuenca et al., 2013) and point-based measurements are too costly to implement (Tang et al., 2009). Monthly ACU estimates for side-by-side conditions could serve as the basis estimating CCU at the larger spatial scales of the Colorado River and its tributaries on the Western Slope.

1.5.2 Remote Sensing Approaches for Assessing ACU

Sensing techniques to estimate ACU use two basic approaches described by Gowda et al. (2008): 1) land surface energy balance, and; 2) reflectance-based coefficient approach. More complex ET methods may not necessarily more accurate than empirical approaches (Kalma et al., 2008), but the operative point is that they can estimate ET on a geo-spatial basis over large and diverse coverage areas and for the land surfaces being evaluated.

1.5.2.1 Land Surface Energy Balance

Kalma et al. (2008) provides a comprehensive review of methods which use remotely sensed surface temperature and energy data to derive ACU estimates. These approaches are based on the law of conservation of energy. On land, the net energy originating from solar radiation, 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:

$$R_n = H + G + LE \tag{1.3}$$

The concept of using an energy balance to determine the movement of heat on 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 the emittance of radiation and absorption of heat by water are described in detail by other published literature sources (Kustas and Norman, 1996).

1.5.2.2 Reflectance-Based Coefficient Approach

The reflectance-based coefficient approach is an empirical (based on observations) approach using measured reflectance data in specific bands to calculate a vegetation index (VI), which distinguishes vegetative biophysical properties (Viña et al., 2011) and then related to ACU for actual field conditions (Seevers and Ottmann, 1994; Rafn et al., 2008; Senay et al., 2011). Spatial characterization of VI is not as computationally intensive and can be done with remote sensing platforms that do not take observations for the thermal band. On the other hand, since thermal band is not used, immediate and short-term stresses may not be captured.

The reflectance-based coefficient concept is based on using coefficients (K_{cr}) that correspond with geospatially referenced VI. Determination of AET is then done by multiplying K_{cr} by ET_r from the nearest weather station. Several previous studies have developed VI-K_c (or K_{cb}) functions for different crops over different areas. These include relationships developed for alfalfa (Singh and Irmak, 2008). Remote sensing based crop coefficients can be used for grain, non-grain and forage crops (Neale et al., 2003). The reflectance-based coefficient approach does not capture soil evaporation because it is modelled based on VI mostly capturing vegetation and biomass changes, so modifications have been performed to account for other background effects (Rondeaux et al., 1996; Huete, 1998; Jiang et al., 2006).

The most common VI is the Normalized Difference Vegetation Index (NDVI). 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. The NDVI was developed by Deering (1978), and is calculated as follows:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}} \tag{1.4}$$

where NIR is the percent reflectance of light in the NIR band and R is the percent reflectance of light in the red band. The value range of NDVI is -1 to 1 where healthy vegetation generally falls between 0.20 to 0.80, and bare soil achieves a value of approximately 0.10.

1.5.3 Remote Sensing Models for Assessing ACU Using Energy-Balance Approaches

Remote sensing-based algorithms are continually being improved to estimate magnitudes and trends in ACU. Remote sensing techniques have proven reliable for assessing ACU at different spatio-temporal scales (Jackson et al., 1984; Gowda et al., 2008). Archived imagery from these satellites may also be used to assess historical ACU, and perhaps find applicability to water-sharing programs across large regions (Wulder et al., 2016). Remotely sensed ACU assessments can also be performed on side-by-side fully-irrigated and partially-irrigated fields, thereby allowing real-time comparisons between fully and limited irrigation regimes on agricultural fields.

Estimating ACU by energy balance with remotely sensed observations involves 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 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 and other land-based parameters like surface emissivity and long-wave radiation. 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 Equation 1.3.

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

Computational approaches using the energy balance to estimate AET were pioneered with the Surface Energy Balance Algorithm for Land (SEBAL) model (Bastiaansen et al., 1998). 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 documented accuracies ranging from 65% to 97.3%, with an average accuracy of 81.8% (Trezza et al., 2002). Since remote sensing provides a snapshot at a particular time of 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). Because SEBAL may underestimate ET in arid and semi-arid regions (such as much of Colorado) where advection is common, 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.

Another 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 (Allen et al., 2007, Trezza et al., 2002). 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). Instead of assuming all available energy consumed for ET at the cold pixel, it assumes cold pixel ET equal to 1.05 times that of alfalfa reference ET calculated from nearest weather station. Similarly, for the hot pixel, instead of assuming ET to be negligible, it uses 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. 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. 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, AET estimations will be performed on the Google Earth Engine. The tool can be viewed currently at the website: http://eeflux-level1.appspot.com(accessed March 23, 2017).

A further modification of SEBAL and METRIC is the Remote Sensing of Evapotranspiration (ReSET) model that explicitly considers the spatial variability in weather data (Elhaddad and Garcia, 2008; Elhaddad and Garcia, 2011). 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). ReSET can be run in either a calibrated or 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 modes, the internal calculations are rasterized such that each pixel is modeled based on 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 possible the incorporation of 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. The ReSET model was used in the Sacramento Valley of California (2008 and 2009 growing seasons) and western Colorado (2006 growing season), but is not part of an operational USBR program Eckhardt (2013).

The estimation of ET for periods longer than daily requires interpolation between consecutive overpass daily ET estimates. While originally SEBAL uses linear interpolation, METRIC uses 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 consecutive overpass dates uses interpolation that considers spatio-temporal variability in weather data (Elhaddad and Garcia, 2008).

1.5.3.2 Other Energy Balance Models

Other energy balance models consider canopy and soil fluxes separately, and multi-layer models 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.

1.6 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 gather observations of reflectance in the visible and NIR bands, along with land surface temperature.

1.7 Challenges Using Remote Sensing on the Western Slope of Colorado

There is still a gap between research studies and practical application of remote sensing techniques for water management (Ambast et al., 2002). The Western Slope of Colorado is one such place where this gap is evident, due to 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. Specifically, corrections to the standard atmospheric lapse rate may be needed to account for the effect of elevation on the energy balance. The standard atmospheric lapse rate of the International Civil Aviation Organization (ICAO) is 3.56 °F per 1,000 ft, but recommendations are made to use different lapse rates for elevations less than 5,740 ft elevations above 5,740 ft (Allen and Snyder, 2011) or even unique lapse rates for each Landsat image (Eckhardt, 2013). To perform these corrections, a digital elevation model (DEM) of the Landsat scene must also be utilized in concert with the chosen energy balance model, requiring additional data processing expertise.

2 Project Objectives

One strategy that is proposed to increase water in the Colorado 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 initiating irrigation only at 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 easily implementable alternative to full 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 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

The first objective was to compare the performance of the ReSET model with other methods, such as irrigation water balances or hand-held radiometric measurements. The purpose of this objective was to evaluate ReSET under conditions where it has not been tested. 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, but ReSET was developed on the Eastern Front Range of Colorado and has been applied to corn and alfalfa fields. Additionally, previous ReSET evaluations were conducted for energy-limiting conditions of crop growth, rather than soil water-limiting conditions where the canopy is not homogenous and therefore the "big-leaf" assumption may not hold. The "big leaf" assumption proposes that the plant canopy is a singular source of both latent and sensible heat at a given height and temperature. Under this assumption, soil evaporation is assumed to be negligible in some models (Cleugh et al., 2007), although it has been shown that where the vegetative cover is lower, the ground heat flux (G) estimation should include the effects of evaporation from the soil surface (Allen, 1998). Thus, the performance of ReSET and the energy-balance approach is valuable for assessing ACU under irrigation stress conditions under for exposed soil may be more of an issue.

2.2 Objective 2: Apply an Energy-Balance Approach (ReSET) to Archived Multi-Spectral Landsat Observations 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 the second objective was to assess historical ACU using another method not typically employed for Western Slope agriculture.

2.3 Objective 3: Compare Crop ACU Derived an Energy-Balance Approach (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 data from weather stations to estimate CU for irrigated parcels. The StateCU Documentation provides a complete description of the model and its capabilities at http://cdss.state.co.us/Modeling/Pages/ConsumptiveUseStateCU.aspx (CDWR, 2008; CDWR, 2011). The purpose of this objective was to compare modeling results typically used for water transactions against methods that employ remote-sensing.

3 Methods

3.1 Study Sites in the Gunnison Basin

Evaluations were performed at one grass pasture site and one alfalfa site in the Lower Gunnison area (Uncompahgre Valley), and another grass pasture site in the Upper Gunnison (Tomichi Creek).

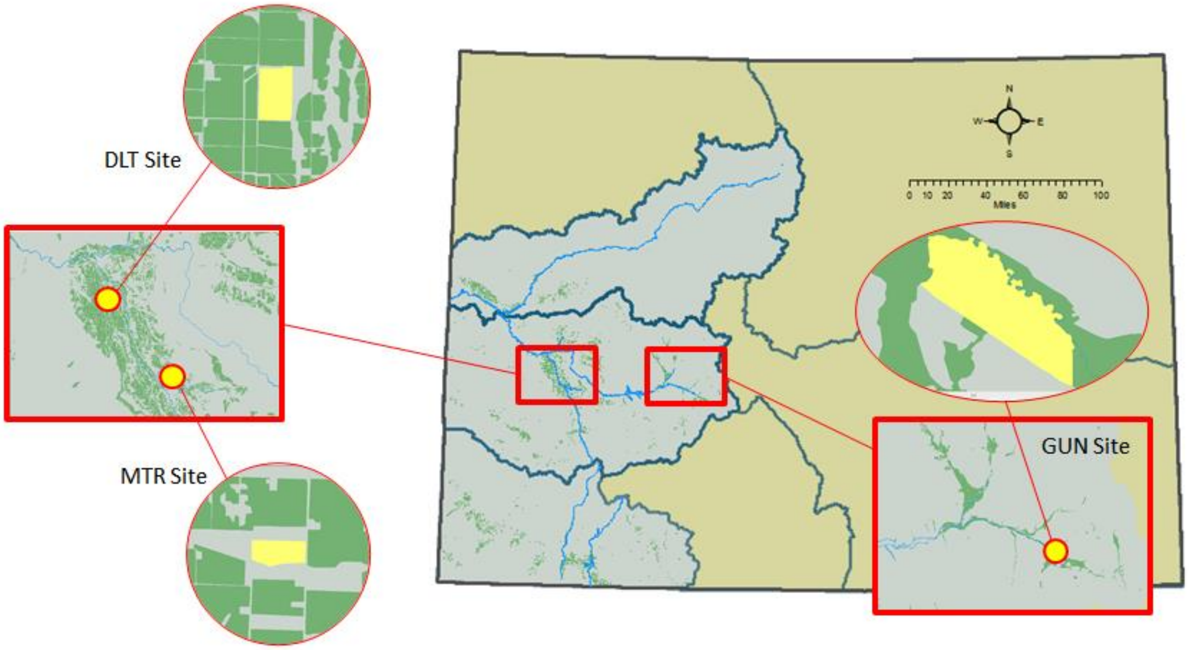

Figure 3.1. Map with Montrose, Delta, and Gunnison field sites highlighted.

3.1.1 Grass Hay/Pasture Site #1 (Montrose, CO)

One of the grass hay/pasture sites is in Montrose, Colorado (MTR) 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 3.2) is 14.50 ac (5.87 ha), was divided into two treatments: 1) full irrigation (REF) replicating irrigation conditions under typical management and historical water diversion, and; 2) reduced (TRT) irrigation replicating a potential water bank scenario where irrigation is applied for part of the season 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 MTR reference plot (REF-MTR) was irrigated throughout the season, while the reduced irrigation plot (TRT-MTR) received no water after August 14 in 2015[11] and after May 12 in 2016. 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*), chicory (*Cichorium intybus*) and some volunteer alfalfa (*Medicago sativa*) was also noted. Plant species

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[11] 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.

composition and cover data was collected using a modified step-point method (Owensby, 1973). Soils are described by the NRCS Soil Survey Geographic (SSURGO) Database as Loutzenheiser silty clay loam. Available moisture in these soils is estimated at 19%, 16%, 16%, 17% and 17% in the profiles 0-4”, 4-13”, 13-36”, 36-47” and 47”-65”, respectively. Soil analyses from several cores (0-12”) on the REF-MTR and TRT-MTR fields was also conducted by Midwest Laboratories (Omaha, NE). Results of the lab analysis were used for irrigation water balance calculations (Table 3.1).

Table 3.1 Soil characteristics at the Montrose (grass hay/pasture) field site.

Irrigation	*Abbrev*	*Area*	*Field Capacity*	*Wilting Point*	*Available Moisture*	*Textural Class*
Full	REF-MTR	6.3 ac	31.29 %	17.47 %	13.82 %	Clay
Full	REF-MTR	6.3 ac	26.62%	11.61%	15.01%	
Full	REF-MTR	6.3 ac	27.10%	11.59%	15.51%	
Partial-Season	TRT-MTR	8.2 ac	33.33 %	12.44 %	20.89 %	Clay Loam
Partial-Season	TRT-MTR	8.2 ac	30.57%	21.49%	9.08%	
Partial-Season	TRT-MTR	8.2 ac	24.79%	14.16%	10.63%	
Partial-Season	TRT-MTR	8.2 ac	33.98%	14.02%	19.96%	
Partial-Season	TRT-MTR	8.2 ac	37.41%	14.88%	22.53%	

Figure 3.2. Montrose (MTR) field site layout with instrumentation.

3.1.2 Grass Hay/Pasture Site #1 (Gunnison, Colorado)

The other grass hay/pasture site is located east of Gunnison, Colorado (GUN) at approximately 38.458˚ N and 106.634˚ W, elevation ~8030 FAMSL. This site is historically wild-flood irrigated using grass swales and temporary dams propped up by polypropylene tarps. Irrigation water is suppled from a shared diversion structure along the Coats Brothers Ditch taking water Tomichi Creek. The study site (Figure 3.3) is 178 ac (72 ha). No treatments were imposed on this site in 2015. In 2016, the entire 178 ac entered 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 of the field suggested that certain portions of the field would receive much less surface and sub irrigation than others. The topographical variation allowed for a diversity of remote-sensing derived ACU estimates.

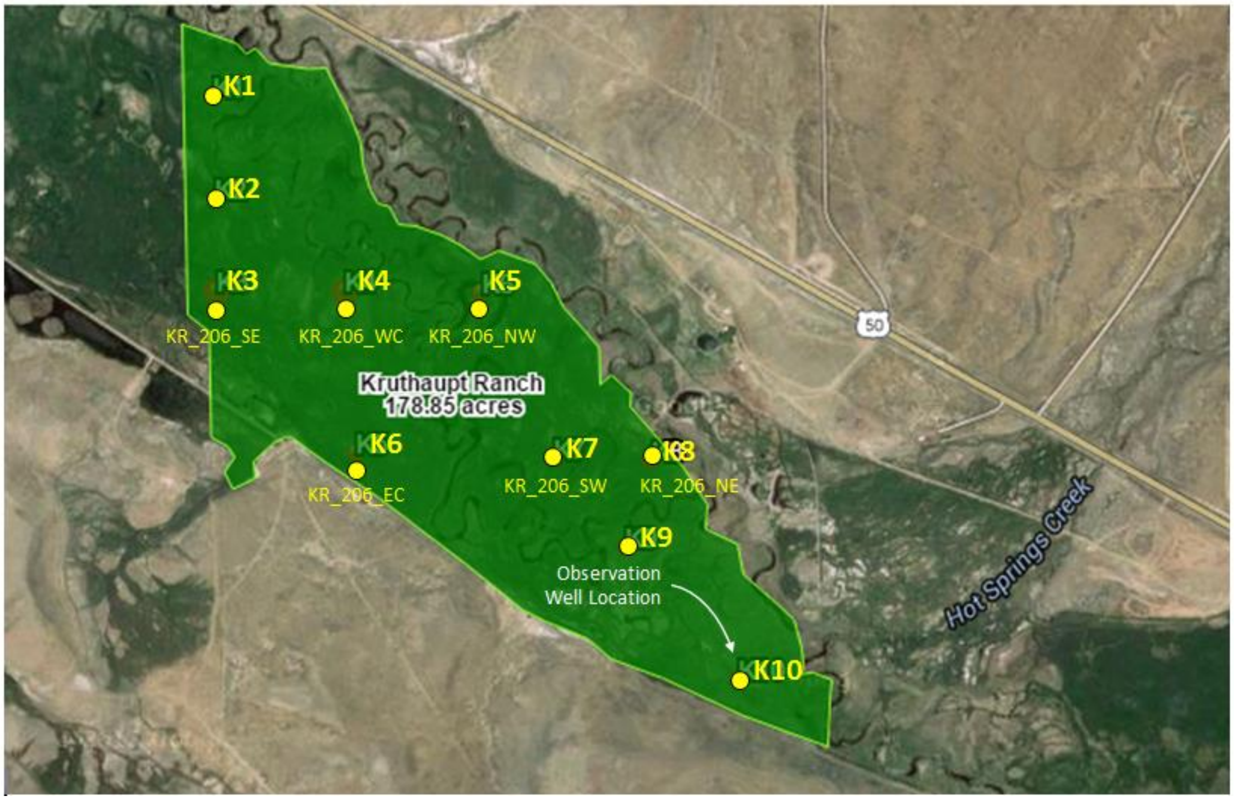

Figure 3.3 Gunnison (GUN) field site layout with instrumentation.

The following table is a list of groundwater well locations and depths corresponding to Figure 3.3. Transducers were installed at the observation wells at K3, K4, K5, K6, K7 and K8.

Table 3.2. Groundwater observation well locations at the Gunnison, Colorado site.

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

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. Soils are described by the NRCS Soil Survey Geographic (SSURGO) Database as Gas Creek, Gold Creek and Irim slightly decomposed plant material. Soils and root zone on these fields are extremely shallow, underlain by river cobble. Available moisture in the field 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.

3.1.3 Alfalfa Site (Delta, Colorado)

The original project scope had planned to include a site in the Grand Valley. In particular, an existing site in Loma, Colorado was to be used where the instrumentation installed was similar to the MTR and GUN sites. However, the scope was modified because Landsat Path 35/Row 33 (which covers all of the Uncompahgre and most of the Grand Valley) does not happen to include Loma, Colorado. This exclusion of the Loma site from Landsat Path 35/Row 33 was not considered when the project proposal was written. Considerable extra time would have been involved in processing an additional Landsat path/row just for Loma, Colorado. Therefore, a substitute location was used in Delta, Colorado.

The Delta (DLT) site used is at approximately 38.664° N and -108.062° W, elevation ~5275 FAMSL located at 54616 Amber Rd, Delta, Colorado 81416. The DLT site was in corn-grain in 2014 and then planted to alfalfa in 2015. The site receives water from the Ironstone Canal. This site is being historically furrow-irrigated using gated pipe until 2014 when an overhead sprinkler-pivot system was installed in 2014. According to the pivot installer specifications, the field (Figure 3.4) is 71.5 ac (44.1 acres for the pivot and an assumed 27.4 acres for the arm), but field observations indicate that the actual irrigated acreage is about 69.3 ac. The timer data chart was provided by the manufacturer, indicating that the pivot is designed to apply water at a maximum of approximately 0.35 in per day.

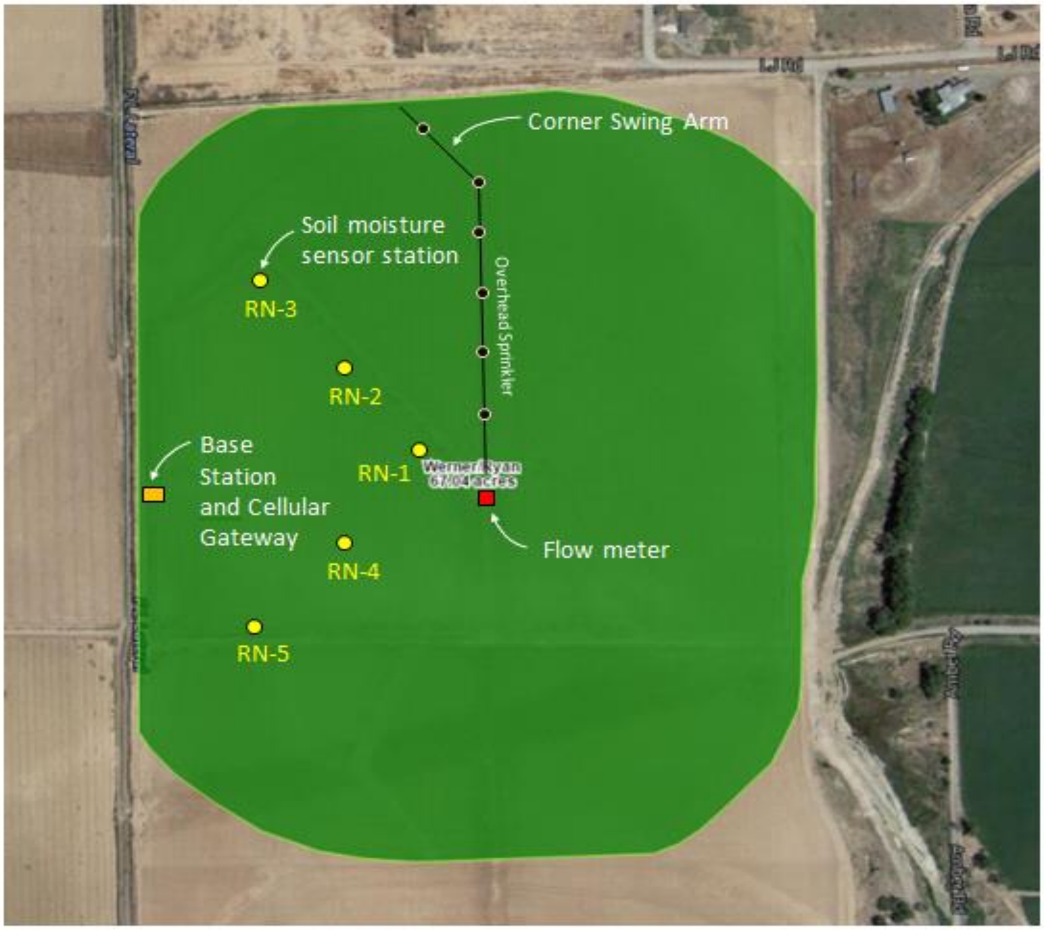

Figure 3.4. Delta field site layout with instrument locations.

Soils are described by the NRCS Soil Survey Geographic (SSURGO) Database as Mesa clay loam. Available moisture in these soils is estimated at 20%, 19%, 15%, 17%, 11% and 1% in the profiles 0-12”, 12-17”, 17-30”, 30-38”, 38”-44” and 44-80”, respectively. Soil analyses from two cores (4-8”) on the DLT field was conducted by the CSU Soils Testing Lab (Fort Collins, Colorado) and Midwest Laboratories (Omaha, Nebraska). Results of the lab analysis were used for irrigation water balance calculations (Table 3.3).

Table 3.3. 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
Full (RN-1)	2016	West	27.08%	9.73%	17.35%			
Full (RN-2)	2016	West	30.26%	11.50%	18.76%			
Full (RN 2)	2016	West	21.32%	9.25%	12.07%			
Full (RN-3)	2016	West	22.96%	8.06%	14.92%			
Full (RN-3)	2016	West	20.90%	8.75%	12.15%			
Average			**22.62 %**	**9.20 %**	**13.42 %**		**22**	**58**

3.2 Irrigation Water Balance Instrumentation

Irrigation, Precipitation and Tailwater. Irrigation water volumes diverted to the DLT an MTR sites were measured using McCrometer® McPropeller™ and SeaMetrics® EX800 flow meters, respectively. Irrigation water was not measured at the GUN site, given the practice of wild flood irrigation and the inability to define the actual closed field system. The MTR flow meter data was delivered to a CR206X data logger (Campbell Scientific, Logan, UT). The DLT flow meter was read weekly and recorded. Tailwater at MTR was recorded using a EZ Flow Nu-Way ramp flume (Welfelt Fabrication, Delta, Colorado) equipped with a stilling well, CS451 (Campbell Scientific, Logan, UT) pressure transducers and CR206X data logger. Flumes in these types of applications are estimated to have measurement accuracy of about ±15 percent. Precipitation was monitored with direct-read rain gauges at MTR and DLT and checked for accuracy against the daily record from the nearest CoAgMet station at www.coagmet.edu.

Soil Moisture and Electrical Conductivity at Montrose and Gunnison. Soil moisture was measured at MTR and GUN using CS655 volumetric content reflectometers (Campbell Scientific, Logan, UT) installed in 2015 at 6 in (150 mm) and 18 in (450 mm). These reflectometers measure volumetric water content, temperature and electrical conductivity. Data was collected from these sensors every 30 minutes using a CR206X datalogger. The MTR site is equipped with two (2) soil moisture sensing stations each in the REF and TRT fields, located at distances of 25% and 75% along the distance of the furrow in the center of each field. The GUN site has six (6) soil moisture sensing stations at locations representing low, middle and high points in the field to capture topographical variations.

Soil samples were taken periodically at the MTR using a Madera Probe (Precision Machine Company, Lincoln, Nebraska), for bulk density, gravimetric, and volumetric water content analysis to develop a calibration curve for the clay loam soils at the MTR site. Samples were oven-dried at 105 ◦C for 24 h, weighed, and volumetric water content (θ_v) was then computed based on the known core volume of 14.4 in^3. Periodic measurements of volumetric water content were also taken at the MTR site using a CPN 503DR Neutron Probe and 1.5 in Schedule 40 PVC access tubes. A correction equation available from the neutron probe manufacturer defined: $M = 3.611\times CR - 0.094$, where M = volumetric water content (in/ft) and CR = count ratio from the neutron probe.

Soil Moisture at Delta. The inclusion of DLT site introduced an unfortunate dissimilarity in soil moisture sensing approaches, given that the MTR and GUN sites were equipped with CS655 sensors, whereas DLT was already equipped with granular matrix tension sensors. Watermark™ (Irrometer, Riverside, CA) sensors were installed in 2015 at 12 in, 24 in and 45 in at the DLT site. Five (5) sensing stations were installed at the DLT site, at locations representing the inner, middle, and outer rings of the pivot coverage area. Rather than measuring soil moisture directly, the Watermark™ sensor effectively measures the soil matric potential (ψ_m) by monitoring water movement through the porous granular matrix when in good contact with the soil. Data was collected from the sensors every 30 minutes through the Irromesh™ node system. The Irromesh™ system delivers data using Zigbee® wireless connectivity to deliver data to an onsite base-station. The data is then conveyed to another cellular gateway device onsite that allows moisture readings to be accessible in real-time by both researcher and farmer. The data is accessed and stored in the Sensmit^{TM} cloud-based management platform.

Groundwater and Upflux. Subsurface movement of water is difficult to monitor in the field. Nevertheless, instrumentation was installed to assess the potential upflux due to capillary rise (U) and loss of water to deep percolation (DP). Because a 1-dimentional IWB model was to be applied at the sites, lateral flow of water was not measured. The occurrence of U and DP were assessed relative to the dynamic depth of the groundwater table, which was recorded using 1.0" PVC observation wells equipped with Level Logger Junior pressure transducers (Solinst®, Georgetown, ON) at the MTR and GUN sites. The transducers installed in the observation wells were corrected for barometric pressure using a separate onsite barometric logger (Solinst®, Georgetown, ON). Groundwater levels were periodically verified using a Model 101B Water Level Measuring Tape (Solinst®, Georgetown, ON). At the DLT site, regular observation well measurements using the 101B Tape indicated no groundwater.

3.3 Separate Evaluations Using Atmometers

An alternative to complex ET prediction equations or detailed field evaluations is to use an atmometer, which is an inexpensive, easy to understand, and require little maintenance aside from periodic refilling (Broner and Law, 1991; Alam and Trooien, 2001). The ETgage Company (Loveland, Colorado), supplies a green canvas #54 cover to simulate alfalfa-based reference ET, and a denser canvas #30 cover is used to simulate ET from a grass reference canopy. Atmometers were installed at the DLT, GUN and MTR sites. The accuracy of atmometers using the #54 alfalfa canvas was compared to the ASCE Standardized Alfalfa Reference ET Equation and exhibited daily underestimation 88% of the time, with an average underestimation of 0.05 in d^{-1} (Gleason et al., 2013). These authors noted that underestimation reported by the atmometer was most frequently correlated with higher wind speeds.

3.4 Separate Evaluations Using Large Aperture Scintillometer

A Kip and Zonen Large Aperture Scintillometer (LAS) was installed to measure sensible heat flux (H) at the Montrose site. 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. The 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) (Moene et al., 2005). This equipment will not be discussed further, however, as the data from its use was inconclusive.

3.5 Study Period

The DLT (alfalfa) site was fully equipped for soil moisture, irrigation flow and groundwater monitoring by May 2015 and has been active continuously since then. The MTR (grass hay) site was fully equipped for soil moisture, irrigation flow, tailwater, and groundwater monitoring by July 2015[12] and has been active

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[12] Soil moisture monitoring equipment was installed in June 2015

continuously since then. Soil moisture and groundwater monitoring instrumentation was installed at the GUN (grass hay) site on August 7, 2015 and has been active continuously since then.

3.6 Estimating ACU with ReSET

The energy balance approach was selected, given the reduced errors in estimation that are associated with models using land surface temperature. The ReSET model (Elhaddad and Garcia, 2011) was chosen for the study because the expertise for running its applications already existed at Colorado State University (CSU) 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.

3.6.1 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.

3.6.2 Weather Data

Weather data was downloaded from Colorado Agricultural Meteorological (CoAgMet) network of weather stations (www.coagmet.com). These weather stations gather meteorological data for air temperature, relative humidity, vapor pressure, solar radiation, wind speed and precipitation. Throughout 2016 and 2015 growing seasons, there were nine functional point weather stations, while from 2011-2014, there were four functional weather stations. While most of these weather stations are in Uncompahgre and Grand Valley, the Gunnison area had one weather station installed in 2015.

3.6.3 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 consider the net cooling of temperature aloft with elevation. Thus, a digital elevation model (DEM) over the area was 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 surface temperature. Cooler temperatures at higher elevations may affect the energy balance and result in higher AET rates being predicted. 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:

$$T_{corr,s} = (DEM - x) \times 0.0065 + T_s \qquad (3.1)$$

Where, $T_{corr,\,s}$ is the corrected surface temperature, T_s is the original surface temperature, DEM is the elevation at any pixel and x is the average elevation of the area of interest in the image.

3.6.4 Crop Cover Data

Crop cover data for alfalfa and grass pasture crops was collected in the Uncompahgre 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 Uncompahgre and Grand Valley are classified as “other pastures” in the Cropscape map, therefore, for Uncompahgre and Grand Valley, ground-truthed data was used (collected visually by intern Carter Stoudt). 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.

3.7 Determination of Daily ACU Using ReSET

The approach used to determine daily ACU using Landsat data followed the ReSET Manual (Elhaddad and Garcia, 2008) with ERDAS IMAGINE software (Hexagon Geospatial, Madison, AL). The ReSET calibrated mode involving inputs of spatially-distributed reference ET (instantaneous as well as daily) and wind speed maps 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 for the 2015 and 2016 evaluations. These spatially distributed maps were created by determining both hourly and daily (24-hour) alfalfa reference ET from the Penman-Monteith method at each weather station, utilizing wind speed data from each weather station, and spatially interpolating these using inverse distance weighting. Daily reference ET at each weather station was calculated by summing up the hourly reference ET for the whole day rather than using daily time-step, because substantial changes in wind speed, humidity, and cloudiness during the day can affect average daily estimates of the parameters of the Penman-Monteith method. 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 an image histogram, conditioning top candidate pixels to be in a cluster of eight 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 MTR imagery, but not for GUN imagery because of the complex topography (mountainous), soil-mineral depositions, network 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 the GUN 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_r) computed from weather station data at the time of the satellite overpass.

$$EToF=ET_i/ET_{ref} \tag{3.2}$$

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:

$$ET_d = EToF \times ET_{d,ref} \tag{3.3}$$

where $ET_{d,\text{ ref is}}$ the daily grass reference ET calculated from the 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, the correction ratio (γ) method, as described by Elhaddad and Garcia (2008) and given below, was implemented.

$$\gamma= [(EToF_i-EToF_{i+1})/N] \tag{3.4}$$

$$ET_{d,i}=[EToF_i-(\gamma*T)]*ET_{d,ref} \tag{3.5}$$

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

The evaluation of ReSET AET assessments was done using three separate criteria. The first evaluation criteria selected involved choosing fully-irrigated alfalfa fields in the study area (after specifically checking that they were not used as calibration/anchor points) and comparing ReSET estimates at those fields with reference alfalfa ET calculated from a weather station, like methods described by Eldeiry et al. (2016). This was done for both MTR and GUN imagery, on day(s) when crops were yet to reach full cover and the crop height was close to 20 in. It was evaluated whether the ReSET-estimated ET at the chosen fully-irrigated alfalfa field was reasonably close to alfalfa reference ET. The second evaluation criteria involved comparing the ET estimated from the irrigation water balance with ReSET-estimated ET. The third evaluation using measured estimates of H, Rn, and G were carried out only for the partial irrigation treatment plot at MTR 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.

3.8 MSR5 Hand-Held Radiometer Equipment

A ground-based level, a hand-held, multi-spectral radiometer (Model MSR5, CROPSCAN, Inc., Rochester, Minnesota) was used to measure surface reflectance in five spectral wavebands like 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. The radiometer position can be adjusted to various heights so, for example, the footprint image taken by the MSR5 at a height of 6.0 ft would be approximately 40 ft^2. 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, Massachusetts f) 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 based on a Normalized Difference Vegetation Index (NDVI) unique to the location being measured.

3.9 Estimating ACU with the MSR5 Using a Reflectance-Based Coefficient Approach

The MSR5 observations were used to calculate NDVI at different field positions. The goal of using the MSR5 was to develop a regression model that could relate a measurable reflectance-based variable. In this case, NDVI to a coefficient akin to K_c. However, the reflectance-based coefficient approach does not use a thermal band, so it may not be able to capture immediate crop stresses, and will only capture them when the stresses start to affect vegetation conditions. For instance, NDVI may decrease due to leaf rolling or stunted growth. Similar work has been performed for corn, soybeans, sorghum, and alfalfa by Singh and Irmak (2009), who developed the following model for irrigated alfalfa from 1,260 pixel values in southeastern Nebraska:

$$K_c = a \times NDVI + b \qquad \text{where a = 0.981 and b = 0.113} \qquad (3.6)$$

Equation 3.6 was used to derive a K_c based on NDVI for the alfalfa site at Delta. It is acknowledged that equation 3.6 may not perform as well in the Western slope of Colorado, since it was developed in agro-climatological conditions of Nebraska.

For the grass sites, a correction was applied to the calculated K_c. The correction procedure was to first use Equation 3.6 to obtain an alfalfa K_c and then adjust it using ratio of reference alfalfa ET to reference grass ET for the day of the MSR5 reading. Both reference ET values were obtained using the software program RefET V3 (Allen, 2008), which considers the grass reference to be a cool-season variety such as perennial fescue or ryegrass. This adjustment therefore provided a modified reference grass K_c. This modified reference K_c was subsequently used to calculate AET for grass at the Montrose and Gunnison sites by multiplying it by the alfalfa PET 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.

3.9.1 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 which 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, which affected the measurement of land surface temperature, this data is still being evaluated for later use. Idso et al. (1981) proposed the equation below:

$$CWSI = (dT_m - dT_{LL})/(dT_{UL} - dT_{LL}) \qquad (3.6)$$

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):

$$dT_{LL} = a + b \times VPD \qquad \text{where a and b are intercept and slope (Idso, 1982)} \qquad (3.7)$$

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

$dT_{UL} = a + b \times VPG$ where a and b are intercept and slope (3.8)

Equations 3.7 and 3.8 are non-water-stressed and non-transpiring baselines, respectively.

Jackson et al. (1981) developed a useful 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:

$$AET = (1 - CWSI) \times PET \tag{3.9}$$

While this approach has been utilized for several vegetative covers like corn, alfalfa, and turfgrass, the "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 our study area on the Western Slope. This need could apply to further research.

4 Results and Discussion

4.1 Irrigation and Management Observations

4.1.1 Irrigation and Management at Grass Hay/Pasture Site #1 (MTR)

Table 4.1 Full and partial irrigation plot dates at the Montrose (grass hay) field site (2015).

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)

Table 4.2. Full and partial irrigation plot dates at the Montrose (grass hay) field site (2016).

Reference Irrigation Field (6.3 ac)	*Reduced (Partial-Season) Irrigation Field (8.2 ac)*
April 27, 2016	April 21, 2016
May 14, 2015	May 11, 2016
July 15, 2016	
July 21, 2016	
July 30, 2016	
August 5, 20.16	

The MTR 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.

4.1.2 Irrigation and Management at Grass Hay/Pasture Site #2 (GUN)

Soil 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.

4.2 Objective 1: Actual Consumptive Use Derived from Irrigation Water Balance, Energy-Balance, and Reflectance-Based Approaches

Objective 1 focused on comparing the results of three methods for estimating ACU on alfalfa and grass hayfields. The three methods evaluated were: 1) irrigation water balance (calculated using data from field equipment installed at the study sites); 2) energy-balance approach (calculated using satellite observations processed with ReSET model), and; 3) reflectance-based approach (calculated using measurements taken with a Cropscan® MSR5hand-held radiometer).

For the three approaches, monthly ACU was the basis for comparison, given that different methods encounter inaccuracies in the estimation of daily ACU. These inaccuracies are under evaluation 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). The ReSET model was evaluated in 2008 against a weighing lysimeter and yielded prediction errors averaging -6.0% (under-prediction) for daily AET on irrigated alfalfa (Elhaddad and Garcia, 2016). Although the accuracy of AET 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 is heavily influenced 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 and labor scheduling constraints. 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.

4.2.1 Monthly ACU for 2015-2016 Using the Irrigation Water Balance Approach

Calculation of monthly ACU by IWB for 2015-2016 was performed by: 1) estimating *daily* ACU by algebraic closure for the crop at the study site, then; 2), adjusting *daily* ACU for days when the IWB results were determined to be inaccurate (discussed in Section 4.1.1.1), and finally; 3) calculating *monthly* ACU by adding daily ACU estimates for any given month. For step one, a daily timestep[13] was used. Monthly ACU was estimated in 2015 and 2016, respectively, for June-August and April-August.

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[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.

The *field-scale monthly* ACU was obtained by averaging the results between the two sensing stations each on the fully- and partially-irrigated fields at MTR, and the five sensing stations for the sprinkler irrigated field at DLT. On the other hand, because of its larger size, AET for each of the 6 sensing stations at GUN site was compared individually to AET from remote-sensing and radiometer observations.

4.2.1.1 Components of the Irrigation Water Balance

For the majority of days, the IWB could be simplified to a function of the change in soil moisture, given that: 1) irrigations were infrequent, and; 2) upflux and capillary rise were negligible (discussed below).

Rooting Depth (DLT). For alfalfa at DLT, rooting depth was estimated at no more than 50 in based on similarity to the maximum depth of 58.8 in specified for alfalfa under ASCE Manual 70. Plant rooting depth is likely impacted by resistant gravel deposits characteristic of the mesa where the site is located. As noted by Ley et al. (1994), if soil depth is shallow or if a soil layer impedes root or water penetration, this depth becomes the effective rooting depth. 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. Previously cited research on two-year-old alfalfa plants grown under irrigation in dry upland soil in New Mexico, for instance, had roots 3 to 4 ft deep where 2 in of water were applied during each irrigation event (Thompson and Barrows, 1920). Lastly, previous research showing that under high frequency irrigation, as practiced by sprinkler systems, crops expected to have four-foot rooting zones in deep uniform soil are often found to be extracting water only to depths of 18 to 24 in in the profile (Ley et al., 1994). This is generally due to the diminished need for plants to seek water from deeper zones in the soil profile. Therefore, it is possible that rooting depth was even shallower, but a more thorough physical examination of root depths is needed. For grass pastures, typical rooting depths are 24-36 in (Jensen et al., 2006; Orloff et al., 2016).

Rooting Depth (MTR). For grasses at MTR, rooting depth was estimated at no more than 30 in. Although this depth is 9.6 in less than specified for grass pasture under ASCE Manual 70, Giddings core sample observations and auguring indicated that 30 in was as deep as roots were likely to penetrate at MTR. Finally, the groundwater table at MTR held at approximately 30 in below the surface for the entire season.

Rooting Depth (GUN). For grasses at GUN, rooting depth was estimated at 18 in, based on previous observations of grass meadows (Coupland and Johnson, 1965; Moore and Rhoades, 1966; Manning et al., 1989). Prior studies of high mountain meadows in Colorado also suggest that a sharp restriction in root matter is expected at the interface of rocky layers found close to the surface and approximately 6 in above the high-water table (Walter et al., 1990). The estimated rooting depth was also consistent with field evaluations, well drilling, and auguring. Additionally, the groundwater table at GUN held at approximately 24 in below the surface, except when rising levels occurred during irrigation.

Soil Moisture Deficit (D_c - D_p). Components D_c and D_p were calculated from sensor data and determined relative to the field capacity of the soils provided in Table 3.1 in section 2. Raw soil moisture data at MTR and GUN was further calibrated using measurements from field and laboratory calibration curves shown in Figure 4.1.

Raw soil matric potential (ψ_m) for the Watermark sensors at DLT had to be related to volumetric water content (θ) using a soil water characteristic curve. Recent studies of Watermark accuracy suggested that these sensors tend to overestimate water concentrations and should therefore be calibrated to specific site applications (Hignett and Evett, 2008; Varble and Chávez, 2011). Because this study did not originally acquire volumetric water content samples at DLT, soil moisture at this location had to be derived from a soil-water characteristic equation for sandy clay loam soils developed using methods described by Saxton and Rawls (2006) and the soils analysis results for the DLT site. The soil characteristic curve used for this site is in Figure 4.2. Subsequent field sampling was performed, which may improve the accuracy of the soil characteristic curve for DLT.

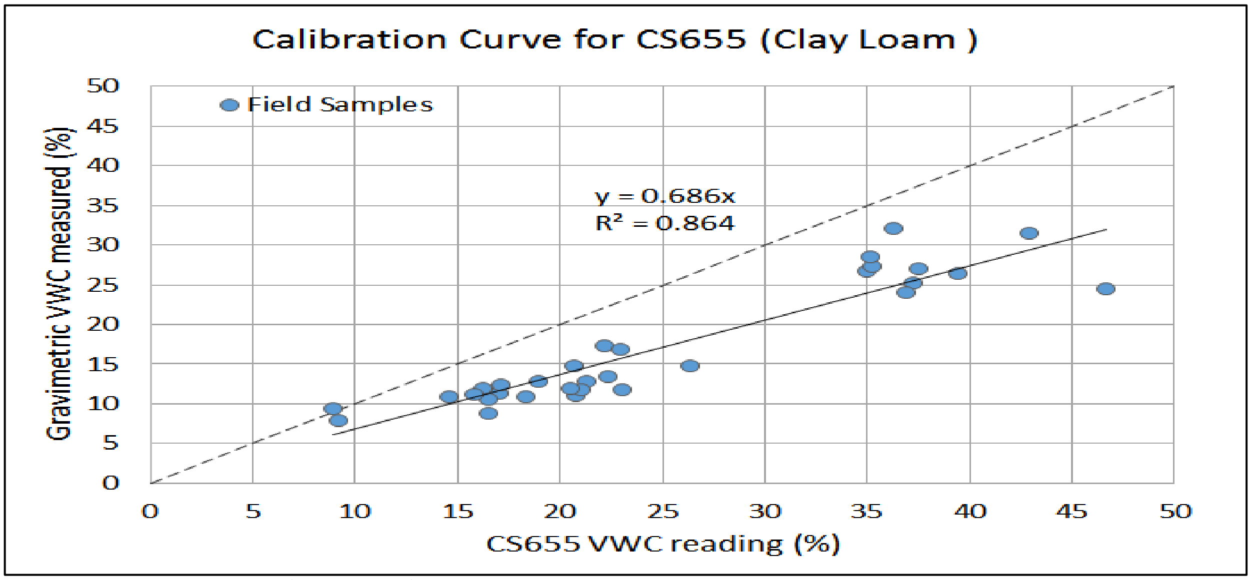

Figure 4.1. Soil calibration (MTR, GUN).

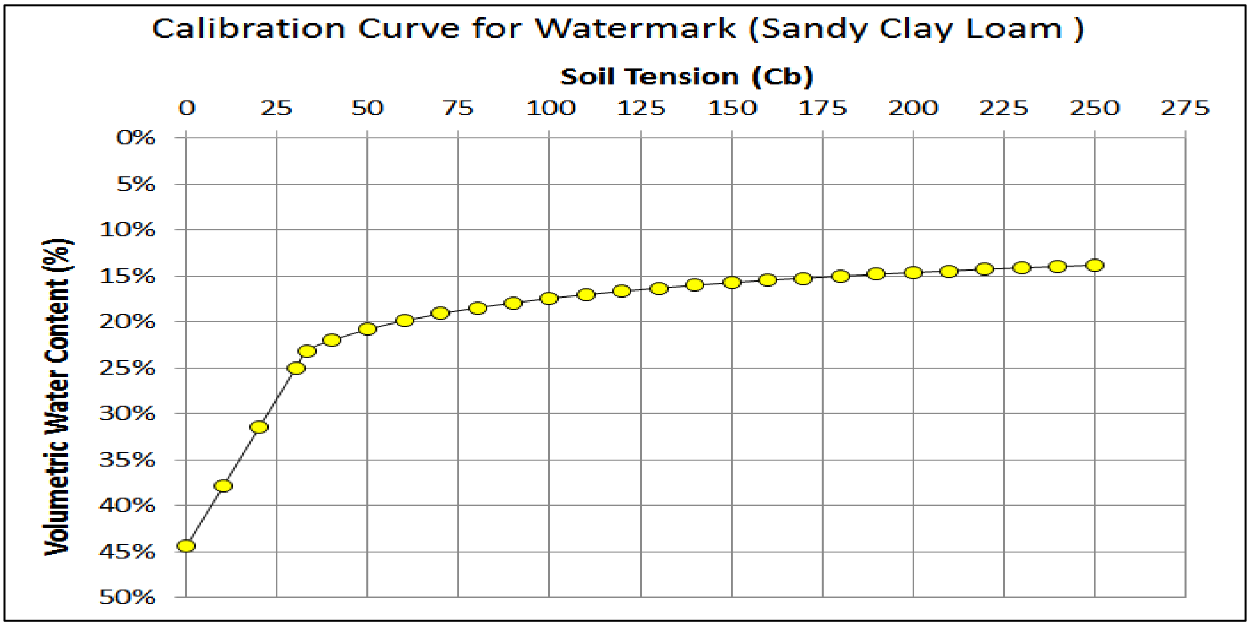

Figure 4.2. Soil characteristic curve, DLT.

Effective Precipitation (P_{eff}). Maximum and median precipitation events are summarized in Table 4.3 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. Volumetric 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, 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 4.3. Precipitation (2015-2016 study period).

	Delta, CO		*Montrose, CO*		*Gunnison, CO*	
	2015	*2016*	*2015*	*2016*	*2015*	*2016*
Median	0.09	0.07	0.05	0.05	0.04	0.05
Maximum	0.41	0.65	0.66	0.88	0.60	0.74

Irrigation (Irr). As mentioned earlier, for most the season, the IWB was unaffected by irrigation. Furthermore, 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 DLT, irrigation rates were cross-checked with recorded flows on the sprinkler system. At MTR, 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 GUN, 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 as the algebraic closure term was unaffected by combining SRO and DP.

Upflux (U). Upflux was nonexistent at DLT based on the nonexistence of a groundwater table at all five observation wells for the entire season. Upflux was negligible at MTR, based on groundwater levels and the dry conditions (near wilting point) observed when irrigation was suspended. Additionally, electrical conductivity (EC) measured by the CS655 sensors showed 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. Upflux at GUN was also negligible, due to the lack of capillary potential in rockier soils. Prior studies of intermountain meadows, for instance, reported that rocky layers as observed in this study pose significant restrictions to the rise of capillary water into zones of heavy rooting (Walter et al., 1990).

4.2.1.2 Results of the Irrigation Water Balance

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

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

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

The results of Equations 4.2 and 4.3 produced two outcomes.

1. *Acceptable*. The most typical was the outcome in which estimated daily ACU fell within an expected range of ACU rates between 0.05 to 0.50 in 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. *Unacceptable*. The second outcome occurred when estimated daily ACU rates were in error, showing much larger or much lower (including negative) than the expected ACU rates. These values were likely due to the simplicity of the 1-dimensional IWB being unable to accurately capture sudden changes in the soil water content. Given the need for representative daily data, unacceptable estimations were replaced with modeled values given by a relationship between AET and PET from the nearest CoAgMet station. Acceptable AET rates at each location, for instance, were found to exhibit curvilinear relationships with PET rates. The curvilinear relationship appeared to represent the fact that under water-supply limiting conditions, AET was much lower than PET, but at water limitations abated, AET more closely corresponded with PET.

Monthly estimated ACU results are shown in Table 4.4 for the study sites during periods of assessment June-August (2015) and April-August (2016).

Table 4.4. Monthly estimated ACU (2015-2016) using the irrigation water balance method (in).

	Delta (alfalfa)		*Montrose (grass)*				*Gunnison (grass)*	
	2015	*2016*	*2015*		*2016*		*2015*	*2016*
Month	*sprinkler*		*full*	*partial*	*full*	*partial*	*flood*	
April		2.87			2.04	1.80		1.61
May		4.70			3.99	3.57		3.42
June		5.62[3]	3.86	3.70[6]	3.78	3.41		4.80
July	n/a[1]	5.87[4]	6.36	6.63	5.05	2.36[8]		4.73
August	2.69[2]	4.29[5]	3.81	3.85	3.95	2.08		3.42
Sept			1.61	1.46[7]				
Oct			1.31	1.14				

[1] Alfalfa seeded on July 1, 2015 | [2] Hay cutting on August 15, 2015 | [3] Hay cutting on June 3, 2016 | [4] Hay cutting on July 12, 2016
[5] Hay cutting on August 16, 2016 | [6] Record of data began June 10, 2015 | [7] Irrigation stopped on August 13, 2015
[8] Irrigation was suspended on July 7, 2016 after the first cutting of grass hay

Table 4.5. Monthly estimated ACU at individual well locations in Gunnison, Colorado (2016) using the irrigation water balance method (in).

	Observation Well ID and Description								
			KR206_SE	*KR206_WC*	*KR206_NW*	*KR206_EC*	*KR206_SW*	*KR206_NE*	
	K1	*K2*	*K3*	*K4*	*K5*	*K6*	*K7*	*K8*	*K9*
Month			*mid*	*Low*	*low*	*mid*	*high*	*mid*	
April			1.37	0.38	2.21	1.75	1.89	2.04	
May			2.09	3.13	4.01	3.72	3.81	3.73	
June			2.59	4.96	5.13	5.41	5.48	5.25	
July			2.52	5.89	4.77	5.10	5.14	4.94	
August			2.04	3.09	3.90	3.75	3.93	3.83	
September									

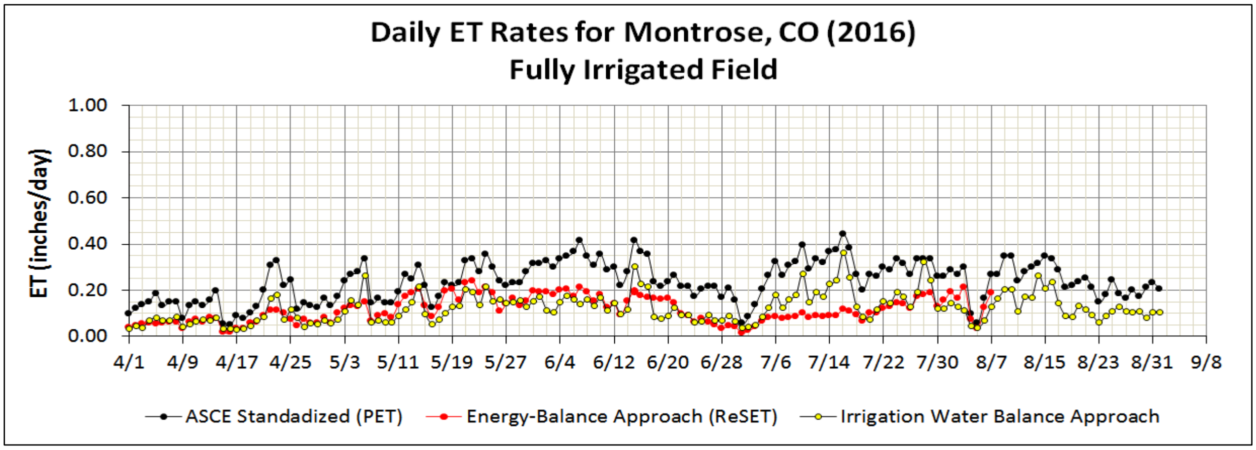

Figure 4.3a. Daily ET rates estimated for fully irrigated MTR field using the energy balance and irrigation water balance approaches, as compared with ASCE standardized (potential ET).

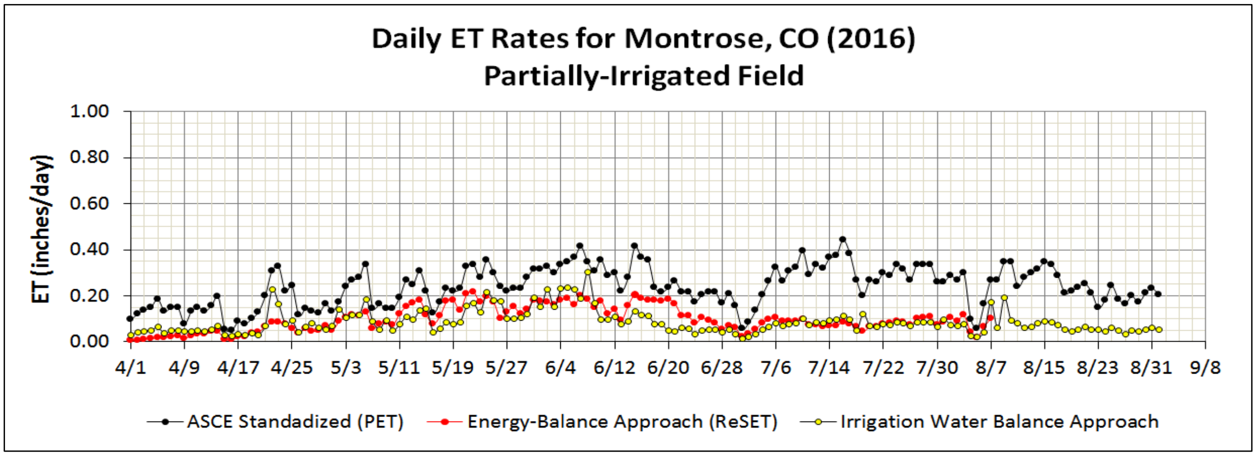

Figure 4.3b. Daily ET rates estimated for split-season irrigated MTR field using the energy balance and irrigation water balance approaches, as compared with ASCE standardized (potential ET).

4.2.2 Monthly ACU for 2015-2016 Using the Energy-Balance Approach

Some striping was noted in the Landsat 7 images, but the Montrose and Delta study sites fortunately lie near the center of the scene and were 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 image dates for the 2015 and 2016 growing season were used 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 4.6 and Table 4.7 for Path 35/Row 33 (DLT, MTR) and for Path 34/Row 33 (GUN), with cloud-free image dates in bold.

Because the Western Slope is 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[14] for those measurements 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[15] 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.

4.2.3 Estimated ACU for Select Dates Using the Reflectance-Based Approach

The procedure for using measuring with the handheld MSR5 was to take readings during solar noon on the exact day of a Landsat overpass. Multiple measurements were taken within a field.

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

Although this project utilized the LANDSAT data to determine the energy balance approach, a separate evaluation was performed by Vashisht (2016) to develop a reflectance-based approach for relating NDVI to “crop coefficients,” as shown in Figure 4.4. Relationships between NDVI and crop coefficients have not been developed. Either a previously-developed VI-Kc relation for a similar crop 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 need to be evaluated and quantified.

While the energy balance approach requires the coarser thermal band, and follows a physically-based approach, the reflectance-based coefficient approach is empirical and can afford higher resolution

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[14] 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.

[15] $H = \rho \, Cp \, (Taero - Ta) / rah$; where, ρ is the density of air, Cp is the specific heat of air, rah is the surface aerodynamic resistance to heat transfer, Taero is the surface aerodynamic temperature, and Ta is the air temperature at screen height (Brutsaert et al., 1993).

without the thermal band (especially for Landsat 8). This may be required for capturing intra-field variability, and is especially applicable for smaller pasture fields on the Western slope where coarse thermal resolution is a limitation and the energy balance method cannot be applied without some contamination of thermal pixels from surrounding areas.

Table 4.6. Growing season cloud-free imagery for Landsat 7 overpass dates.

Path 35/Row 33 (Delta, CO; Montrose, CO)				*Path 34/Row 33 (Gunnison, CO)*			
2015		*2016*		*2015*		*2016*	
Date	*Cloud Cover*	*Date*	*Cloud Cover*	*Date*	*Cloud Cover*	*Date*	*Cloud Cover*
Mar 30	2%	**Apr 1**	**44%**	Apr 8	48%	Apr 10	69%
Apr 15	65%	Apr 17	91%	Apr 24	88%	Apr 26	84%
May 1	41%	**May 3**	**0%**	May 10	92%	**May 12**	**0%**
May 17		**May 19**	**53%**	May 26	76%	May 28	54%
Jun 2	**0%**	**Jun 4**	**12%**	Jun 11	67%	**Jun 13**	**45%**
Jun 18	**11%**	**Jun 20**	**3%**	**Jun 27**	**15%**	Jun 29	56%
Jul 4	39%	**Jul 6**	**6%**	**Jul 13**	**61%**	Jul 15	42%
Jul 20	**46%**	Jul 22	22%	Jul 29	16%	Jul 31	64%
Aug 5	**4%**	**Aug 7**	**13%**	**Aug 14**	**19%**	Aug 16	47%
Aug 21	**1%**	Aug 23		**Aug 30**	**22%**	Sep 1	37%
Sep 6	**34%**	Sep 8	0%	Sep 15	48%	Sep 17	
Sep 22		Sep 24		Oct 1		Oct 3	
Oct 8	0%	Oct 10		Oct 17		Oct 19	

Table 4.7. Growing season cloud-free imagery for Landsat 8 overpass dates.

Path 35/Row 33 (Delta, CO; Montrose, CO)				*Path 34/Row 33 (Gunnison, CO)*			
2015		*2016*		*2015*		*2016*	
Date	*Cloud Cover*	*Date*	*Cloud Cover*	*Date*	*Cloud Cover*	*Date*	*Cloud Cover*
Apr 7	3%	Apr 9	67%	Mar 31	7%	**Apr 2**	**6%**
Apr 23	37%	Apr 25	47%	Apr 16	72%	Apr 18	73%
May 9	59%	May 11	40%	May 2	38%	**May 4**	**3%**
May 25	62%	**May 27**	**45%**	May 18	58%	May 20	65%
Jun 10		Jun 12	28%	Jun 3	3%	**Jun 5**	**16%**
Jun 26	**1%**	**Jun 28**	**3%**	**Jun 19**	**3%**	**Jun 21**	**4%**
Jul 12	**9%**	**Jul 14**	**1%**	Jul 5	79%	**Jul 7**	**1%**
Jul 28	**1%**	Jul 30	32%	**Jul 21**	**38%**	**Jul 23**	**13%**
Aug 13	**15%**	Aug 15	6%	**Aug 6**	**8%**	Aug 8	32%
Aug 29	**9%**	Aug 31	16%	Aug 22	13%	Aug 24	65%
Sep 14	80%	Sep 16	2%	Sep 7	48%	Sep 9	
Sep 30	64%	Oct 2		**Sep 23**	**6%**	Sep 25	
Oct 16	7%	Oct 18		**Oct 9**		Oct 11	

Table 4.8. Monthly estimated ACU at study sites (2015-2016) using the energy balance method (in).

	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[§]	5.00	5.15
August	5.39		4.81	4.77[‡]			5.09	
Sept			4.01	3.40				
October			2.56	2.12				

[‡] Irrigation was suspended on August 13, 2015.

[§] Irrigation was suspended on July 7, 2016 after the first cutting of grass hay.

Table 4.9. Monthly estimated ACU at individual station locations at Gunnison, Colorado (2016) using the energy balance method (in).

	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									

Table 4.10. Estimated ACU at study sites (on specific 2015-2016 overpass dates) comparing IWB, EB, and reflectance-based approaches (in/day).

	Delta (alfalfa)			*Montrose (grass hay)*						*Gunnison (grass hay)*			
	sprinkler			*full*			*partial*			*partial*			*full*
Date	*IWB*	*EB*	*Reflec*	*IWB*	*EB*	*Reflec*	*IWB*	*EB*	*Reflec*	*IWB*	*EB*	*Reflec*	*EB*
8/13/2015	0.104	0.226		0.188	0.153		0.167	0.173	0.160				
9/23/2015												0.051	
10/1/2015	0.062			0.050	0.139		0.058	0.097	0.067				
6/21/2016										0.158	0.247	0.108	
6/28/2016	0.175	0.215	0.224	0.070	0.032	0.076	0.043	0.055	0.088				
7/7/2016										0.170	0.286	0.143	
7/14/2016	0.190	0.120	0.128	0.242	0.088	0.107	0.093	0.070	0.123				
7/22/2016	0.149	0.134	0.184	0.153	0.119	0.104	0.076	0.075	0.096				
7/23/2016										0.140	0.111	0.110	
7/30/2016	0.121	0.092	0.132	0.121	0.128	0.105	0.066	0.072	0.064				

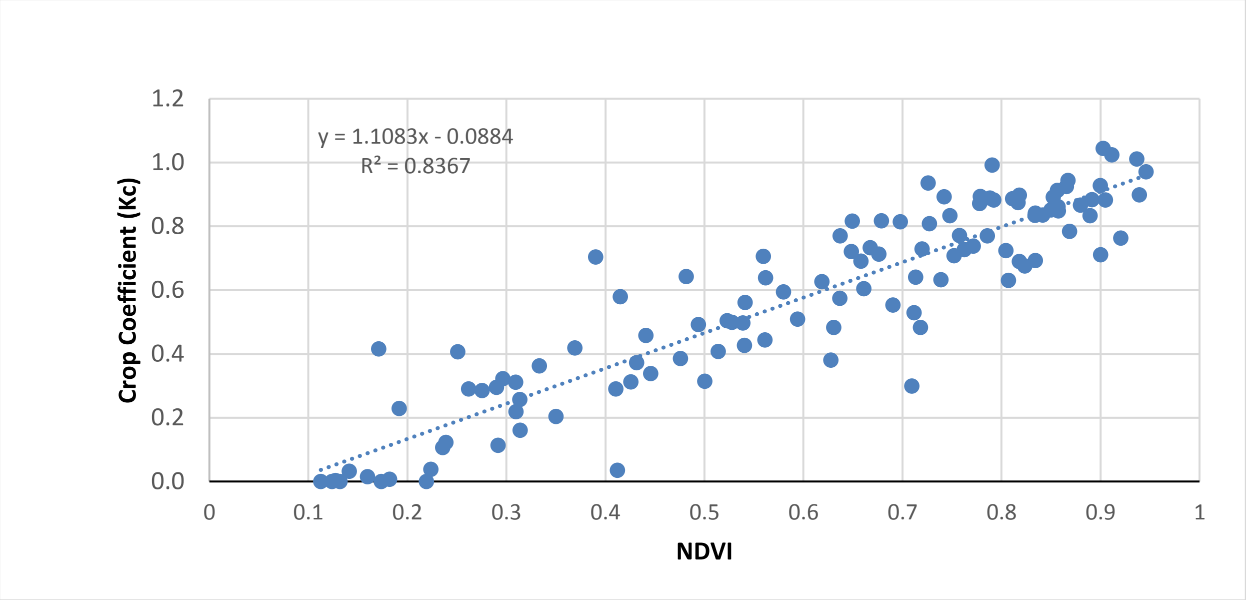

Figure 4.4. Relationship between NDVI and a crop coefficient for grass pastures.

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 climatological conditions of the area and can be compared to generic FAO-56 tabulated coefficients to check tabulated coefficient 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.

4.2.5 Incidental Atmometer Observations

Atmometer observations at two locations were compared with the ASCE Standardized Alfalfa Reference ET provided by CoAgMet. For the DLT site (alfalfa canvas #54), the total ET recorded between 5/24 and 10/18 was 30.70 in versus the ASCE Standardized ET estimation of 37.18 in. For the KR site (grass canvas #30), however, the total ET recorded between 6/9 and 9/29 was 19.20 in versus ASCE ET estimation of 22.11 in, again slightly underestimating.

4.2.6 Discussion of Different ACU Estimation Approaches

Possible explanations for over/under estimation using ReSET:

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

advantage is more fine scale and more densely sampled field.

4.3 Objective 2: Apply the Energy-Balance Approach to Archived Multi-Spectral Imagery to Estimate Historical ACU on Alfalfa and Grass Fields in Mesa, Delta, Montrose, and Gunnison Counties.

There were seven 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 assumes H=0 at cold points and LE=0 at hot points, but models each area based on its local hot and cold pixels. The rest of the procedure for processing Gunnison imagery was mostly similar, except extrapolation from hourly to daily was done based on Evaporative Fraction (EF) as in SEBAL, and interpolation between consecutive overpass days was done based on 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, as described earlier. 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.

4.3.1 Monthly ACU for 2011, 2013, and 2014 Using the Energy-Balance Approach

The second objective of this project was to apply the energy balance method (through ReSET) to archived Landsat data, for 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 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.

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.

For the assessment of historical ACU from 2011, 2013, and 2014, 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.

Table 4.11. Growing season cloud-free imagery for Landsat 7 overpass dates.

Path 35/Row 33 (Delta, CO; Montrose, CO)				*Path 34/Row 33 (Gunnison, CO)*			
2013		*2014*		*2013*		*2014*	
Date	*Cloud Cover*	*Date*	*Cloud Cover*	*Date*	*Cloud Cover*	*Date*	*Cloud Cover*
April 25	85%	April 12	91%	March 17	75%	March 20	6%
May 11	**43%**	April 28	85%	April 2	76%	April 5	96%
May 27	29%	**May 14**	**64%**	April 18	93%	April 21	31%
June 12	14%	May 30	71%	May 4	49%	May 7	50%
June 28	21%	June 15	44%	May 20	85%	May 23	75%
July 14	30%	**July 1**	**0%**	June 5	32%	June 24	28%
July 30	**18%**	**July 17**	**20%**	June 21	1%	July 10	22%
Aug 15	20%	**Aug 2**	**11%**	July 7	45%	July 26	37%
Aug 31	**44%**	**Aug 18**	**15%**	July 23	12%	Aug 11	13%
Sep 16	**39%**	**Sep 3**	**0%**	Aug 8	78%	Aug 27	53%
Oct 2	45%	Sep 19	22%	Aug 24	50%		
Oct 18	**56%**						

Table 4.12. Growing season cloud-free imagery for Landsat 8 overpass dates.

Path 35/Row 33 (Delta, CO; Montrose, CO)				*Path 34/Row 33 (Gunnison, CO)*			
2013		*2014*		*2013*		*2014*	
Date	*Cloud Cover*	*Date*	*Cloud Cover*	*Date*	*Cloud Cover*	*Date*	*Cloud Cover*
		April 4	54%			Mar 28	38%
April 17	56%	April 20	38%				
May 3	**2%**	May 5	18%	May 12	41%	May 15	55%
May 19	44%	May 22	51%	May 28	58%	May 31	24%
June 4	**19%**	**June 7**	**7%**	June 13	36%	June 16	13%
June 20	**0%**	June 23	29%	June 29	34%	July 2	13%
July 6	59%	**July 9**	**8%**	July 15	64%	July 18	24%
July 22	**2%**	July 25	59%	July 31	26%	Aug 3	17%
		Aug 10	**7%**	Aug 16	14%	Aug 19	49%
Aug 23	23%	Aug 26	48%	Sep 1	38%		
Sep 8	38%	**Sep 11**	**1%**				
Sep 24	**1%**	**Sep 27**	**21%**				
		Oct 13	**10%**				
		Oct 29	**0%**				

Table 4.13: Growing season cloud-free imagery for Landsat 5 and 7 overpass dates in 2011.

Path 35/Row 33 (Delta, CO; Montrose, CO)				*Path 34/Row 33 (Gunnison, CO)*			
Landsat 5		*Landsat 7*		*Landsat 5*		*Landsat 7*	
Date	*Cloud Cover*	*Date*	*Cloud Cover*	*Date*	*Cloud Cover*	*Date*	*Cloud Cover*
---	---	---	---	Mar 20	79%	Mar 28	82%
---	---	Apr 4	14%	Apr 5	16%	Apr 13	16%
Apr 12	93%	Apr 20	19%	Apr 21	56%	Apr 29	64%
Apr 28	**4%**	May 6	18%	May 7	3%	May 15	67%
May 14	45%	May 22	72%	May 23	66%	May 31	1%
May 30	55%	**Jun 7**	**0%**	Jun 8	1%	Jun 16	31%
Jun 15	**0%**	**Jun 23**	**11%**	Jun 24	15%	July 2	15%
July 1	**4%**	**July 9**	**54%**	July 10	65%	July 18	34%
July 17	36%	**July 25**	**15%**	July 26	26%	Aug 3	25%
Aug 2	38%	**Aug 10**	**5%**	Aug 11	16%	Aug 19	88%
Aug 18	5%	Aug 26	52%	Aug 27	15%	---	---
Sep 3	13%	**Sep 11**	**43%**	---	---	---	---
Sep 19	15%	**Sep 27**	**15%**	---	---	---	---

4.3.2 Remote-Sensing Data Applied to Archived Imagery

Appendix A of this report provides several snapshot images of various ET maps developed for the regions of interest.

4.4 Objective 3: Compare Crop ACU Derived from the Energy-Balance Approach Against the StateCU Model

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

4.4.1 Monthly Historical ACU Derived from StateCU Model

Historical irrigation rates were created using HydroBase Wizard. 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 the consumptive irrigation requirement to estimate ACU.

Table 4.14. Field site characteristics.

Site	*County*	*WDID*	*Water Source*	*Acreage*	*Irrigation*	*Efficiency*	*Crop Type (2015)*
RN	Delta	4100534	Ironstone Canal	20956.6	Furrow	45%	Alfalfa
FG	Montrose	4100537	Loutsenhizer Canal	3263.6	Furrow	45%	Grass Pasture
KR	Gunnison	2800532 2800513	Coats Bros Ditch	246.3 43.5	Flood	45%	Grass Pasture

Table 4.15. Monthly estimated WSLCU at study sites (2015-2016) using StateCU (in).

	Delta (alfalfa)		*Montrose (grass)*				*Gunnison (grass)*	
	2015	*2016*	*2015*		*2016*		*2015*	*2016*
Month	*sprinkler*		*full*	*partial*	*full*	*partial*	*flood*	
April	nd	nd	1.89	na	nd	na	nd	nd
May	nd	nd	2.51	na	nd	na	nd	nd
June	nd	nd	6.41	na	nd	na	nd	nd
July	nd	nd	6.54	na	nd	na	nd	nd
August	nd	nd	6.04	na	nd	na	nd	nd
Sept	nd	nd	4.32	na	nd	na	nd	nd
October	nd	nd	1.69	na	nd	na	nd	nd

na = not applicable nd = no data

Table 4.16. Monthly estimated PET[†] at study sites using StateCU (in/mo).

	Delta, CO (alfalfa)			*Montrose, CO (grass hay)*			*Gunnison, CO (grass hay)*		
Month	*Start*	*End*	*PET (in)*	*Start*	*End*	*PET (in)*	*Start*	*End*	*PET (in)*
April	1998	2014	0.94	1998	2015	1.90			
May	1998	2014	5.19	1998	2015	4.23	1998	2014	2.18
June	1998	2014	7.55	1998	2015	6.47	1998	2014	4.44
July	1998	2014	9.30	1998	2015	7.94	1998	2014	6.09
August	1998	2014	7.69	1998	2015	6.54	1998	2014	5.10
September	1998	2014	4.70	1998	2015	4.21	1998	2014	3.17
October	1998	2014	0.86	1998	2015	2.09	1998	2014	0.82

[†] Using Modified Blaney-Criddle method

Table 4.17. Monthly estimated IWR at study sites 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	2014	0.83	1998	2016	1.07	1998	2014	0.36
May	1998	2014	4.85	1998	2016	2.32	1998	2014	1.76
June	1998	2014	7.48	1998	2016	4.11	1998	2014	4.25
July	1998	2014	8.32	1998	2016	4.46	1998	2014	5.21
August	1998	2014	6.93	1998	2016	3.62	1998	2014	4.09
September	1998	2014	3.96	1998	2016	2.20	1998	2014	2.65
October	1998	2014	0.56	1998	2016	0.99	1998	2014	0.57

Table 4.18. Monthly estimated WSLCU at study sites using StateCU (AF/ac).

	Delta, CO (alfalfa)			*Montrose, CO (grass hay)*			*Gunnison, CO (grass hay)*		
Month	*Start*	*End*	*WSLCU*	*Start*	*End*	*WSLCU*	*Start*	*End*	*WSLCU*
April	1998	2014	1.33	1998	2015	1.86	1998	2014	0.00
May	1998	2014	4.80	1998	2015	3.58	1998	2014	1.78
June	1998	2014	7.36	1998	2015	6.35	1998	2014	4.25
July	1998	2014	8.23	1998	2015	6.89	1998	2014	5.16
August	1998	2014	6.78	1998	2015	5.60	1998	2014	0.92
September	1998	2014	3.90	1998	2015	3.40	1998	2014	1.36
October	1998	2014	0.66	1998	2015	1.54	1998	2014	0.27

Table 5.1. Monthly estimated ACU at study sites (2015-2016) from the irrigation water balance, energy balance and WSLCU (StateCU model) approaches (in/day).

	Delta (alfalfa)			*Montrose (grass hay)*			*Gunnison (grass hay)*		
Month	*IWB*	*EB*	*WSLCU*	*IWB*	*EB*	*WSLCU*	*IWB*	*EB*	*WSLCU*
April	2.87	3.23	1.33	2.04	1.85	1.86	1.61		0.00
May	4.70	5.27	4.80	3.99	4.03	3.58	3.42	6.10	1.78
June	5.62	5.95	7.36	3.82	5.39	6.35	4.80	7.27	4.25
July	5.87	5.28	8.23	5.71	4.37	6.89	4.73	5.08	5.16
August	4.29	3.23	6.78	3.88	4.64	5.60	3.42	5.09	0.92
September		5.39	3.90		3.39	3.40		3.91	1.36
October			0.66			1.54			0.27

5 Conclusions and Recommendations for Future Research

In regards to objective 1, the results from the ReSET model were reasonably consistent with the measurements of ACU as determined from the irrigation water balance, as summarized in Table 5.1 below. In general, the energy balance method overestimated relative to the irrigation water balance. Evaluations at the DLT-alfalfa and MTR-grass sites resulted in an average 13% and 19% overestimation of monthly AET by ReSET. Evaluations at the GUN-grass site resulted in an average 47% overestimation of monthly AET, based on the data collected in this study. Correspondence between the IWB and energy balance approaches was best during well-irrigated conditions. One explanation for this fact could be that as the field receives less water and bare soil is exposed, the "big leaf" assumption may fail. Others have reported surface temperatures of stressed vegetation as being an important factor that can lead to overestimation by energy balance methods (Sun et al., 2013).

The issue of temporal accuracy will continue to force users of Landsat imagery to rely on splining or other interpolation techniques to extrapolate between Landsat passes. The use of Sentinel data in addition to Landsat may increase temporal frequency and should be examined as a means of improving the inter-pass accuracy. Given that the MSR5 also showed some degree of consistency with other measures of ACU, periodic targeted field visits may also prove useful in improving the accuracy of spatial models to estimate ACU.

In regards to objectives 2 and 3, the work performed for this report entailed the application of ReSET to prior years archived Landsat imagery. While these results are not comparable to irrigation water balances (since instrumentation was not installed prior to 2015), it was possible to compare the AET rates estimated by ReSET against the modeled results supplied by StateCU, as summarized in Table 5.1. Given that StateCU relies on weather-based models to describe ET, it is not surprising that the rates described by the model are generally larger than what is predicted by the energy-balance and irrigation water balance methods.

A final point of note - although the ReSET model is still in use at Colorado State University (CSU), 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⟩. This model may be more appropriate for long-term administrative use under an entity seeking to conduct and monitor water sharing arrangements.

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Appendix A: Mapping of Historical ET Rates for Landsat Path 35/Row 33 and Path 34/Row33

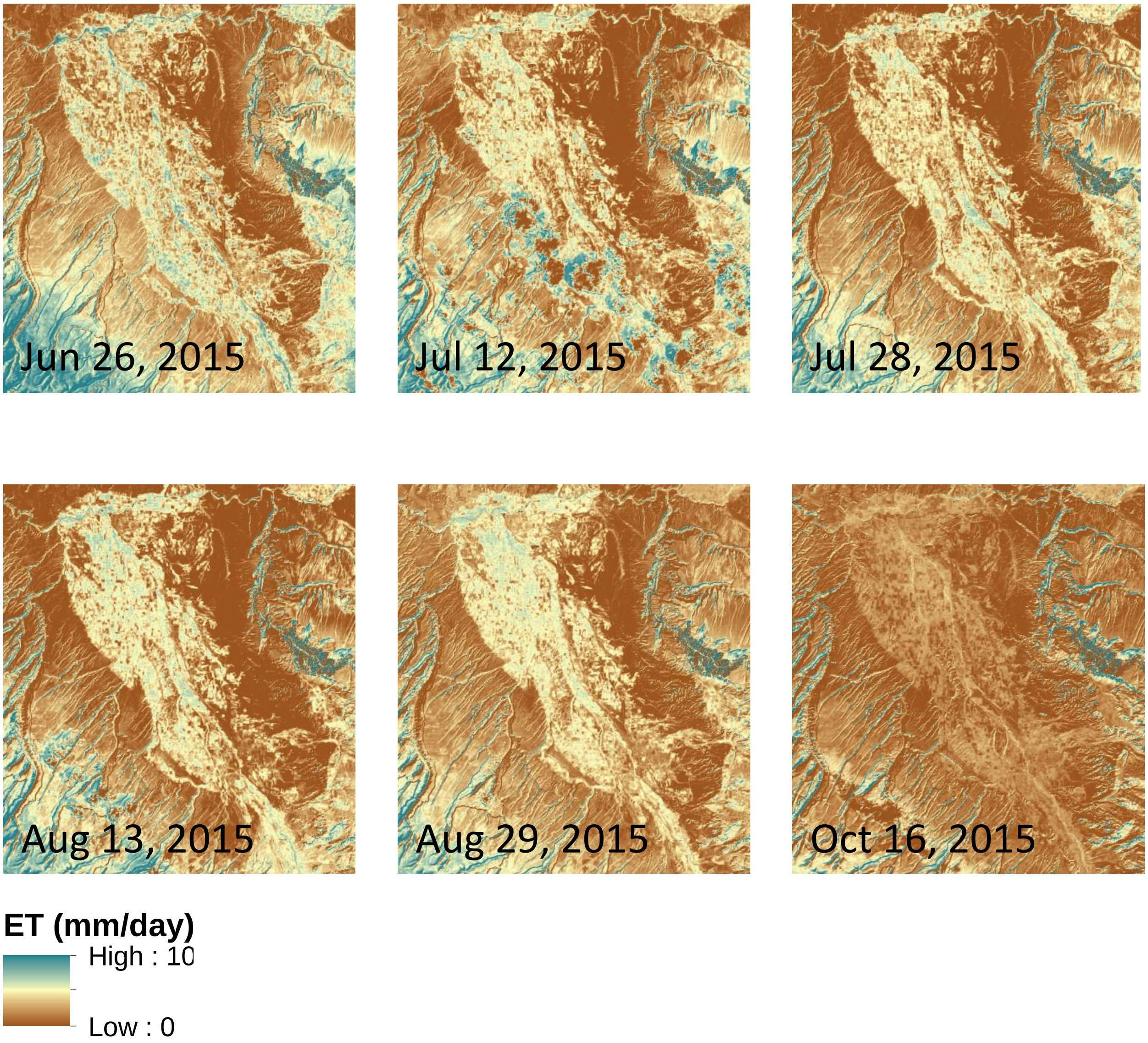

Figure A.1. Spatially mapped ET rates for Path 35/Row 33 in 2015, comprising the area of the Uncompahgre Valley Water Users Association.

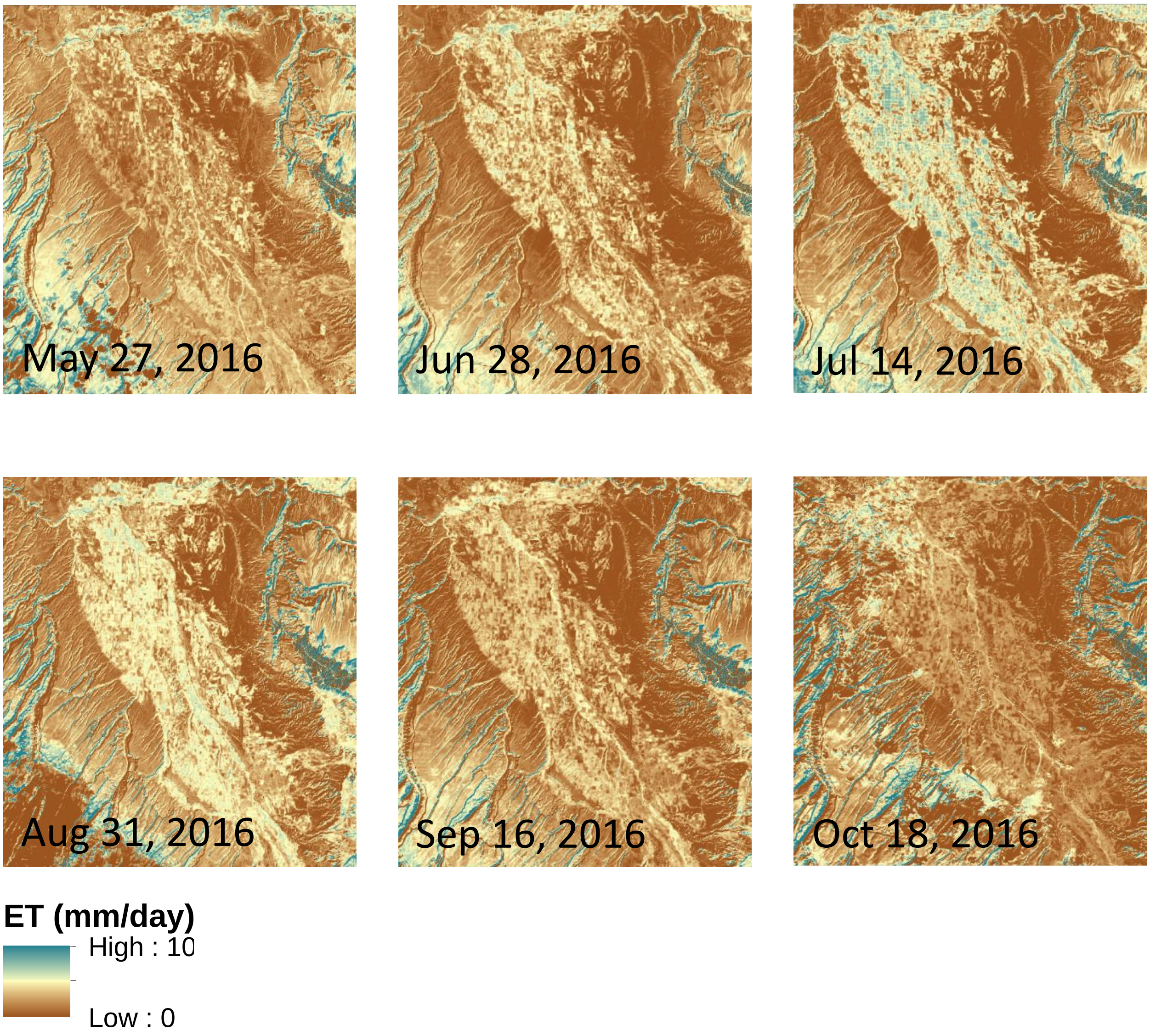

Figure A.2. Spatially mapped ET rates for Path 35/Row 33 in 2016, comprising the area of the Uncompahgre Valley Water Users Association.

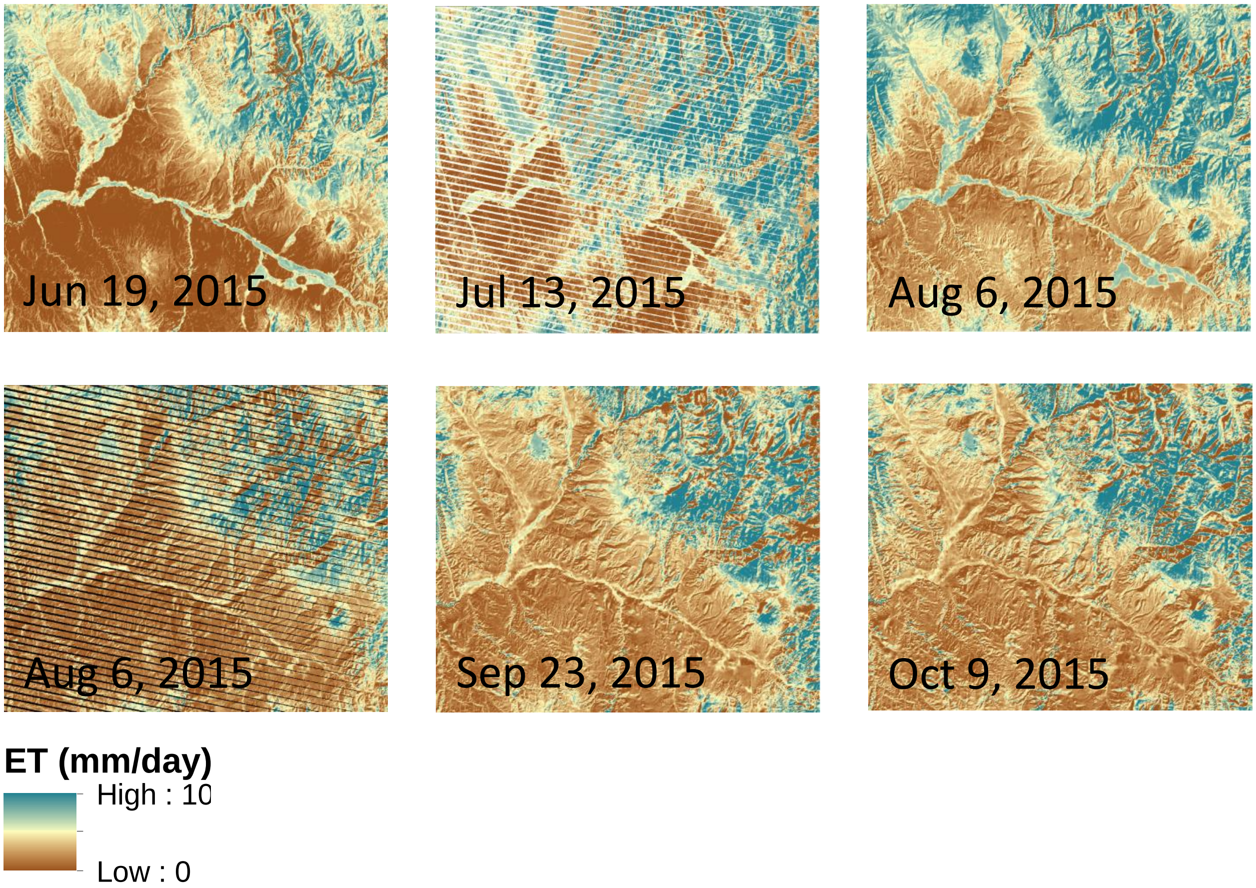

Figure A.3. Spatially mapped ET rates for Path 34/Row 33 in 2015, comprising the area of the Upper Gunnison River Water Conservancy District.

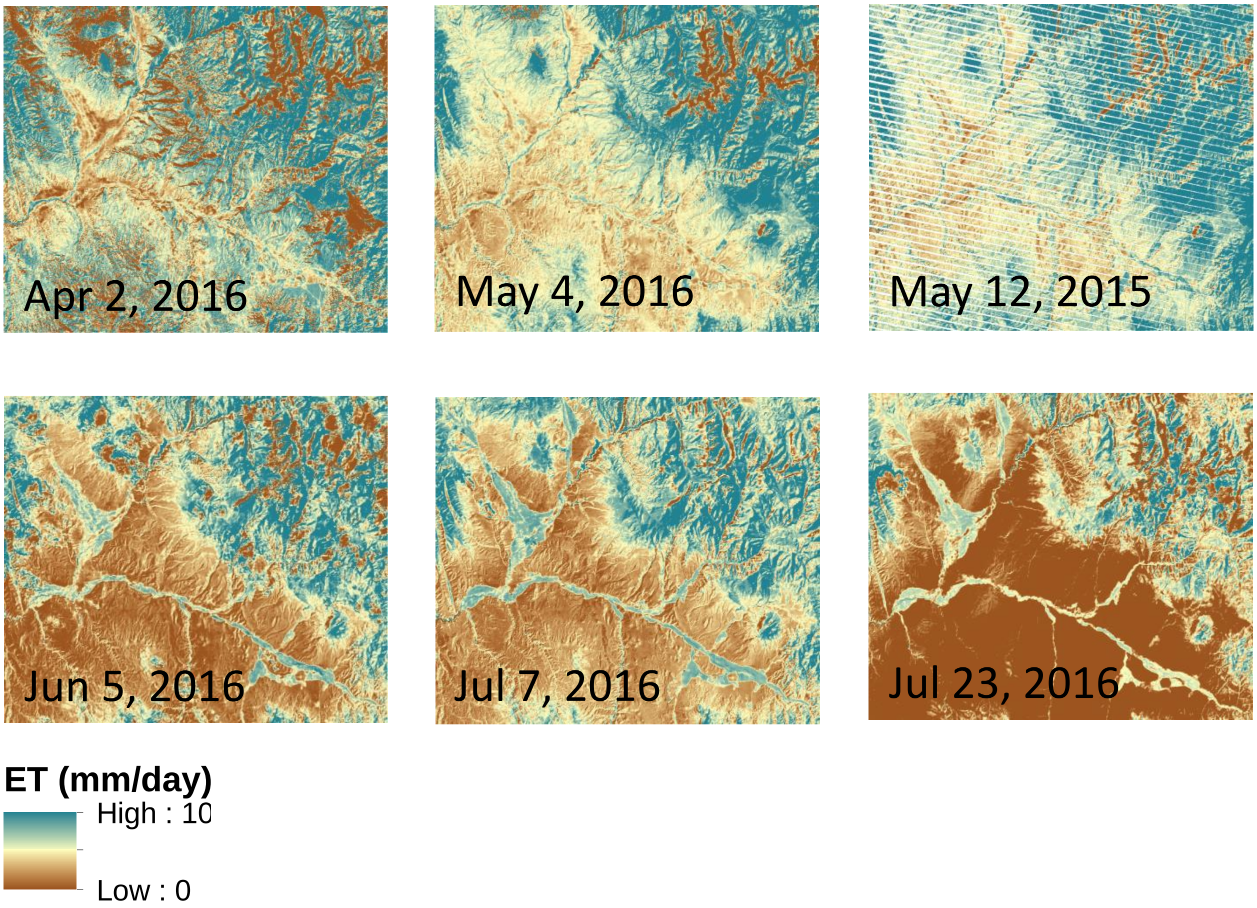

Figure A.4. Spatially mapped ET rates for Path 34/Row 33 in 2016, comprising the area of the Upper Gunnison River Water Conservancy District.